ENERGY IN A FINITE WORLD

A Global Systems Analysis

Report by the Energy Systems Program Group
of the International Institute for Applied Systems Analysis
Wolf Häfele, Program Leader

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FOREWORD

In June 1973 the first scientist arrived at the International Institute for Applied Systems Analysis. He came, just nine months after the signing of IIASA's charter, to work on the Institute's first major study—the Energy Project. In the years since, more than 140 other scientists have come from over nineteen countries to participate in what has become IIASA's Energy Systems Program. Under the leadership of Professor Wolf Häfele, they have carried out a truly comprehensive analysis of the world's energy future.

This book reports their findings. It is also a "first"—the first complete report of a major IIASA program. As such, it carries a dual responsibility. On the one hand, it provides a clear, thorough, and objective presentation of the results of a large, multifaceted study. On the other hand, it demonstrates to a wide and interested audience the nature of the contribution that IIASA can make to a better understanding of major international issues.

Although analysis strives to be objective, it cannot avoid completely the imprint of personality or the influence of individual and group experience. Consequently this study, like all others, reflects the character and background of its authors. Good analysis, however, tries to make these influences and assumptions explicit, so that the user of the analysis can be aware of and compensate for them. Professor Häfele and his team have taken special care in this report to state carefully the assumptions they have made and to distinguish their "visions" from their calculations.

The Institute, for its part, has provided the environment in which this major international and interdisciplinary study could be carried out. And it has established the procedures for scientific review of the report by an international group of experts on energy. But the findings of the study are those of the Energy Systems Program under the leadership of Professor Wolf Häfele and should not necessarily be ascribed to the Institute, its Council, or its National Member Organizations.

The global energy problem is so complex that no single study can hope for complete acceptance. This analysis instead aspires to contribute to the continuing debate and discussion by providing a globally comprehensive framework and a long-term perspective. Inevitably, there will be those who disagree with some of its assumptions, methods, or conclusions. They are challenged to trace the consequences of their alternative views within the same constraints that everything add up across and over time. The discipline of quantification and the necessity of coherence are prerequisites for serious energy analysis.

The global energy problem is so difficult that no nation acting alone can solve it. Yet for the necessary international cooperation to succeed, there must be a base of shared understanding of the nature of the problem and its possible solutions. The IIASA Energy Systems Program has aspired to contribute to the development of that understanding. It has done so both through its own research and through the creation of an international network of collaborating energy institutions and specialists who share its perspective and approach. Thus, this book is just one—very important—dimension of the results of the Energy Program. As it is disseminated and read, we hope that it will help to enlarge the network of those who have a common understanding of the global energy problem and, thereby, will help to establish the basis for wise, successful, and equitable international collaboration in its solution.

When the first IIASA scientist began working on energy seven years ago, the Institute's aspirations were high, but its prospects for success were uncertain. This book demonstrates, we believe, that the Institute's international and interdisciplinary analysis can contribute to a better understanding and resolution of major problems of international importance.

Jermen Gvishiani
Chairman of the IIASA Council

Roger E. Levien
Director of IIASA

PREFACE

This book presents the findings of the study of the global energy system by the Energy Systems Program, Phase I, of the International Institute for Applied Systems Analysis (IIASA). The study, which began in the summer of 1973, focused for the first two years on understanding and conceptualizing the energy problem. This led to the design of a set of energy models that were subsequently used for developing two scenarios—the principal tool of our quantitative analysis. A preliminary draft of our findings was completed in 1978 and sent out for review. The widespread substantive comments received on this draft were carefully considered in finalizing our report. This book, which was completed in December 1979, reflects our work up to this date.

The purpose of this book is not to advance the state of the art of a particular discipline, although we would be pleased if this were to happen. What we have tried to do is to look at each of the different aspects of the energy problem in a new way—to view them as an integral part of an overall pattern. We therefore suggest that the reader consider this book as a picture or a pattern and not concentrate solely on individual chapters or subjects.

This book is divided into parts that cover broad areas of research. In Part I we give some general observations that provide a frame of reference for the whole study. In our discussion of the various global supply options in Part II, and in our treatment of possible constraints on energy strategies in Part III, we have adopted a somewhat visionary approach. We purposely stretched our thinking to the limits so as to provide the reader with the broadest possible choices of input data and parameters for understanding our quantitative analysis in Part IV. Thus, this book has an inherent duality—realism and vision. For our quantitative analysis, we had to be realistic and pragmatic; otherwise we would not have been able to achieve the factual basis on which to consider possible longer term solutions. Yet, morally, we regard this realistic approach as unsatisfactory, since we could assume only modest growth in the developing countries. In Part V, we give some perspectives that we arrived at after having gone through such an exercise.

Our aim throughout this book has been to be objective. However, in adding it all up we recognized the need to take a position and to express the views we actually hold. Thus, the assessments and implications of our study for energy policy, presented in Part VI, cannot be defended merely on an objective scientific basis. They are either evident or not.

IIASA is a small research institution, and the group studying the energy problem was accordingly small. We did not judge it useful to compete with the energy research of larger national and regional study groups. Our intent was to complement their work by providing a long-range, global view of the problems facing civilization. In particular, we aimed for complementarity with the Workshop on Alternative Energy Strategies (WAES). Similarly, our thinking was stimulated by the World Energy Conferences of Detroit (1974) and of Instanbul (1977) and by our contacts with major groups in the energy field such as those of the USSR Academy of Sciences and of the European Community.

IIASA, as a nongovernmental institution, is fortunate to receive the cooperation and support of its seventeen National Member Organizations, which span both East and West. The Energy Systems Program has benefited greatly from the diverse political, social, and economic points of view on the energy problems in these countries. For a truly global perspective, one must also consider the dynamics of the developing countries, and we are grateful for the cooperation received from numerous institutions, groups, and individuals from these countries. We especially wish to acknowledge the support of the United Nations Environment Programme (UNEP) in Nairobi, which helped us to strengthen our rapport with the developing world.

This book was not written by a single author. Given the diversity of contributions and subjects, we felt it would add richness to the exposition if there were some disparity of style as well as individual formats of exposition. Thus, in both the technical and literary editing, the individual authors' viewpoints have been preserved, and the reader may want to take note of our explanations about authorship below.

We would not have been able to complete the research reported on here without the help and support of many institutions, groups, and individuals. In the list below we gratefully acknowledge the help received from these bodies by means of contracts and cooperative agreements. It would give a false impression, however, if this list were considered exhaustive. It is simply impossible to include all here.

UNEP awarded us a major contract on "The Comparison of Energy Options: A Methodological Study," which covered a major portion of our work. Thus, to some extent, UNEP could be considered a co-sponsor of this phase of the Energy Systems Program. UNEP also awarded us a contract on "A Systems Study of Energy and Climate," which permitted us to examine the possible climatic impacts of energy technologies.

The Meteorological Office, Bracknell, United Kingdom, cooperated very closely with us in our study of man's impact on the climate system. Specifically, they provided us with their Global Circulation Model, which served as the basis of our numerical experiments carried out with the above-mentioned UNEP support. We are also grateful to the office for providing us with experimental output.

The Nuclear Research Center (Kernforschungszentrum), Karlsruhe, FRG, provided us with large amounts of inexpensive computer time for executing the numerical experiments supported by UNEP and the Meteorological Office.

For our research on the impacts of solar energy production on the mesoscale climate, we received the cooperation of the Stanford Research Institute, Palo Alto, California, United States.

The National Center for Atmospheric Research, Boulder, Colorado, United States, lent their cooperative assistance to the above-mentioned climate studies supported by UNEP.

The International Atomic Energy Agency (IAEA), Vienna, Austria, formed a joint team with IIASA to study risks. This team made important contributions to IIASA's work in this field.

The Volkswagen Foundation (Stiftung Volkswagenwerk), Hannover, FRG, awarded us a contract for studying "Procedures for the Setting of Standards," which complemented the work of the joint IIASA/IAEA risk team. The Volkswagen Foundation also gave us a contract for studying "The Mechanisms of Market Penetration," which very much expedited our work in this area.

The Federal Ministry of Research and Technology (Bundesministerium für Forschung und Technologie), Bonn, FRG, awarded us a major contract for a "Systems Study on the Possibilities of Intensified Use of Solar Energy in the Federal Republic of Germany (FRG)." Through this assistance we were able to broaden our knowledge of developments in the field of solar power.

The Austrian National Bank (Österreichische Nationalbank), Vienna, Austria, awarded us a contract for studying "Capital and Currency Demand As a Constraint For Future Technological Strategies For Meeting Demand." Their support helped us in the development of the IIASA set of mathematical energy models.

The Siberian Power Institute of the Siberian Department of the USSR Academy of Sciences, Irkutsk, cooperated closely with us, in particular by giving us the early version of a computer program that, after adaptation at IASA, became the economic IMPACT model.

The USSR Academy of Sciences, through the Kurchatov and the High Temperature Institutes in Moscow, participated in our study of "The Fusion and the Fission Breeder Reactor."

The Electric Power Research Institute, Palo Alto, California, United States, contributed to our study of "The Fusion and the Fast Breeder Reactors."

The Institute of Energy Economics and Law (Institut Economique et Juridique de l'Energie), Grenoble, France, cooperated with us, in particular by providing us with a computer program that, after adaptation at IIASA, became the MEDEE-2 model.

Shell Austria, through the Technical University of Vienna, contributed a grant in support of our WELMM studies.

We also wish to acknowledge here the close cooperation of the National Coal Board, United Kingdom; of the United Association of German Hard Coal Mines (Gesamtverband des Deutschen Steinkohlenbergbaus) and the Hard Coal Mining Association (Steinkohlenbergbauverein), FRG; and of the institutions in Poland, the USSR, and the United States that helped us with our assessment of the coal option.

Additionally, we were greatly assisted in our work by the following institutions and industrial firms: The Institute of National Planning, Cairo, Egypt; Siemens, Erlangen, FRG; Kraftwerk Union, Erlangen, FRG; Shell, Vienna, Austria, and London, United Kingdom; General Electric, New York, United States; The Organization of Arab Petroleum Exporting Countries, Kuwait; The Technical University of Vienna, Austria; Gulf Corporation, Pittsburgh, Pennsylvania, United States; Electricité de France, Paris, France; Institut Français du Pétrole, Paris, France; Bureau de Recherches Géologiques et Minières, Orleans, France; Charbonnages de France, Paris, France; Centre National de la Recherche Scientifique, Paris, France; and Institut für Kernenergetik und Energiesysteme der Universität Stuttgart, FRG.

Here, a note on authorship is in order. This book is the product of a closely cooperating, multinational team. In addition to scientists from both East and West, we were assisted by scientists from the developing countries who shared with us their first-hand knowledge of energy problems in their countries. A list of the members of the Energy Systems Program over the study period is given at the beginning of this book. Each member who was with us at Laxenburg for more than a month is included, with the average period of service being between one and two years.

Our team was also multidisciplinary: economists, physicists, engineers, geologists, mathematicians, psychologists, a psychiatrist, and an ethnologist gave us their different views of the energy problem. Thus it was impossible for us to hold an extreme, one-sided view.

Part I, "Introduction," and Chapter 1, "The Problem," was written by W. Häfele, with contributions from B. Spinrad.

Part II, "Energy Supply," was coordinated by B. Spinrad. Chapter 2, "Fossil Energy Resources," was written by M. Grenon. Chapter 3, "The Coal Option," was written by W. Sassin, with contributions from B. Spinrad and

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We hope this book will contribute to a better understanding of and among people and also of nature, which makes it possible for us to live on the earth. We mean this book to contribute to keeping the peace.

Wolf Häfele
Program Leader
Energy Systems Program
IIASA

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INTRODUCTION

1 THE PROBLEM

Roughly 70 percent of today's global primary energy supply comes from oil and natural gas, and roughly 20 percent of the oil is crude from the Persian Gulf. Oil and gas are clean, versatile, and relatively easy to use fuels. The high specific energy content of oil, close to 10,000 kcal/kg, together with the physical properties of a liquid permit easy storage and transportation at relatively low cost. Distances of a global scale, 10,000 km and more, can be traversed relatively easily. Cheap extraction and production of oil from the Persian Gulf states has resulted in growing imports from that source for Western Europe, Japan, and the United States. The low price of oil also stimulated its use in a number of technologies, as a fuel and as a feedstock.

During the 1950s and 1960s, most of the world's economies had relatively high GNP growth rates and, related to that, relatively high energy consumption growth rates. A figure of orientation for both is 5 percent per year. This led to high absolute energy consumptions. Table 1-1 gives global primary energy supply figures for 1975. Roughly 8.1 TWyr/yr[a] of commercial energy and roughly 0.6 TWyr/yr of noncommercial energy (e.g., fuelwood and agricultural waste) were consumed in that year. Such high consumption at relatively constant energy prices has led, in general, to decreasing reserve-to-production ratios for crude oil and natural gas.

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[a] Here and throughout the book we have distinguished between installed power capacity (TW) and annual energy production (TWyr/yr).

Table 1-1. Estimated global primary energy supply, 1975.

Type	*Level (TWyr/yr)*
Commercial energy	
Oil	3.8
Of which oil from Middle East and North Africa	(1.6)
Natural Gas	1.5
Other	2.9
Total commercial energy	8.2
Noncommercial energy (e.g., fuelwood, agricultural waste)	0.6
Total energy	8.8

Sources: Commercial primary energy supply estimates are based on data from United Nations (1978). Estimates of noncommercial energy supply are taken from Parikh (1978).

Until the early 1970s there was no broad awareness of an energy problem. However, by the early 1970s, a new set of political, economic, and social conditions had evolved in the world. The oil-exporting countries have been willing and able to make the price of oil a political determinant, as the price escalation of late 1973 first illustrated. Also, many of the developing countries that export raw materials see the case of oil as an example to be emulated for other products. This has led to a greater political unification of the countries of the South, as has been evident at recent U.N. conferences. The increasing price of oil has made it more difficult for the industrializing countries to accelerate their development and for the industrialized countries to maintain their growing economies.

Since the late 1960s, the impacts of human activities on the environment are no longer considered small and negligible. Increasingly, the globe is seen as finite and sensitive to what humanity does with it. This has inhibited the classical substitution of other resources and technologies for those that have become too expensive. Specifically, neither coal nor nuclear power has been deployed at the rates they might have been had the "energy crisis" occurred in, say, 1960.

THE NATURE OF THE PROBLEM

Today's energy problem is defined by the political and economic stresses brought about by the availability and price of oil and by the limited substitution of other fuels because of environmental constraints. If the problem had arisen in a fairly static world, it might have been solved in time by a combination of efficiency adjustments (e.g., conservation) and substitutions of new supply technologies.

But the world is dynamic. The population is growing. The workforce is growing. Aspirations for amenity are growing. National economies are growing, and for the populations of the Southern hemisphere, this growth must be rapid if they are to achieve reasonable living standards in a reasonable time.

Development takes energy. With existing patterns of national economies and their growth rates, of development in the Southern hemisphere, and of related management of resources prevailing, one could indeed expect a serious energy problem. In fact, the problem already exists. Even if there were no oil problem now, sooner or later the world would have come to grips with the finite nature of the principal fuels in use today. Oil and natural gas are finite. Natural uranium of a quality usable for nuclear power today is finite. While there is plenty of coal, it too is finite. The more we use these fuels, the closer we get to running out of supply or, more exactly, to finding that the remaining supplies are too expensive to use. The world must cope not only with an oil problem, not only with problems of increasing demand, but also with the problems of substituting effectively infinite energy sources for the ones now in use. And here the question is not whether, but when.

The energy problem cannot be broken down into individual elements requiring solution; rather, it is the whole pattern of the energy system that constitutes the problem. It is from this basis that the following elements must be considered:

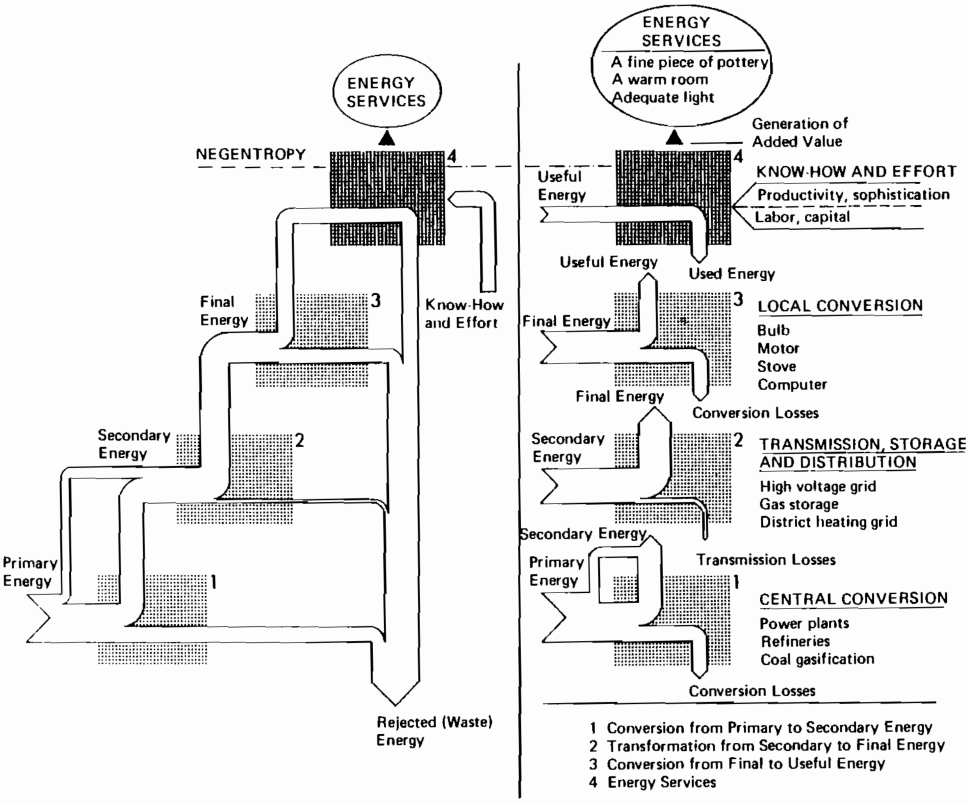
- Absolute size of energy demand;
- Rate of annual increase of energy demand;
- Allocation of global resources to countries—features of world energy trade;
- Buildup rates of technical supply facilities;
- Innovation rates;
- Absolute size of resources;
- Absolute size of environmental and ecological impacts;
- Management of environmental and ecological impacts;
- Societal and political acceptance of technical and economical changes;
- Relationship between energy problems and policies and more general social problems.

Energy Forms and Levels

In order to clarify the nature of the energy problem, we differentiate here between energy at various stages of conversion and use. Figure 1-1 is helpful for understanding this point. *Primary energy* is the energy recovered from nature—water flowing over a dam, coal freshly mined, oil, natural gas, natural uranium. Only rarely can primary energy be used to supply *final energy*—energy used to supply energy services. One of the few forms of primary energy that can be used as final energy is natural gas, which is why it is a fuel of preference whenever it is available.

For the most part, primary energy is converted into *secondary energy*—de-

Figure 1-1. Energy conversion and use.



fined as an energy form that can be used over a broad spectrum of applications. Examples are electricity, gasoline, and natural gas; at lesser convenience (which is why they are declining in their market shares), one could also consider charcoal, sorted and graded coal, and cut and split fuelwood as secondary energy forms. In order to apply energy without making undue demands on the consumer, it must be converted into a form that is readily transported and distributed and that can be used in a variety of devices. The trend has been toward grids, for obvious reasons—specifically electricity, gas, and district heating grids. For convenience of storage, portability, and transportability, the trend has also been to liquid fuels, of which gasoline and diesel oil are the best examples.

Primary energy is converted into secondary energy in several different ways. Central power plants produce electricity and sometimes district heat. Refineries convert petroleum, which is not an easy fuel to use at the end point, to more convenient liquid fuels—gasoline, jet fuel, diesel oil, and naphtha. When gasoline is not available, coal conversion plants can make liquid fuels. Sometimes the conversion plant is the end point of a system, as with nuclear fission energy (for which chemical conversion, isotopic enrichment, and fuel fabrication all precede the power plant); sometimes, as with a hydroelectric or a wind generator, it is a simple machine. But, regardless, there are conversion losses in going with primary to secondary energy and transmission losses in getting that energy to the consumer. It is wrong to think of these losses as waste. They represent a trade-off of efficiencies: the use of energy to transform and transmit energy permits the end user to apply it efficiently for his purposes. These final steps are the conversion of secondary energy into final energy—the energy in a motor, a stove, a computer, or a lightbulb—and of final energy into useful energy—the energy actually stored in a product or used for a service. It is important to realize that in providing the service (say, a well-lit room), energy is not merely a stored entity, but even more an input for the efficient use of other resources—of labor, of capital, and especially of skill.

THE IIASA ENERGY STUDY AND ITS OBJECTIVE

We aimed for a new way of looking at the energy problem that would put the above ten elements of the energy problem into a new pattern. How can such a problem be approached? What substantive questions should be put to the forefront? What methods can be employed? During the early years of the IIASA Energy Systems Program, we conceptualized the problem by exploring ranges of the parameters involved, by identifying terms and their mutual relations, and by defining explicitly the objective of the study.

What we were looking for were ways of characterizing demands, supply opportunities, and supply constraints and ways of matching them all up. When we tried to define the nature of the problem, we came to grips with at least six of these ten elements. For three of these—innovation rates, management of environmental and ecological impacts, and social and political acceptance of technoeconomic changes—we cannot claim to have done complete research. And we purposely refrained from dealing with the last element of the relationship between energy problems and policies and more general social problems. IIASA is a small research institute that grew out of the belief that the problems of civilization would gradually become of a global nature and would thereby require more and more East-West cooperation. As the relationship between energy problems and policies and social problems varies greatly from country to country, this topic was therefore deleted, at least for the present phase of IIASA research. The IIASA approach was to concentrate on the factual basis of the energy problem. Political judgment and action, which is indeed an overwhelming problem, could then be viewed on such a basis.

The approach adopted was ultimately multidimensional. By writing our results in this book in a linear manner, we cannot hope to transmit the true flavor of the approach. In a sense, we did everything at once. By doing this, it was possible to cross-fertilize everything with everything else. In what follows, we present our approach in a more orthodox, orderly fashion. It follows the order in which subjects appear in this book.

Assumptions

A completely comprehensive study of energy problems of the future is impossible. One would have to list all conceivable eventualities and trace out their structures and consequences. This is manifestly an infinite task. Observing then somewhat more closely the objective of our study, we made a number of assumptions, which helped to reduce the job to a finite one.

First, we limited the constraints on solutions to the energy problem to those that are physical or structural. Political and social constraints are recognized, but were not applied explicitly. This allowed us to explore the entire range of the possible.

Second, our study assumed a surprise-free future. No major catastrophes such as wars or large local upheavals were assumed to take place. We also assumed no positive technological breakthroughs of a nature that cannot be expected today. This was not meant to exclude such positive unforeseen breakthroughs, but we did not want to rely on them.

Third, we assumed in general only a modest population and economic growth. To keep the energy problem manageable, we assumed major energy conservation and aggressive exploration for additional energy resources. We also assumed a functioning world trade in oil, gas, and coal such that the needs of the various parts of the world can be taken care of.

Fourth, we assumed in all evaluations of the study that the U.S. dollar, and any other monetary unit, has a constant value. This is a more sweeping assumption; it amounts to decoupling the terms of trade from the side effects of inflation. In effect, we note that these problems are of a social and political nature, so that ignoring them is consistent with the first assumption.

We emphasized as much as possible the economic and energy growth of less industrialized as compared with more industrialized countries. This was done on a per capita basis as well as on a national or regional basis.

The Temporal Frame

We used a standard time frame of fifty years. That is, we visualized the scenarios of energy demands, supplies, and potential opportunities up to the year 2030. There were many reasons for this selection.

Our first intuition was that we would have to imagine the world as it might be when natural petroleum could no longer be the reference energy source. This is not a matter of simply guessing when the oil will run out. It means examining how long it might take to change the current infrastructure as other things are substituted for oil. Such changes have occurred in the past; for example, about 120 years ago in much of Europe a real or impending fuelwood crisis was mastered by the substitution of coal for wood. From the time when the crisis was recognized, it took about fifty years before coal could contribute 50 percent to the then global primary energy demand.

We arrived at our fifty-year estimate in other, less sophisticated ways. For instance, fifty years is roughly twice the lifetime of a power plant, a characteristic system within the existing energy supply infrastructure. Two such lifetimes might encompass a major technological change. In order to begin to penetrate a competitive market, a new large-scale technology must pass the thresholds of scientific feasibility, of technical feasibility on an industrial scale, and of commercial feasibility. When all three thresholds are considered and it is realized that they precede actual market penetration, then fifty years may be on the short side. Indeed, it is very probable that all of the technologies in widespread use fifty years from now (at least for providing energy) have already been applied at some level today. Finally, fifty years is two human generations, and this is needed to accommodate changes in the social infrastructure that must parallel changes in the technical infrastructure. We also considered that fifty years might be required to reach a stable world population, a point that will be discussed later in this chapter.

For certain aspects of our study, fifty years is definitely not long enough. This is particularly the case when one looks ahead to the inevitable time when there really are no fossil resources available. For some of our supply considerations, we had to look beyond 2030. By extrapolating to the year 2030, we hoped to conceptualize the energy situation of the world after 2030. We expect this post-2030 world to be very different from the present one, and therefore our temporal frame defines a period of transition. When might we see the beginnings of that transition?

Several studies, including those of the Workshop on Alternative Energy Strategies (1977) and the Pestel-Mesarovic group (1974), attempted to extrapolate from now to around the year 2000. The indications are that the energy problem will become more difficult, but that the world could "muddle through" by rationalizing and correcting the existing infrastructure. Just this way of expressing the results suggests that the year 2000 should mark the beginning of a transition.

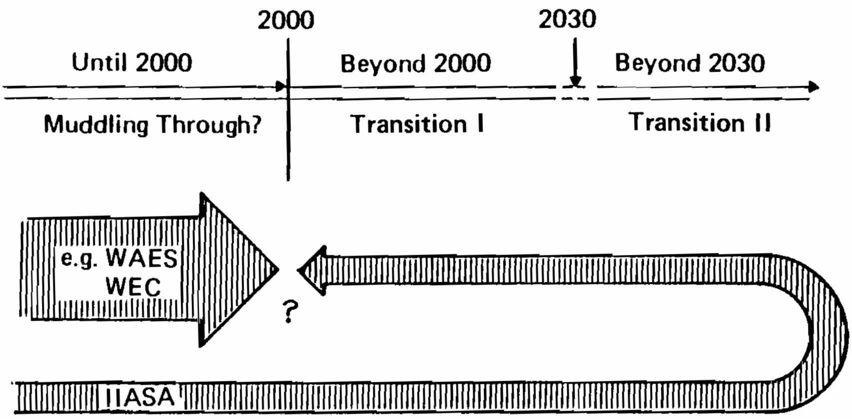
It is then appropriate to consider three time phases:

- The present phase: from now to 1995–2000;
- A first transition phase: from 1995–2000 to 2030;
- The ultimate transition phase: from 2030 onward.

The present phase is one of dealing with the oil supply problem as we know it today, while the first transition phase is that of moving from relatively cheap and clean oil to one or more different reference energy carriers. The third phase, from 2030 onward, would involve what we think of as a second transition toward a sustainable, asymptotic energy supply system.

How our study relates to the present phase can be visualized with the help of Figure 1-2. The question mark indicates the question, Are the short-range projections for, say, up to about the year 2000, consistent with the con-

Figure 1-2. Time phases of energy.



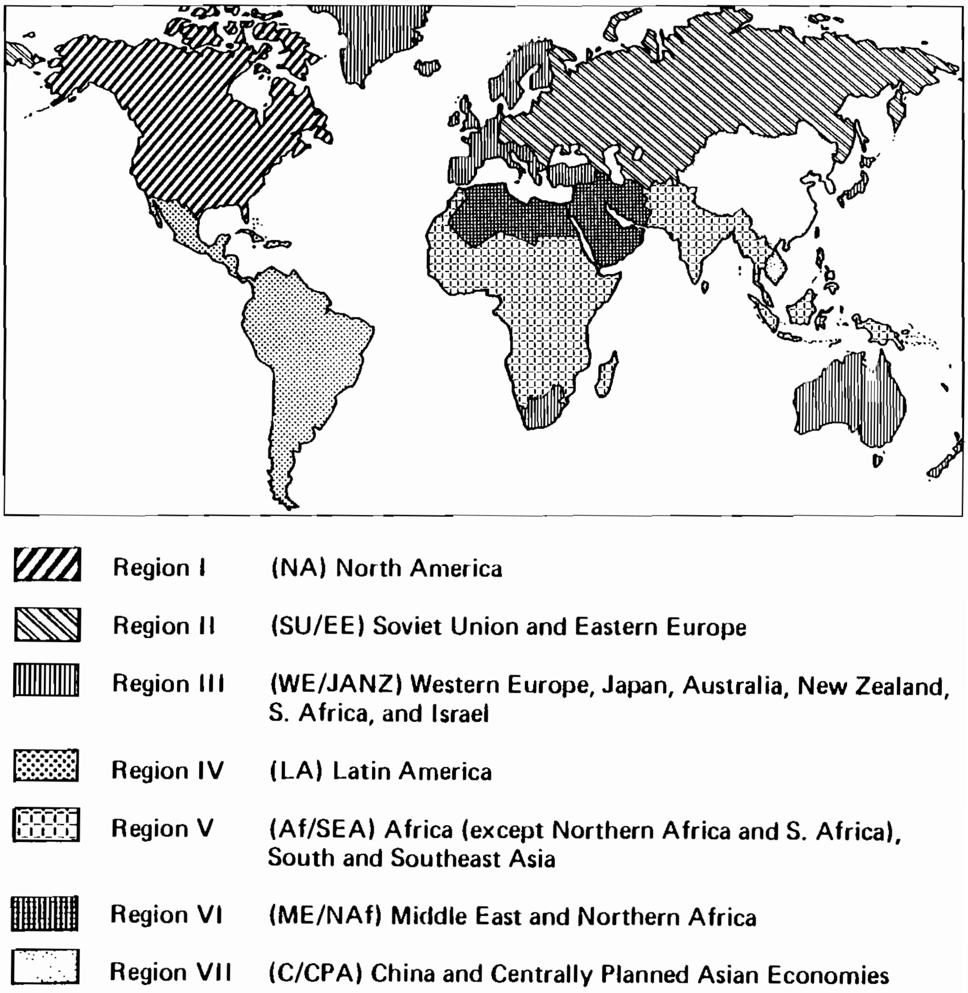
dition that the period after 2000 must be one of transition? How can we reach the starting point of that first transition?

The Spatial Frame

We also made some specific assumptions that gave structure to our study. Clearly, we inhabit a single world; yet various parts of the world have different resources, economic systems, and industrial structures. To account for this, we divided the world into seven, homogeneous groupings. These regions were selected principally for their economic and energy similarities and not so much for geographic proximity. Of course, such a definition is to some extent arbitrary. Nevertheless, we characterized region I, North America, as a region with a developed market economy and rich in resources. Region II, the Soviet Union and Eastern Europe, has a developed, centrally planned economy and is rich in resources. Region III, which is essentially the member countries of the Organisation for Economic Co-operation and Development (OECD) minus North America, has a developed market economy and not many resources. Region IV, Latin America, is a developing region with market economies and many resources. Region V, Africa and South and Southeast Asia, is also a developing region, with mostly market economies but not many resources. The countries of the Middle East and Northern Africa, region VI, are a special case with their rich oil and gas resources. And finally, region VII, China and the centrally planned Asian economies, is a developing region with centrally planned economies, but it is not so rich in resources. Figure 1-3 gives an overview of these regions; a list of the countries in each of the seven world regions is given in Appendix A to this chapter.

In considering the seven IIASA world regions, we did not merely add up national energy projections and resource production figures. There are a number of national studies that have done this, and their principal significance is to provide short-term (fifteen or twenty year) estimates of how much oil would be needed. Instead, we examined regional economic growth patterns and energy intensity trends that, when coupled with population figures and prices, could provide long-term estimates of energy demand. Similarly, we used our own definition of resources and estimated them in units that we judge appropriate to the field, thereby avoiding the idiosyncrasies that appear in many national evaluations. In any case, it was not the purpose of our study to describe the energy future of each country to some approximation. This leads too much into the political domain and away from the idea of exploring what is physically possible.

Figure 1-3. The IIASA world regions.



▨	Region I	(NA) North America
▧	Region II	(SU/EE) Soviet Union and Eastern Europe
▥	Region III	(WE/JANZ) Western Europe, Japan, Australia, New Zealand, S. Africa, and Israel
░	Region IV	(LA) Latin America
▦	Region V	(Af/SEA) Africa (except Northern Africa and S. Africa), South and Southeast Asia
▩	Region VI	(ME/NAf) Middle East and Northern Africa
□	Region VII	(C/CPA) China and Centrally Planned Asian Economies

FACTORS AFFECTING ENERGY DEMAND

There are three reasons for energy demand to change—population growth, economic growth, and technological progress. There is also the associated change in lifestyles of the people affected by these factors and, related to that, the problem of urbanization. It is necessary to estimate these factors on a finer scale than the global one, and even the breakdown into world regions that we used is not quite adequate. With this caveat, we discuss some general features of population and economic growth; more specific aspects of such growth are a major part of the discussion of the two IIASA scenarios that appears in Part IV of this book.

Population

For our study we relied on population estimates prepared by Keyfitz (1977). In the course of this book we refer repeatedly to his estimates for the various parts of the world.

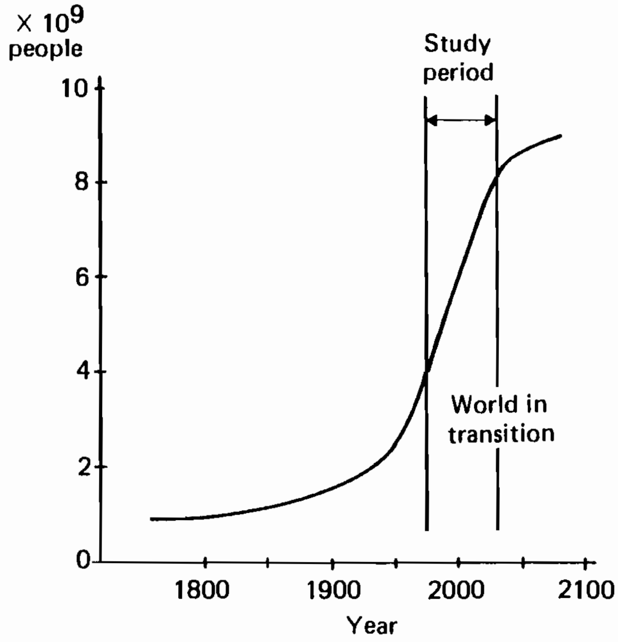
There are four billion (10^9) people on earth today; by 2030, the expected number is eight billion people, as illustrated in Figure 1–4. A condition is that, by 2015, the average population replacement rate would have come down to one. Besides leading to eight billion people by 2030, the population projection means that the flattening of the population growth curve would have largely taken place by then. Optimistically, one may then envisage conditions that become sustainable.

Economics and Lifestyles

The population projection leads to different population growth rates in different parts of the world. In particular, it shows more growth in poorer countries than in richer ones. Since it is always a target to improve the material standards of the poorest people, this also means that a very considerable economic growth is called for globally.

Changes in lifestyle and in the type of economy being considered can greatly influence the relationship between economic growth and energy growth. The major features can be illustrated by examining some overall statistics on energy consumption per capita. Currently, the global primary energy consumption average is close to 2 kWyr/yr per capita. But consumption is unevenly distributed. Roughly 70 percent of the world's population lives with less than the average, and most of this 70 percent with only 0.2 kWyr/yr per capita of commercial energy consumption; we add to this number in the developing countries another 0.3 kWyr/yr per capita of noncommercial energy. Even so, distribution remains extremely uneven, and any smoothing of this distribution that leaves the high per capita energy consumption untouched would lead to an increase in the average per capita consumption.

Figure 1-4. World population. Projections to 2030 based on data from Keyfitz (1977).

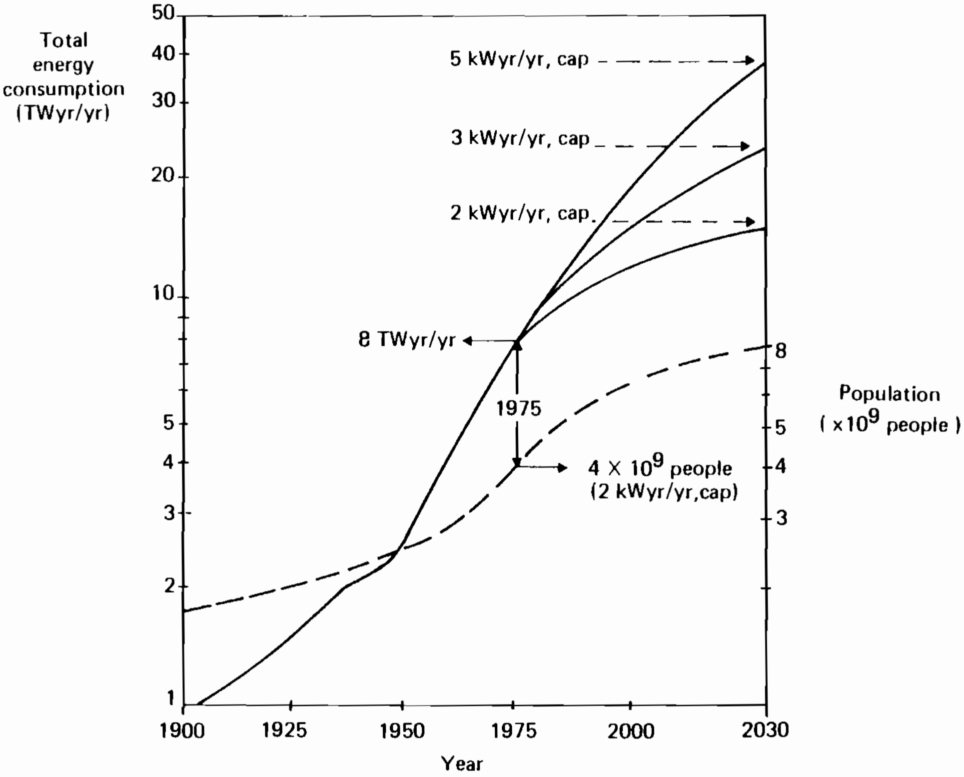


Let us now consider increases in the average primary energy consumption value from 2 kWyr/yr per capita to 3 and to 5 kWyr/yr per capita. Of course, such assumptions must be substantiated by looking at the details of energy demand in each of the seven world regions, as is done in Chapter 17. Taking the numbers 2, 3, and 5 kWyr/yr per capita and combining them with the anticipated population growth leads to estimates of 16, 24, and 40 TWyr/yr, respectively, of total global primary energy demand in 2030. This is shown in Figure 1-5. From this consideration we selected a range of 16 to 40 TWyr/yr as our study range. This range should not be confused with the projections of the two IIASA scenarios that resulted from our middle of the road quantitative analysis of energy supply and demand (see Part IV). The range of 16 to 40 TWyr/yr only defines the order of magnitude that we considered interesting.

Efficiency and Conservation

One other important factor that must be considered is the "real" price of energy—that is, the price of energy relative to other goods and services. The use or the nonuse of energy cannot be considered a principal goal; energy is an input to our lives and work, along with other resources. Depending on the relative prices paid for all the inputs, one varies their amounts in order

Figure 1-5. Total energy consumption, 1975-2030: three possibilities. The solid lines indicate energy consumption; the dashed line indicates world population.



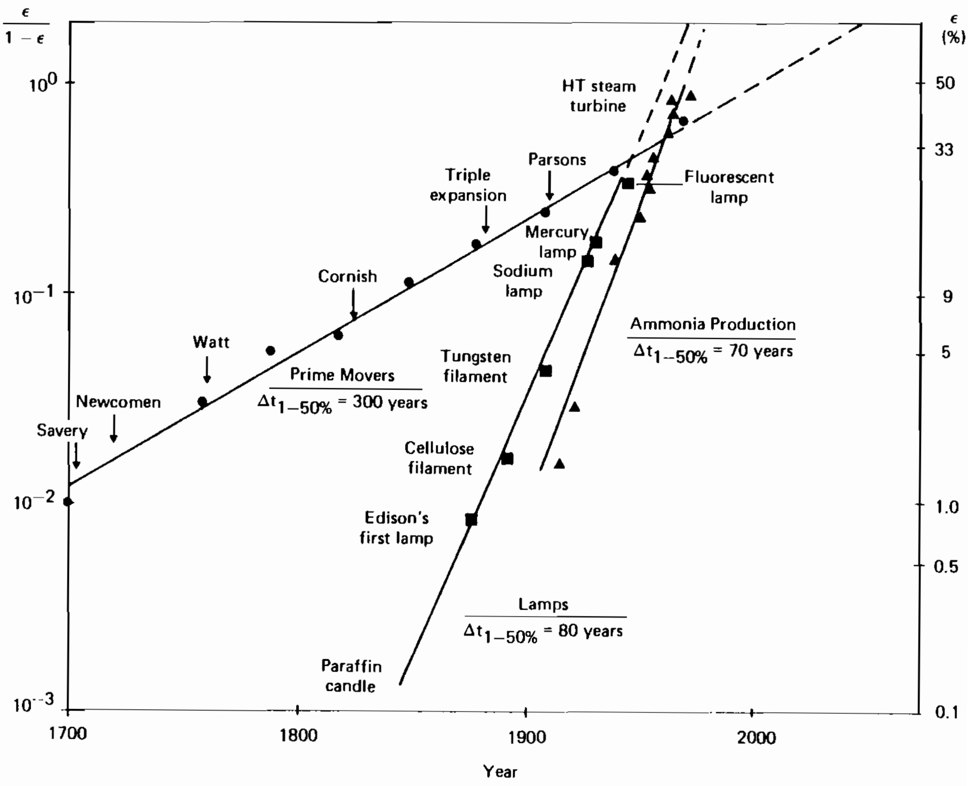
to produce the results one wants. If the price of energy goes up, we use less energy and more of other things. For example, in cold climate countries, more material and labor is invested in insulation and in other measures to conserve building heat—that is, to save energy. This price-induced conservation is simply rational economics.

Technological progress tends to decrease energy demand. This arises because such progress leads to improved efficiencies of conversion from primary to secondary energy forms and also to improved efficiencies in end use—in the conversion of secondary energy to final energy and/or energy services. Of these two roads to energy conservation, the second—the improvement of end use efficiencies—probably has the greater technical potential. Three examples of improved efficiencies of end use are plotted in Figure 1-6, indicating that such improvements have taken place in the past. In fact, historical data indicate that the market penetration process appears with stunning regularity. The very ponderousness of the system suggests that these evolutions are more than likely to occur.

Evolution of lifestyles can increase or decrease energy demand. There are some trends that appear to be part of the process of industrial development. For example, as industrialization begins, energy demand increases, both from the capital goods sectors that are being built up and equipped and from the individual consumers to whom more goods and services can be provided. As societies move into a postindustrial era of affluence, increasing buying power tends to increase energy demand, while the market basket tends to shift toward less energy-intensive services. The result up to now has been a decrease in energy demand per unit of productive output as measured in gross domestic product (GDP) and a continuing increase in per capita energy demand. Even this latter increase could be slowed or reversed by societies whose lifestyles become less materialistic. (But the virtues of the "simple life" seem to have the greatest appeal only after considerable material wealth has already been accumulated.)

We exclude from consideration of evolving lifestyles those changes and simplifications that are politically imposed on people but are not voluntary or economically rational. For example, "carless weekends" could be an appropriate response to an emergency shortage of motor fuel, but would not be tolerated after the emergency has passed.

Figure 1-6. Historical trends in efficiencies. ϵ is second law efficiency; $\Delta t_{1-50\%}$ is time necessary to evolve from an efficiency of 1 percent to one of 50 percent.



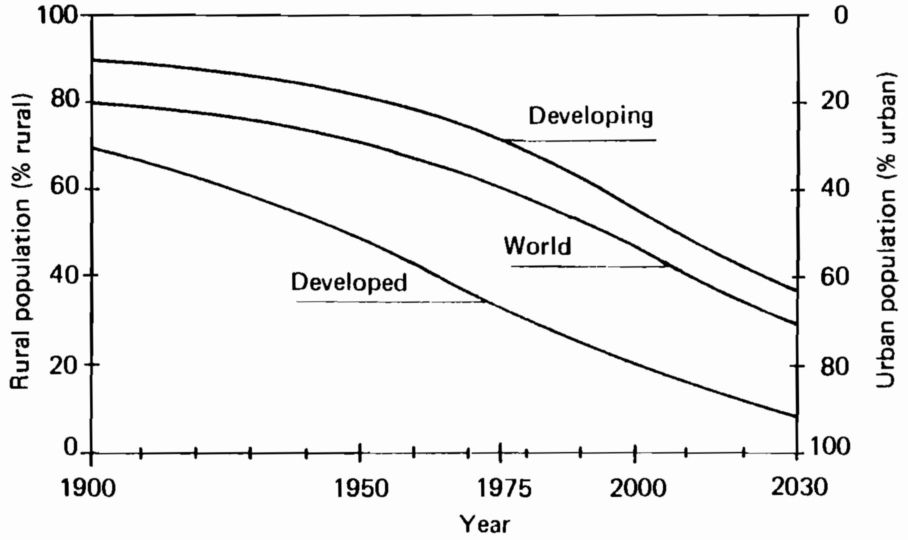
Urbanization and Energy Consumption Densities

In considering the spatial frame of our study, urbanization is an important driving force. It matters where and how people live. When conducting our study we discovered, somewhat to our surprise, an apparent trend toward a constant energy consumption density (as measured in energy per unit area) in cities. The consumption density of urban areas in advanced industrial countries is of the order of 5 W/m^2. The immediate question is whether this is also true for urban areas in developing countries.

We should not be too surprised if it turns out that way. All cities today have a similar infrastructure. There are streets, houses, streetcars, and automobiles that are all similar in size, and this leads to similar energy consumption densities. What is vastly different is the amount of people that use this infrastructure. There are indeed large differences between developed and developing urban areas, with the developing urban areas featuring much higher population densities. In that sense, development means an increase of the urban area per inhabitant. With a constant area consumption density, this implies an increasing per capita consumption of energy.

In Figure 1-7 we plot the expected degree of urbanization evaluated by the United Nations Population Conference in Bucharest (1974). Accordingly, one could expect 70 percent of the world's eight billion people of 2030 to live in urban areas. For the purpose of a quick orientation only, let us assume for 2030 a population density in the urban areas of 1000 people/km^2. With an energy consumption density of 5 W/m^2, one arrives at a figure of

Figure 1-7. Estimated distribution of rural-urban population, 2030. Based on papers submitted to the U.N. Population Conference, Bucharest, 1974.



28 TWyr/yr of total energy consumption in the urban areas of the world. With 30 percent of the eight billion people living in rural areas and with a population density of 120 people/km^2 and a consumption density of 0.1 W/m^2, one gets an additional 2 TWyr/yr, thus arriving at a global total of 30 TWyr/yr. This is not an unreasonable figure. The salient point is that a consideration of a spatial quality can lead us to expected energy demand figures by the year 2030 once the population and the degree of urbanization for that time have been given. Such a spatial consideration is of a quite different nature than time considerations or the evolution of economic activities. When they coincide, as they do here in our study, it is reassuring. The implication is that we have assumed explicitly or implicitly an increasing degree of urbanization of the kind that was given in Figure 1-7. In view of the importance that we attribute to such spatial considerations, we have studied this in greater detail and reported on the results.

This quick orientation is, of course, no substitute for careful evaluation. These considerations of the quality and texture of the spatial framework could also specify a range of interest for energy consumption from different socioeconomic considerations. More detailed studies of energy consumption densities, urban densities, and degrees or urbanization can be useful for understanding the nature of the energy problem.

EXPLORATIONS OF SUPPLY SYSTEMS

Let us consider two correct but conflicting statements. On the one hand, in a physical sense, there is no energy supply problem. There are energy sources whose production rate and durability could be virtually unlimited. This is true for nuclear breeders and fusion reactors and for solar power. Similarly, environmental and ecological impacts of energy supply can be sharply reduced, if not totally eliminated, with large investments of capital and skill. Therefore, again, in a physical sense, there need not be an environmental or ecological problem of energy supply. Also, the problem of energy demand can be met in part by the enforcement of strong energy conservation measures. On the other hand, there is an energy problem, and it is getting worse. Either there is no visible path for providing the unlimited supplies that are in principle possible, or no visible way to persuade humanity to trim its demands, or both.

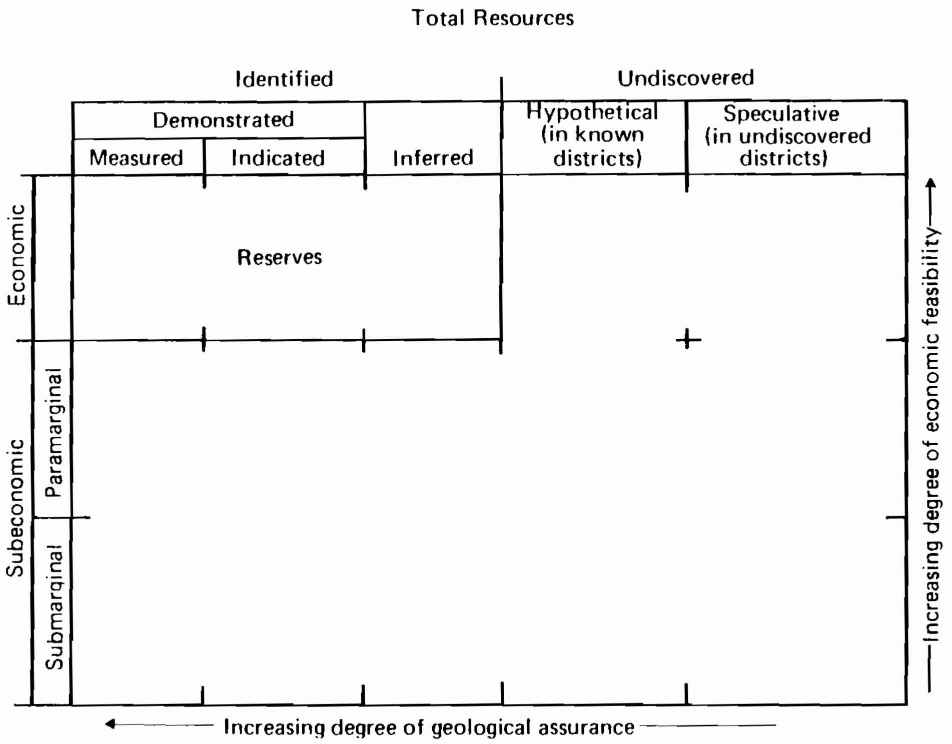
The problem of energy supply is that of realizing the supply potential that exists globally. This realizable potential is less than what can be imagined on purely physical grounds because of constraints. In our study we formally examined some of the major constraints (e.g., market penetration, risk, WELMM).

Here, let us consider our explorations of supply capabilities. These capabilities are constrained by whatever forces limit each particular technology, such as public approval for nuclear power, carbon dioxide for fossil fuel combustion, market penetration, and the economics of central station solar power. However, virtually every technology will undoubtedly be used at a lower level than what we judge to be technically possible. Nevertheless, in order to give decisionmakers the maximum range of options, we had to bump up against these limits.

Fossil Resources

Today's fuel supply is based on estimates of reserves of fossil fuels, but these reserves are only a fraction of the resources. *Reserves* are those deposits that are known and measured and that can be produced at economic costs. Beyond that point are *resources*—deposits that are known fairly well, shading out into those that are known only generally, and continuing into those that exist only as estimates of what we might find if we looked. In the cost dimension, resources that are marginally economic, shading out into those that can only be produced at higher and higher prices. The well-known McKelvey diagram (Figure 1-8) illustrates the distinction. Resources become transferred into reserves through discovery and measurement, through improvements in production technology that decrease production costs, and through economic changes that increase the price of the product and therefore the cost that is acceptable in extracting the product.

Figure 1-8. McKelvey diagram for the classification of fossil reserves and resources.

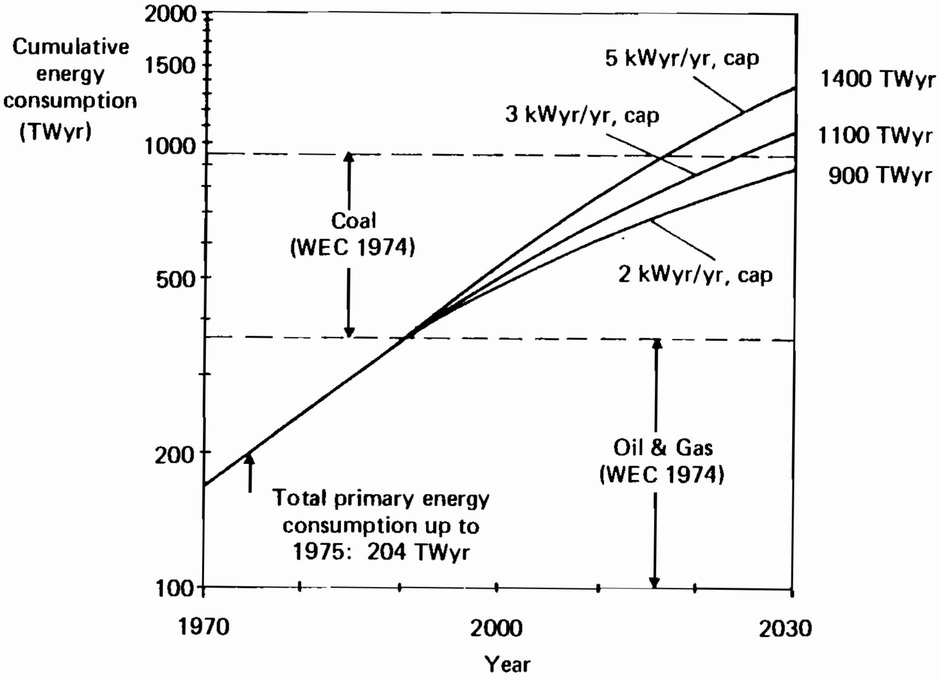


In order to determine supply capabilities over the next fifty years, we had to estimate a "usable" resource base. This involved using our geological knowledge to extrapolate improvements in extraction techniques and assigning cost categories. We evaluated costs in constant value currency; otherwise, there would be shifts in and out of cost categories that depend only on inflation or deflation and not on anything tangible.

The salient question we asked was, How much more oil, natural gas, and coal is likely to be available when we examine cost categories that are more expensive than the reserves that are currently exploited? The costs that we considered run up to about three times what we pay today. So we had to go further and consider unconventional fossil resources—tertiary oil recovery, heavy oils, tar sands, shale oil, and "exotic" (i.e., permafrost) coal fields. These resources are large. Thus, as contrasted with estimates of conventional fossil resources that tend to be, globally, of the order of 1000 TWyr, the possibility exists of exploiting additional unconventional resources to bring the estimate of the global fossil fuel resources to the range of 3000 TWyr.

This makes a difference. Figure 1-9 extrapolates cumulative resource consumption up to the year 2030, under assumptions of energy consumption rates of 2, 3, and 5 kWyr/yr per capita. The cumulative primary energy consumption by 2030 runs from 900 to 1400 TWyr. What this suggests is that the expensive and, because of the problems of their extraction, "dirtier"

Figure 1-9. Cumulative energy consumption for three assumed consumption rates, 1975-2030.



fossil fuels (coal, tar sands, heavy oils) could be a bridge between today and the future era of durable and abundant nonfossil energy sources.

Coal

The reserves of coal correspond to 600 TWyr/yr of primary energy, and the total amount of recoverable coal that might fall within reach of economically viable technical capabilities considering high cost categories is probably 2000 or 3000 TWyr and perhaps more. On today's scale of use this seems to make coal a very large resource indeed. Note from Figure 1-9 that even with energy consumption at 5 kWyr/yr per capita, only 1400 TWyr of primary energy would be consumed by 2030.

This makes coal a very comfortable looking crutch for the world's energy supply. But is it really? Two things stand out when one takes a longer view. First, at the highest rates of use contemplated, one would still have to look for something else before the year 2100; and second, even coal consumption at 2 kWyr/yr per capita by the year 2030 would call for 16 TWyr/yr of coal consumption by that year, which is more than seven times as much coal as is used now. Besides the problems of building up all the mining and transportation capability to handle all this coal, and besides its very large WELMM requirements, burning so much coal would certainly violate the qualitative limits that we would like to set on carbon dioxide emissions, at least until we know better what the carbon dioxide problem really means.

So we must look at coal in a different way. It cannot be the dominant energy source of a high energy-consuming world. But, it is a large resource of chemically reduced carbon, and as such it can be used to synthesize liquid fuels when and if unconventional oils become too expensive. We therefore devoted most of our coal study to an examination of ways to convert the coal enterprise, stepwise, into a liquid fuel synthesis industry.

Nuclear Power

Central station nuclear power is technically in an excellent position to supplement fossil fuel over the next fifty years. Light-water- and heavy-water-cooled burner reactors, which are commercial now, are the cheapest source of electricity in many parts of the world. More advanced systems, producing heat at higher temperatures both for chemical processing and for more efficient conversion of heat to electricity, are ready for commercialization. These are high temperature gas-cooled reactors and liquid-metal-cooled fast breeder reactors, for which the required demonstration units are already operating.

Breeders are particularly important because they have an extremely high efficiency rate of use of uranium and thorium, while with the use of burner reactors only, the resources of high grade natural uranium would be used up rapidly. One would then be forced into mining rock containing small amounts of uranium—a scheme we refer to as mining "yellow coal." But by the use of breeders, the "good" uranium would last a very long time, and even if some "yellow coal" has to be used several centuries from now, the amount needed would be very small.

All this defines a related set of technical problems. First, one must estimate the magnitude of the uranium resource. And second, one must find a schedule of reactor construction that satisfies several constraints: it must not use more natural uranium than the resource base provides, and at a definite time—for our study, the year 2030—it must be capable of operating virtually independently at the power level achieved by that time, without requiring still more natural uranium.

Solar Power

Central station solar power can provide electricity and hydrogen, just as nuclear power can. It uses much more land and materials, but once installed an in operation, it is practically risk free, very well accepted, and truly inexhaustible. Again, comparing it with nuclear power, central station solar has larger WELMM impacts and larger capital costs. This will doubtlessly affect the pace at which solar power can be installed, and the realization of its potential could occur only one or two decades later than that of nuclear power.

Continuing the comparison with nuclear power, in a competitive situation, relative economics will be decisive. (Money is a surrogate for the ability to make investments of human and physical capital and must not, therefore, be ignored.) For the fission breeder, cost targets exist, starting from considerable experience with pilot systems. Targets also exist for central solar stations: they are based not as much on experience, but are more readily derivable from general industrial experience. We can only speculate whether solar or nuclear will ultimately capture the larger market.

Because of the tremendous thermodynamic quality of sunlight (theoretically a 90 percent efficiency conversion into mechanical, electrical, or chemical energy), we have considered the direct use of sunlight separately from other renewable sources.

Small-scale Solar and Other Renewable Resources

For small-scale solar power installations, considerable investment burdens are placed on the final consumer, who can neither profit from technical economies of scale nor invest in as sophisticated a manner. The question is, If the world improves its efficiency of energy consumption in end use, will there be a market for small-scale solar devices? For example, conservation-oriented building designs reduce domestic energy demand for hot water and comfort heat in temperate climates, and the demand is in any case small in tropical and equatorial climates. Most of the solar energy used would be in "passive" construction techniques.

A possible exception exists for household photovoltaic systems, which could provide power for air conditioning at minimum and revolutionize electric utility service if widely used. How realistic are the hopes for cost breakthroughs?

Other renewable energy sources must likewise be evaluated—wet geothermal energy, hydroelectricity, wind power, and less developed systems such as OTEC and wave and tidal power. For these, the problems are not only to evaluate the resources—which are generally far smaller than the energy coming directly from sunlight—but also to determine how much could be tapped without interfering with the dynamics of weather, air and ocean water flow, and the other properties of earth's machine.

And finally, we must look at biomass. How much is available, how much can reasonably be harvested, what to do with it? Biomass has a unique property that sharply differentiates it from all other renewable energy sources: its energy is stored in chemical form, as chemically reduced carbon. This means that in the long run it can be thought of as "renewable coal." Thus, just as with coal, it is important not merely to evaluate the resource base, but also to consider how these resources can be processed efficiently into secondary energy carriers.

SYSTEM PROPERTIES AND CONSTRAINTS

The energy problem exists in the context of the continuity of human institutions and the existence of a "healthy" world. The term healthy refers both to the human population and to the natural environment throughout the planet. Because this context limits what can reasonably be done to attack the energy problem, these considerations function as constraints—be they of a social, political, or environmental nature.

Market Substitution

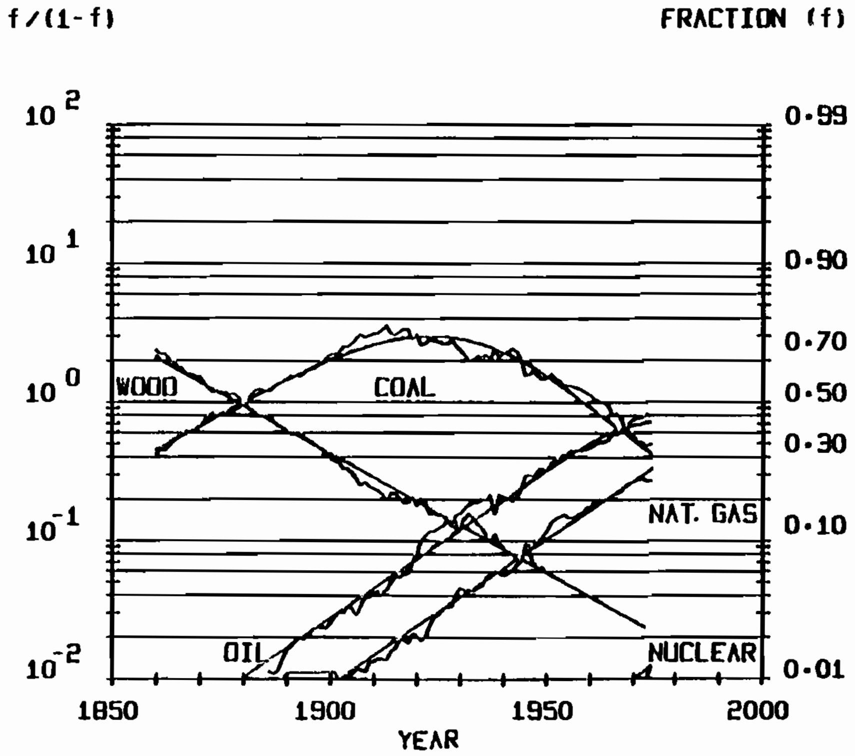
We considered as future possibilities some forms of energy supply that are not in common use today. For example, electricity from solar heat or from photovoltaic conversion of sunlight is currently a negligible factor in global energy supply, although there are high hopes. The same might be said for wind power, ocean thermal power, and tidal power. Even technologies closer at hand, such as conversion of coal to liquids and gases, or nuclear fission electricity, or the use of heavy oils, are not yet major components of energy supply on a global scale. They must penetrate the energy market before they can become more important.

Market penetration is a phenomenon that has economic and even psychological components. It can function as a constraint on the growth of a new energy supply system. We therefore devote considerable attention to the market penetration factor, building on the logistic model developed by

Fisher and Pry (1970). While there have been attempts to explain market substitution from first principles, at this stage it must be treated phenomenologically.

Qualitatively, we know that wood was the world's primary fuel until the late nineteenth century, only to be replaced by coal, which at a later date gave way to oil and natural gas. The dynamics of the substitution process, whatever its causes may be, set limits on our expectations. When we plotted market shares against time, using as our scale the logistic function—which amounts to taking as our ordinate the logarithm of $f/(1-f)$ where f is the fraction of the market held by a particular energy form—a remarkably consistent pattern emerged (Figure 1-10). There are straight lines over surprisingly large time intervals, which implies that the substitution process follows the S-shaped logistic function. Figure 1-10 also demonstrates that, globally, it has taken roughly fifty years for a particular type of primary energy to increase its market share from 10 to 50 percent of the total supply. This substantiates our choice of a fifty-year extrapolation period as being necessary to determine the results of new energy sources.

Figure 1-10. Global primary energy substitution. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



Environmental Considerations: WELMM

A considerable amount of work on environmental problems has been done at IIASA by Foell and his colleagues (see Foell et al. 1979a, 1979b). This work was performed on a district scale—the state of Wisconsin in the United States, the Rhone-Alpes area in France, district "X" in the German Democratic Republic, and Austria. The Energy Systems Program used insights gained from these local studies to build up a global understanding of the environmental implications of energy systems.

Some of the environmental problems that arise must be examined as problems of specific energy sources—for example, energy from biomass and hydroelectricity have definite ecological consequences. Some are mediated by the earth's climate, as will be discussed later in this section. However, there are some encompassing descriptions that can be very useful. In this spirit, we examined the total commitments of land, water, and materials to a specific energy technology. Thus, for a given energy system—fossil, nuclear, or solar—all the land needed for mining, transportation, processing, and any other required operations is totaled as a land commitment. Similarly, water and materials commitments are accounted for. The process can also incorporate commitments of energy and manpower inputs, and this has been done. The result is a system called WELMM; the acronym stands for Water, Energy, Land, Materials, and Manpower. WELMM results are not, of course, a substitute for a detailed study of environmental impacts, but they give a qualitative understanding of the total impacts of types of energy systems. They provide a similar view of related impacts as well, the most obvious one being requirements for capital.

WELMM results were used at several points in our study—for example, to measure the impacts of recovering uranium from low grade deposits, a process that, because of its comparability to obtaining the same energy from coal, we labeled mining "yellow coal"; to compare what it means to recover fossil fuels from difficult or exotic deposits, as against today's "clean" oil and gas; and to understand the impacts of large-scale central station solar electricity.

Environmental Considerations: Climate

All energy that is used, except for a small share that is stored as chemical binding energy, is degraded ultimately to waste heat. This heat is dissipated to water and air, is transported to the upper atmosphere, and leaves the earth as infrared radiation. Even considering that the quantity of heat produced by human activities is small compared with what the earth receives from the sun and reradiates to space, we must examine the implications of these activities. The disturbances created by gathering, converting, and using energy (as well as by other activities of humankind) might have catalytic effects on the ecosphere, the hydrosphere, and the atmosphere, producing much greater consequences than the rather puny scale of these activities would imply. Such effects would appear as climatic changes.

As with other environmental constraints, some of the climatic impacts are specific to individual technologies and were examined in our study with references to these technologies. For example, ocean thermal energy conversion (OTEC) and harnessing power from ocean currents are probably limited by the effects they would have on the flow of heat in the ocean. Of more general concern are the possible climatic effects of dissipating too much waste heat at the wrong locations and of disturbing the carbon dioxide balance of the atmosphere by burning fossil fuels.

As to waste heat, the question is whether these effects are global. Most of the impacts appear to be of a local and regional nature. The coupling of such impacts into the global weather system is nonlinear and inherently noisy, making the job of modeling the process both untidy and difficult. Are there places that we can nevertheless pinpoint as poor locations for concentrated dissipation of waste heat?

The situation is quite different with the carbon dioxide problem, which is of a truly global nature. It takes only a few years for a given amount of carbon dioxide to dissipate uniformly across all the globe's atmosphere, but a thousand years or so to dissolve it in the deep ocean. In between, it can concentrate in the atmosphere. An increase in the carbon dioxide content of the atmosphere has already been noted over the past one hundred years. The significance of this is that high carbon dioxide content could lead to noticeable increases in atmospheric temperatures, through the well-known greenhouse effect (i.e., the absorption of infrared radiation from the earth). How this might affect climate, particularly what the net effects might be when such carbon-dioxide-related effects as those of atmospheric aerosols are also included, cannot be precisely modeled. However, the information now available does not rule out the possibility of large-scale climatic changes, particularly if fossil fuel supplies are burned up quickly.

The effect of large-scale deforestation on the carbon dioxide problem in particular and on continental weather patterns in general is also still moot. Even the substitution of silviculture for natural forest growth could have a climatic effect.

Risk

The management and containment of the stream of energy through the ecosphere, the hydrosphere, and the atmosphere requires the establishment of standards and regulations on a global or at least a regional level. This is because the uncontrolled use and release of energy presents risks, ecological and environmental. When we think of risks, we are usually referring to direct impacts on human health, and it is in that sense that risks were investigated in our study. The risks that have received the most attention worldwide are those arising from nuclear power, but one should consider risks of all energy sources.

There are two levels at which risk should be considered. One is the level of scientific estimation—of trying to determine how much risk, of what sort, is presented by specific energy systems. This work has been performed by many groups, and it is necessary to evaluate the data. The question that we must seek to answer is whether any of the energy technologies being considered can add a significant amount to everyday risks.

There is yet another level at which risks should be considered—the level of perception and preference. Human beings do not perceive scientific facts; rather, they extrapolate from experience and information. This adds a needed critical viewpoint to what is claimed to be "fact": it also makes it possible for perceptions to be erroneous. These perceptions are then filtered through a mixture of value judgments and prejudices that are combined as "preferences"; again, something is added (by considering values) and something is lost (by considering unreasonable biases) in the process.

We are all aware of the mutable nature of perceptions and preferences. They change with new information, new propaganda, and new paradigms for viewing the human experience. This makes the study of perception a very soft science indeed; it is nevertheless an important topic, since perception of risk, more than risk itself, can limit the deployment of any technology. Specifically for nuclear power, perceived risks have clearly slowed down the very high rate of market penetration that was evidenced some years ago. How to extrapolate from present understanding of the nature of risk perception is still unknown. Our study could contribute to the reconciliation of scientific and political realities over the long run and is presented in that spirit.

SYNTHESIS THROUGH ENERGY SCENARIOS

The topics of energy demands, resources, technologies, and constraints must be synthesized or integrated into a coherent whole in order to achieve our goal—a comprehensive understanding of the nature of global energy systems over the next 50 years. The synthesis is an important piece of analysis in its own right, but it also interacts, iteratively and reiteratively, with the topics already discussed.

The synthesis approach that we chose is neither unique nor "best." But it does allow us to explore the changing scale of global energy needs—the central role of large-scale primary energies and the structural changes underlying the long-term transition from cheap oil and gas to unconventional fossil fuels and, eventually, to sustainable energy systems.

The long-range asymptotic target postulated in our study is to reach a sustainable supply of liquid fuels through the use of the "endowments" of nuclear breeders, the sun, and other renewable sources. The question addressed in the synthesis is, To what extent might the world approach this sustainable condition by the year 2030?

The analytical approach followed for the synthesis is not necessarily easily identified. A first criterion for us was quantification. The energy problem is extraordinarily complex, as we have already noted. One can hope to at least be clear, if not exhaustive, by relying on quantitative analyses. Our synthesis of energy demands, supplies, and constraints is a dynamic, quantitative one.

The aim was to start with the general considerations and then proceed to the specific. This is true both of quantitative aspects and of the setting of the procedure: the analysis is global and is meant to provide a setting wherein national policies can be tested and evaluated.

The particular approach chosen for the synthesis uses a set of mathematical models. These models are a special kind of tool. As introduction to them, it may be helpful to distinguish three kinds of models.

The first comprises all laws of nature as incorporated in the natural sciences, mostly physics. These laws are meant to represent nature precisely and exactly within a given scope. More, they are seen as the ultimate expression of the behavior of nature for the type of phenomena in question. The second kind of quantitative model is based largely on statistical or other experimental data, without (necessarily, at least) implying the existence of rigorous laws of nature. Such models are meant to approximate reality. Examples are economic models that may forecast the development of an economy for, say two or three years. It is conceded that there can be errors in these forecasts, but the aim is to project real developments. A third kind of model is meant to conceptualize a complex and conceivable development. While such models are also quantitative, here such quantification is meant to deal with an otherwise unmanageable complexity by providing inherent consistency and an explicit identification of assumptions and results. In other words, the third kind of model provides synthesis. The results of such models are therefore not forecasts or predictions, in spite of being quantitative. This clarification can hardly be overstated.

The models of the kind that we use here provide only a way of examining the consequences of the assumptions that are made. The use of numbers in these models is meant only to express qualitative features. In other words, the numbers are intended solely as a means for expressing patterns. They are indicative, not accurate and exhaustive.

Data-intensive methods are not very helpful for our purposes. It is, for instance, not helpful to treat the long-range global energy problem on an input-output basis. A fifty times fifty input-output matrix requires 2500 coefficients. With seven world regions, this would mean 17,500 coefficients. Then one must study their self-consistent evolution in time, whereas transitions of the underlying infrastructure are the real focus of our attention. While giving the appearance of exactness, quite often this only means that persisting ignorance is expressed in that format. Quite to the contrary, for more short-term or immediate purposes such as input-output analysis, our approach is highly valuable. Indeed, we employed an input-output analysis for the more limited purpose of understanding investment implications of the scenarios for particular world regions.

The desire for data robustness dictated our decision to avoid an approach relying completely on prices, although we do not exclude the possibility of this being ultimately feasible. Instead, we tried to grasp the energy problem primarily in physical terms. For example, supplies were called for to match the accounting of specific, technological energy end uses when studying energy demand.

Energy prices do matter, of course. They will have much to say about future evolutions of energy systems. We took up the question of prices and evaluated our results in that dimension. But future costs and prices are not unambiguously known quantities. Our cost estimates are best described, perhaps, as informed estimates. We therefore started from substantive, if not engineering, analyses and then considered economy and world trade.

We tried to make explicit as many assumptions as possible. And for practical reasons as well as for reasons of principle, we wrote only two scenarios. The first, the IIASA High scenario, arrived at average per capita consumption values that are close to 5 kWyr/yr; the other, the IIASA Low scenario, came close to 3 kWyr/yr. By writing more than one scenario, we emphasize that we are not making predictions. There is inevitable uncertainty. And by having two scenarios, two benchmarks were established that permit inter- and extrapolation. Therefore, these two benchmark scenarios should not be considered necessarily upper and lower limits. It is not difficult to conceive of cases with more than 5 kWyr/yr per capita energy consumption or with less than 5 kWyr/yr per capita energy consumption or with less than 3 kWyr/yr per capita.

We also considered three alternative cases, although not with the same degree of completeness as the two scenarios. One of these alternatives deals with a rigorous case of energy conservation in developed countries: it keeps the global per capita energy consumption at 2 kWyr/yr. Another alternative explored the effects of a worldwide nuclear moratorium; a final case postulated a future with as much nuclear power as possible.

The writing of the High and the Low scenarios and the consideration of the alternatives was done by the use of mathematical models. Originally we were tempted to have one overall model. Obviously this would become a large and complex model. Realizing the persisting uncertainty and lack of data, as well as the need for constant cross-checking and judgment of intermediate results, we decided to have a set of (sub)models where each model evaluates only a particular aspect of the problem.

This decision necessitated interfaces among the models where the output of a precursor became the input of the follower model. This allowed for human cross-checking and adjustment. Indeed, a judgmental element in the modeling process was established, and this is intentional. It requires the user of this model set to have a clear understanding of the problem that he or she wants to evaluate. In a sense he or she must have understood the problem beforehand. Donella Meadows, in a seminar at IIASA, called this having a "mental model." This is essential; otherwise one is not able to ask intelligent questions.

More than half of the effort of the IIASA Energy Systems Program was devoted to developing a set of such mental models. Once the situation is understood, semiquantitatively, by a mental model, the purpose of operating the model set is to make analysis fully quantitative. This requires a choice of input and relations for this analysis. Providing a background for such choices was one of the purposes of the chapters of Parts II and III of this book, where the exploratory research on the various topics in question is reported. It is therefore not necessarily so that the full range of findings in these chapters of exploratory research is represented in the scenarios. It is possible to arrive at a different set of input data than that used here in our scenarios—that is, in the quantitative analysis of Part IV. But by having both—the exploratory chapters and the quantitative analysis—the full picture should be visible, and the reader is left with judgments of his or her own.

Along the lines of identifying more precisely the meaning of our quantitative scenarios, it may be useful to list a number of questions that we had in mind when building our model set:

- How much investment is needed to master the transition for the various alternatives considered?
- To what extent does the use of unconventional fossil resources ease the investment situation?
- What are the indirect impacts of these investments?
- Are there circumstances where the economy has to work for energy instead of having energy work for the economy?
- What is the timing of such investments and what is their sequence?
- What are reasonable allocations of resources to the various world regions?
- What is the impact of an energy strategy chosen by one world region on the other world regions?
- Can the developing countries make it?
- What is the strategic potential of energy conservation?
- How do alternative technologies compare in light of the above questions?

This list is meant to be illustrative but by no means exhaustive. Basically, it all centers around the question, Do we have enough time? This is a question of extreme importance, and its nature is broader than the scope expressed in our scenarios. The exercise of going through our scenarios is therefore meant to give insights and perspectives. Once that is accomplished, once a pattern becomes visible, one may well forget the numbers of the scenarios (eventually).

THINGS TO THINK ABOUT

The supply explorations and the scenario constructions are, in a sense, the tangible products of our study; from them, insights and new views have emerged. Yet, any study as comprehensive as our keeps turning up hints of new things to think about. Many of these seem to us to be insights, but until they are broadly accepted as such, they are opinions and hunches.

Still, there is no point in keeping them a secret. Perhaps our thoughts have value. We selected a few of our opinions, ideas, and hunches and have presented them separately in the book. They follow the supply and the scenario parts, because the ideas emerged from considering these questions. They are *not* conclusions.

We sought to improve understanding of the term "energy services" and "capital stock services" used throughout the book. If the terms refer to something immaterial, then what is the precise meaning? This led us to the notion of negentropy (i.e., negative entropy increment) and information: indeed, for a small group of the scientific community this is a well-known subject. We have tried to explain this relationship and, perhaps even more, to view it within the context of our energy study as reported here. Some, perhaps important, generalizations emerged, mostly of a heuristic nature. Nevertheless, they have given greater insight into the notion of consumptive and investive uses of resources and the related idea of endowments of negentropy that allow one to receive energy services indefinitely.

A second example is old new technologies. Priorities for research and development will undoubtedly change when compared with today's situation, particularly with respect to development work on unconventional fossil fuels, long-range transportation of natural gas, energy storage, water splitting for the generation of hydrogen, and schemes for coal liquefaction. We examined the numerous preferences and historically based trends in an indicative manner only. But, given the nature of the IIASA Energy Systems Program, it was not possible to explore in depth vast technological areas. There are excellent groups worldwide that are well qualified to do this. Rather, our goal was to focus on the pattern of which these technologies are a part and thereby to view them anew.

We also examined the notion of energy densities for both consumption and production. This has been useful in our consideration of urbanization, underscoring the importance of spatial considerations as opposed to temporal ones. Research on energy densities is only at the beginning stage and will contribute greatly to the understanding of the relationships among energy, urban planning, and regional development. While this subject is beyond the scope of the Energy Systems Program, we hope that we have been able to make a contribution.

Finally, we addressed ourselves to the hotly debated hard-soft controversy. In fact, this sometimes seems to be *the* energy controversy. We therefore did more than our expressed aim of merely providing a factual basis for political decisionmaking. Again, we recognize the seriousness and dimensions of such political and societal issues. However, through the exploratory and quantitative stages of our analysis, we have gained a certain perspective on the hard-soft controversy that needs to be explained.

ADDING IT ALL UP

Ultimately, it is necessary to synthesize our findings and to define a pattern for the global energy problem, since it is this pattern—along with other elements—that will affect the future of individuals and of mankind as a whole. We have done this in Part VI, in which we have made assessments and considered the implications of the study findings.

A positive view has emerged: the energy problem can be solved, but at an expense. It may well turn out that the institutional, societal, and political problems that have not been dealt with explicitly in this study are overwhelmingly large and that their solution might be expensive. But by clarifying the factual basis of the energy problem we hope to have contributed to their solution.

Throughout the study we have been guided by the belief in the earth as a "finite" world. Indeed, the fossil resources of the earth are finite; the global comprehensiveness of our study has shown us this. But the reality of the situation has led us to view conditions and facts anew and to develop a vision of how the global energy problem could be solved.

APPENDIX 1A: THE SEVEN WORLD REGIONS OF THE IIASA ENERGY SYSTEMS PROGRAM

Region I: North America (NA)

Highly developed market economies with energy resources.

Canada
United States of America

Region II: The Soviet Union and Eastern Europe (SU/EE)

Highly developed centrally planned economies with energy resources.

Albania
Bulgaria
Czechoslovakia
German Democratic Republic
Hungary
Poland
Romania
Union of Soviet Socialist Republics

Region III: W. Europe, Japan, Australia, New Zealand, South Africa, and Israel (WE/JANZ)

Highly developed market economies with relatively low energy resources.

Member Countries of the European Community

Belgium
Denmark
France
Germany, Federal Republic of
Ireland
Italy
Luxemburg
Netherlands
United Kingdom

Other Western European Countries

Austria
Cyprus
Finland
Greece
Iceland
Norway
Portugal
Spain
Sweden
Switzerland
Turkey
Yugoslavia

Others

Australia
Israel
Japan
New Zealand
South Africa

Region IV: Latin America (LA)

Developing economies with some energy resources and significant population growth.

Argentina
Bahamas
Belize
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Dominican Republic
Ecuador
El Salvador
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Surinam
Trinidad and Tobago
Uruguay
Venezuela
Other Caribbean

Region V: Africa (Except Northern Africa and South Africa), South and Southeast Asia (Af/SEA)

Slowly developing economies with some energy resources and significant population growth.

Africa

Angola
Benin
Botswana
Burundi
Cameroon
Cape Verde

Africa

Central African Republic
Chad
Congo
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea Bissau
Ivory Coast
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Malta
Mauritania
Mauritius
Morocco
Mozambique
Namibia
Niger
Nigeria
Reunion
Rhodesia
Rwanda
Senegal
Sierra Leone
Somalia
Sudan
Swaziland
Tanzania, United Republic of
Togo
Tunisia
Uganda
Upper Volta
Western Sahara
Zaire
Zambia

Asia

Afghanistan
Bangladesh
Brunei
Burma
Comoros
Hong Kong
India
Indonesia
Korea, Republic of (South)
Macau
Malaysia
Nepal
Pakistan
Papua New Guinea
Philippines
Singapore
Sri Lanka
Taiwan
Thailand
East Timor
West South Asia n.e.s.

Region VI: Middle East and Northern Africa (ME/NAf)

Developing economies with large energy resources.

Member Countries of the Organization of Arab Petroleum Exporting Countries (OAPEC)

Algeria
Bahrain
Egypt
Iraq

Member Countries of the Organization of Arab Petroleum Exporting Countries (OAPEC)

Kuwait
Libyan Arab Republic
Qatar
Saudi Arabia
Syrian Arab Republic
United Arab Emirates

Others

Iran
Jordan
Lebanon
Oman
Yemen
Yemen, People's Democratic Republic of

Region VII: China and Centrally Planned Asian Economies (C/CPA)

Developing centrally planned economies with energy resources.

China, People's Republic of
Kampuchea, Democratic (formerly Cambodia)
Korea, Democratic Republic of
Laos, People's Democratic Republic of
Mongolia
Viet-Nam, Socialist Republic of

APPENDIX 1B: UNITS AND DEFINITIONS

Conversion Factors

The following gives the definitions of units of measure used throughout this book as numerical multiples of coherent Standard International (SI) units. The exact definition is indicated by √; other numbers are approximate to the number of digits shown.

1 acre = 4,046.8564224 m^2 √
1 bar = 100,000 $\mathrm{N/m}^2$ √
1 barrel (petroleum, 42 gallons) = 0.1589873 m^3
1 Btu (British thermal unit) = 1055 J
1 calorie (thermochemical) = 4.184 J √
1 electron volt = 1.60210×10^{-19} J
1 erg = 10^{-7} J √
1 foot = 0.3048 m √
1 gallon (U.K., liquid) = $4.546087 \times 10^{-3}\ \mathrm{m}^3$
1 gallon (U.S., liquid) = $3.785411784 \times 10^{-3}\ \mathrm{m}^3$ √

1 hectare = 10,000 m^2 √
1 horsepower (metric) = 736 W √
1 inch = 0.0254 m √
1 kilopond = 9.80665 N √
1 langley = 41,840 J/m^2 √
1 pound force = 4.4482216152605 N √
1 pound mass = 0.45359237 kg √
1 mile (U.S. statute) = 1609.344 m √
1 millibar = 100 N/m^2 √
1 nautical mile = 1852 m √
1 ton (long) = 1016.0469088 kg √
1 ton (metric) = 1000 kg √
1 ton (short, 2000 pounds) = 907.18474 kg √
1 Wyr = $31{,}536 \times 10^3$ J √
1 yard = 0.9144 m √

Useful Approximations

1 million barrels of oil per day (1 mbd) ≅ 71 GWyr/yr
1 Mbd ≅ 50 million tons of oil per year
1 Btu ≅ 1 kJ
1TWyr ≅ 30 Quad
1 TWyr ≅ 10^9 tce

Prefixes

Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	D
10^{12}[a]	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^1	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

[a] 1 TW (terawatt) = 10^{12}W.

APPENDIX 1C: CONVERSION TABLE FOR COMMON ENERGY UNITS

	J	*Btu*	*Quad*	*kcal*	*mtce*	*10^6 mtce*	*boe*
1 J =	1	947.9×10^{-6}	947.9×10^{-21}	239×10^{-6}	34.14×10^{-12}	34.14×10^{-18}	163.4×10^{-12}
1 Btu =	1055	1	1×10^{-15}	0.2522	36.02×10^{-9}	36.02×10^{-15}	172.4×10^{-9}
1 QUAD =	1055×10^{15}	1×10^{15}	1	252×10^{12}	36.02×10^{6}	36.02	172.4×10^{6}
1 kcal =	4184	3.966	3966×10^{-18}	1	142.9×10^{-9}	142.9×10^{-15}	683.8×10^{-9}
1 mtce =	29.29×10^{9}	27.76×10^{6}	27.76×10^{-9}	7×10^{6}	1	1×10^{-6}	4.786
10^6 mtce =	29.29×10^{15}	27.76×10^{12}	27.76×10^{-3}	7×10^{12}	1×10^{6}	1	4.786×10^{6}
1 boe =	6119×10^{6}	5.8×10^{6}	5.8×10^{-9}	1462×10^{3}	0.2089	208.9×10^{-9}	1
10^6 boe =	6119×10^{12}	5.8×10^{12}	5.8×10^{-3}	1462×10^{9}	208.9×10^{3}	0.2089	1×10^{6}
1 mtoe =	44.76×10^{9}	42.43×10^{6}	42.43×10^{-9}	10.7×10^{6}	1.528	1528×10^{-9}	7.315
10^6 mtoe =	44.76×10^{15}	42.43×10^{12}	42.43×10^{-3}	10.7×10^{12}	1528×10^{3}	1.528	7315×10^{3}
1 m^3 gas =	37.26×10^{6}	35.31×10^{3}	35.31×10^{-12}	8905	1272×10^{-6}	1272×10^{-12}	6089×10^{-6}
1 ft^3 gas =	1055×10^{3}	1000	1×10^{-12}	252.2	36×10^{-6}	36×10^{-12}	172.4×10^{-6}
1 kWyr =	31.54×10^{9}	29.89×10^{6}	29.89×10^{-9}	7537×10^{3}	1.076	1076×10^{-9}	5.154
1 GWyr =	31.54×10^{15}	29.89×10^{12}	29.89×10^{-3}	7537×10^{9}	1076×10^{3}	1.076	5154×10^{3}
1 TWyr =	31.54×10^{18}	29.89×10^{15}	29.89	7537×10^{12}	1076×10^{6}	1076	5154×10^{6}

	10^6 boe	*mtoe*	*10^6 mtoe*	*m^3 gas*	*ft^3 gas*	*kWyr*	*GWyr*	*TWyr*
1 J =	163.4×10^{-18}	22.34×10^{-12}	22.34×10^{-18}	26.84×10^{-9}	948×10^{-9}	31.71×10^{-12}	31.71×10^{-18}	31.71×10^{-21}
1 Btu =	172.4×10^{-15}	23.57×10^{-9}	23.57×10^{-15}	28.32×10^{-6}	0.001	33.45×10^{-9}	33.45×10^{-15}	33.45×10^{-18}
1 QUAD =	172.4	23.57×10^{6}	23.57	28.32×10^{9}	1×10^{12}	33.45×10^{6}	33.45	33.45×10^{-3}
1 kcal =	683.8×10^{-15}	$93.47 \times 10-9$	93.47×10^{-15}	112.3×10^{-6}	3966×19^{-6}	132.7×10^{-9}	132.7×19^{-15}	132.7×10^{-18}
1 mtce =	4.786×10^{-6}	0.6543	654.3×10^{-9}	786.1	27.76×10^{3}	0.9287	928.7×10^{-9}	928.7×10^{-12}
10^6 mtce =	4.786	654.3×10^{3}	0.6543	786.1×10^{6}	27.76×10^{9}	928.7×10^{3}	0.9287	928.7×10^{-6}
1 boe =	1×10^{-6}	0.1367	136.7×10^{-9}	164.2	5800	0.194	194×10^{-9}	194×10^{-12}
10^6 boe =	1	136.7×10^{3}	0.1367	164.2×10^{6}	5.8×10^{9}	194×10^{3}	0.194	194×10^{-6}
1 mtoe =	7315×10^{-9}	1	1×10^{-6}	1201	42.43×10^{3}	1.419	1419×10^{-9}	1419×10^{-12}
10^6 mtoe =	7.315	1×10^{6}	1	1201×10^{6}	42.43×10^{9}	1419×10^{3}	1.419	1419×10^{-6}
1 m^3 gas =	6089×10^{-12}	832.3×10^{-6}	832.3×10^{-12}	1	35.31	1181×10^{-6}	1181×10^{-12}	1181×10^{-15}
1 ft^3 gas =	172.4×10^{-12}	23.57×10^{-6}	23.57×10^{-12}	28.32×10^{-3}	1	33.45×10^{-6}	33.45×10^{-12}	33.45×10^{-15}
1 kWyr =	5154×10^{-9}	0.7045	704.5×10^{-9}	846.4	29.89×10^{3}	1	1×10^{-6}	1×10^{-9}
1 GWyr =	5.154	704.5×10^{3}	0.7045	846.4×10^{6}	29.89×10^{9}	1×10^{6}	1	1×10^{-3}
1 TWyr =	5154	704.5×10^{6}	704.5	846.4×10^{9}	29.89×10^{12}	1×10^{9}	1000	1

mt = metric tons.

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II ENERGY SUPPLY

2 FOSSIL ENERGY RESOURCES

INTRODUCTION

Fossil resources play a major role in present energy balances and will continue to do so during the ultimate transition to the use of nonfossil fuels. And over the long term, fossil resources will still be needed as feedstocks for the chemical industry and/or as raw materials for producing substitute fuels, such as gasoline and methanol.

The cumulative demand for fossil energy resources up to the year 2030 will depend on the absolute level of energy consumption—the larger the total energy consumption, the larger will be the probable demand for fossil fuels. Such demand is likely because of the inherent market penetration difficulties of new energy technologies—as experienced today with nuclear fission. (See Chapter 8 for a discussion of the market penetration process.)

Shifting too soon or too quickly to more expensive (both economically and socially) energy sources and structures could harm society needlessly. Shifting too late or too slowly might also impose inescapable pressures on some fossil resources. Both actions could result, for example, in soaring energy prices and consequent damage to economies, as has already been experienced during the 1973-1974 oil crisis.

The transition from the use of fossil fuels is inevitable. However, the massive supply infrastructure now in place to use fossil resources—particularly refined petroleum, methane, and coal—will have to be employed during this transition from fossil fuel use; in fact, this infrastructure may determine the kinds of synthetic fuels that will have to be produced over the next twenty to thirty years. Thereafter, a new infrastructure can be adapted to different synthetic fuels.

How long this transitional period will last and at what rate it will take place will be governed by the availability of fossil fuels. Availability, in turn, will depend upon the real amount of fossil resources and on the physical, political, and institutional capabilities to supply them.

Knowledge of the amount of fossil energy resources, especially of hydrocarbons, and of the fraction that could be recovered is unfortunately inadequate at present for planning a smooth and optimized transition. Because access to the geological data depends greatly on governments, such knowledge can be gained only through joint, international effort.

RESERVES AND RESOURCES

A summary of the differences between reserves and resources is given below, based on the McKelvey classification of resources and reserves presented earlier in Figure 1-8.

- *Reserves* are geologically and geographically identified resources that are economically and technically recoverable and producible under present conditions or under conditions that are expected to prevail in the near future.
- *Resources* can be of two types—identified resources that are presently considered nonproducible for economic reasons (e.g., oil shale deposits or uranium from sea water) or those portions of a given resource that are not identified but are surmised to exist. This latter group can be further divided into so-called hypothetical resources that occur in areas that are only partially explored or geologically known (e.g., potential oil fields in the North Sea) or into so-called speculative resources that occur in practically unknown or unexplored geological areas (e.g., deep ocean basins).

There are three major ways of increasing reserves.

- By raising the price. Previously uneconomical deposits may then become profitable. (Of course, we are assuming that production costs will not increase as much. This happened after the 1973-1974 oil price increases, with apparently no, or very little, increase in oil reserves.)
- By improving the technology or developing new technologies. The success of underground coal gasification, for instance, could increase global coal reserves dramatically; enhanced oil recovery is another example. Very often, raising the price and improving a developing technology act jointly to increase reserves.
- By discovery, as a result of exploration. (This includes revisions and/or extensions to known deposits.) Thus, hypothetical or speculative resources are transferred to the identified category.

When we say that energy resources are poorly known we mean that there is generally no reliable assessment of unidentified, undiscovered resources and/or that our understanding of the possible role of new technologies is too poor to permit reasonable estimates over the next 50 years. Nevertheless, a long-term perspective must rely on energy resources and not on energy reserves. In order to better grasp the resource problem, we present in Table 2-1 a comparison of reserves and resources supplementary to the McKelvey classification of resources and reserves. Because of the large amount of coal reserves and the much debated situation of oil and gas resources, we shall concentrate here more on oil resource problems. However, many of the arguments could be valid—possibly with minor changes—for other mineral resources.

Interest in reserves has always been very large, since they serve as a basis for planning industrial production. On the other hand, interest in resources has been mostly episodic, often on a "hobby" basis and generally lacking strong official support. The time horizon for reserves is short to medium term—say, about twenty years—which is sufficient for sustaining industrial activity. Resources have a longer term horizon, generally fifty years or more. In fact, in Canada the time horizon for resources is about 25 years, whereas some Soviet publications mention one hundred years. The World Energy Conference (WEC) of 1974 refers to a "foreseeable future" and the World Energy Conference of 1978 to "some time in the future." While such time horizons appear highly uncertain, decisions for the energy sector are binding for a growing length of time.

Up to now, reserves had to be economically recoverable—that is, profitable. Criteria for determining profitability were established by industry, which, as a result, concentrated mostly on these so-defined profitable deposits (e.g., giant or supergiant oil fields). Clearly, these criteria should be—and are being—revised from a more national viewpoint. Resources by definition are known to be either presently noneconomical or hypothetical (or

Table 2-1. Comparison of reserves versus resources.

	Reserves	*Resources*
Interest in	Large	None in the past, now emerging
Time horizon	10 to 30 years	Long or very long term
Economic aspect	Must be profitable	Nonprofitable today, "science fiction" technology
Estimated by	Industry	Industrial or governmental institutions
Data	More or less reliable, conservative, "proprietary," and exploitation oriented	Uncertain or speculative, but scientifically oriented
Methods	Industrial work (expensive): exploration, drilling, and measurements	Paper or computer work: "geological," "historical," and so forth

even speculative) by nature. It is sometimes assumed that they will become economical in the medium- or long-term future because of a breakthrough of new technologies, which has the flavor of science fiction when looked at by today's industrial criteria.

The crucial problem of resource assessment is posed by the data. Many countries and/or specialized organizations publish national and international data on reserves of coal, oil, and gas. But comparing and aggregating these data are often difficult because of varying definitions. The problem is even more difficult at the global level. For coal, WEC is making a major effort to collect national data. However, there is no similar effort for oil and gas, and many countries generally do not publish data on resources or any related data that would permit their calculation. Additionally, most of these data are proprietary.[a]

Some individuals and institutions—for example, the U.S. Geological Survey or the American Gas Association—publish periodic estimates of global oil or gas resources, disaggregated at best into a handful of regional groupings (and rarely given in detail). Few if any of these estimates can claim "official value." Apart from a few recent exceptions, none of them has given the data used and with which a cross-checking of the results would be possible. Only a few groups have stated the assumptions or explained the methodology used, usually in very general terms.

Basically there are two methods for assessing oil resources—historical statistics and geological analogy—and in many instances both can be used jointly. A summary of these methods is given in Table 2-2.

Historical statistics became famous with M. King Hubbert (of the U.S. Geological Survey). The method involves the use of production, reserves, and mostly, discovery statistics (e.g., the historical evolution of oil discovered according to the drilling footage) to calculate the ultimate amount of oil to be produced. The method is interesting but relies too much on the assumed continuation of past trends far into the future. Moreover, on a global basis, its main weakness is the scarcity of good historical data for most countries: the only reliable data are generally those for production. Statistics on reserves generally do not distinguish between revisions (with possible backdating to the year of the discovery) and new discoveries. Data on drilling are poor and generally do not separate exploratory from development drilling, for instance. The mathematical treatment emphasizes too much the logistic type of curve (for cumulative production and discoveries) and assumes somewhat arbitrarily a negative exponential for the discovery rate per foot of drilling, placing too much importance on the last recorded point on which the curve is fitted.

Geological analogy has been used on a broad scale. In its more detailed and refined version, it has been the favorite tool of oil companies for about a decade. Major petroleum companies are practically the only ones to own a

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[a] For petroleum resource assessment, one must also consider the purpose of the assessment and be aware of any possible bias introduced by those making the assessment. This is also probably true for coal and other mineral resources.

Table 2-2. Comparison of methods for assessing oil resources.

Historical Statistics	*Geological Analogy*
Principles	
Choice of representative statistics, e.g., discovery rate $\Delta R/\Delta X$	Definition of sedimentary regions or basins
Extrapolation to the future	Comparisons with some reference regions or basins: Subjective (current method) Scientific (being developed)
Disadvantages	
Requires long statistical history that only very few countries have	Poor (and insufficient) knowledge of unexplored or little explored basins
Biased by political, economic, and technological factors	No precise experience of ultimate recovery in a reference basin (even in the United States)

large amount of data, resulting from exploration and exploitation. A few of these companies have such data on a global basis (although the data do not include comparative figures from most countries with centrally planned economies). These limitations must be kept in mind when considering the few published global fossil energy resource assessments.

COAL RESOURCES

In the United States, coal was displaced by oil and gas as a prime energy fuel shortly before the Second World War; this substitution occurred in the rest of the Western world somewhat later. Oil and gas are much cheaper to produce (especially in the prolific fields of the Middle East) and much easier to handle and to use. However, the international oil crisis of 1973–1974, the fear of potential oil embargoes, and the feeling that oil and gas reserves and resources are dwindling have led to renewed interest in global resources of coal, which are enormous.

Global Coal Resources and Reserves

According to WEC (1978a), global coal resources are estimated at 10,126 billion (10^9) tons of coal equivalent (tce)—or more than 1200 years of today's total global commercial energy consumption (or almost 4000 years of present global coal production). This figure does not include coal occurrences that are known and exist worldwide; nevertheless, this estimate is considered realistic by the WEC experts. Although the data given are accompanied by particulars of seam thickness and depth, a breakdown of the tables according to seam thickness and depths is not possible.

Less staggering are the WEC (1978a) figures for global coal reserves. The coal reserves currently estimated as technically and economically recoverable amount to 637 billion tce. (This figure is almost five times higher than the WEC (1978b) figure for oil reserves and almost one and a half times higher than the present estimates of ultimately recoverable conventional oil resources.) Moreover, according to WEC experts it is very likely that this coal reserve figure could double over the next decades, reaching a value of about 1200 billion tce by 2020. In other words, assuming no additions to the 10,000 billion tce of coal resources, only 6 percent of the localized resources would have to be transferred to the reserves to reach the figure of 1200 billion tce. Or equivalently, some 0.14 percent of the presently known coal resources would have to be transferred every year to the reserves in order to reach the reserve figure of 1200 billion tce in 2020 (plus the amount necessary to compensate for cumulative consumption, of course).

These figures should be looked at in the light of the rate of increase from 1974 WEC estimates: resources increased from 8603 billion tce in 1974 to 9045 billion tce in 1975 and to 10,126 billion tce in 1977—that is, a 1523 billion tce increase over the three-year period or an average increase of 5.9 percent per year. Similarly, reserves increased from 473 billion tce in 1974 to 560 billion tce in 1975 and to 637 billion tce in 1977—that is, a 164 billion tce increase in three years or an average increase of 11.6 percent per year (mostly because of improved economic conditions due to energy price increases). Or equivalently, about 0.5 percent per year of the resources were transferred to reserves (as compared to 0.14 percent mentioned in the above paragraph).

Evidently this process of additions to resources and reserves is far from being at an end (Häfele et al. 1976). In fact, the experts of the WEC study judge that in addition to currently estimated resources and reserves, there is a considerable "potential behind the potential."

Resources and reserves have to be looked at dynamically. Nothing illustrates better the potential for additions even in a known coal district than the Selby story: a new coal field of 600 million tons of clean, dirt-free reserves was discovered in 1972 in the Yorkshire coal region in the United Kingdom that had previously been explored unsuccessfully.

In contrast to oil, there has not yet been a very intensive search for coal, mainly because of the convenience of known reserves and the declining use of coal as an energy source in many countries. Conditions are changing and new tools and techniques (e.g., seismic exploration adapted from the oil industry) are opening up interesting possibilities for coal exploration (e.g., Grenon 1977; Meyer 1977). These could be of particular importance for developing countries, for obvious reasons. First, in many of these countries coal occurrences are already known to exist. There too, manpower can be made available relatively cheaply. Of course, there as elsewhere pollution problems cannot be ignored, but they are not considered so imminent as in developed countries, and solutions therefore need not be immediate. Most important, even small-sized discoveries could be worthy of special attention. For a developing country, with energy consumption equivalent at best to a few million tce per year (say, at a 50 to 500 kg of coal equivalent per capita level), a coal deposit of a few tens of millions of tons could be valuable.

Some additional comments on global coal resources and reserves are in order here. WEC (1978a) does not give details on the share of strippable coal resources, which is unfortunate in light of the growing importance of surface mining (Grenon 1979). Recall that in the 1974 WEC survey of energy resources, about 23 percent of U.S. coal reserves were estimated to be economically recoverable by stripping. For geological and geographical reasons, this percentage is probably too high at the global level.

As mentioned above, the transfer of resources to reserves can occur in one of three ways–by increasing prices, by technical change, and by discovery (i.e., improving geological knowledge). For coal, technological change can and will undoubtedly play a major role. The booming importance of surface mining is a striking example. Surface coal mines in the western part of the United States now operate at a 10 to 20 million ton per year level. Garsdorf, in the FRG, has established a record with 50 million tons per year; a few kilometers away, in Hambach, plans are being made for a possible 100 million ton per year operation by the end of this century. Mines producing 50 or even 100 million tons per year are also planned or projected in Siberia.

But the coal industry, if it wants to survive globally for a long time, will have to go underground. Not much has been done yet, and surface mining can only buy time. Of the many possibilities–from robotization to chemical or bacterial leaching–only underground gasification has been used (mainly in the USSR) and is presently being explored thoroughly in, for example, Belgium, France, the FRG, Poland, and the United States.[b] The possible success of this technology could influence strongly the transfer of resources to reserves, as well as the addition of new resources. For instance, the success of the INIEX (Belgium) under pressure coal gasification process would open up quite new resources–namely, coal deposits located deeper than 1000 or 1200 meters that are generally not included in the reserves estimates. (For example, in northern extensions of the FRG Ruhr coal fields or in offshore coal fields such as those under the North Sea, the limit for resources is generally at 1800 or 2000 meters.) Considering all these factors, some experts have suggested that ultimately, total global coal resources could possibly be two or even three times higher than the presently accepted figure of some 10,000 billion tce.

However, there are factors that may also lower coal resources and reserves. Prices and costs are two such factors. Oil prices could demonstrate some tendency toward stabilization (in constant money), while coal costs, on the other hand, may continue their upward trend, thereby reducing progressively their temporary economic advantage. As a result, reserves could

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[b] It is interesting to note that sloping coal beds too steep for practical mining actually present an advantage from the viewpoint of underground gasification–a good example of the influence of technology on the dynamic evolution of reserves and resources.

again be shifted back to identified but uneconomical resources. (This happened in the United Kingdom during the 1950s and 1960s.)

The ability of coal deposits to be mined is also a major open question, especially for underground coal fields. Some experts (e.g., Fettweis 1979) have expressed doubt that all "recoverable" reserves are actually mineable or that they would be mined, because of decreased accessibility, among other reasons.

Finally, the difficulties and the associated high costs of transporting coal over long distances (2000 to 5000 km) should be carefully considered in estimating coal resources and reserves. Major coal fields, such as those in the western part of the United States or in Soviet Siberia, lie very far from consuming centers. This problem is aggravated by the low quality of the coal in these areas (mostly subbituminous coal or lignite). However, coal "refining" technologies are now emerging and pointing to the possibilities of transforming coal into almost anything—synthetic natural gas, liquid fuels, methanol, and so forth—although the economic picture is still somewhat less promising. In Chapter 3, we discuss the use of coal for liquid fuel production, presenting a strategy for using coal prudently during the transition period from conventional fossil fuels.

Regional Distribution of Coal Resources and Reserves

Coal resources and reserves are very unevenly distributed worldwide, as can be seen from Table 2-3. The three major coal countries—China, the USSR, and the United States—together have some 8868 billion tce or about 87.6 percent of the world's total coal resources. These three countries also have the largest reserves (178 billion tce for the United States, 110 billion tce for the USSR, and 99 billion tce for China), although their total share of 386 billion tce is proportionately smaller than that for coal resources (60 percent as against 87.6 percent). This is normal because the smaller the resources, the greater the efforts to know more about reserves.

Note also in Table 2-3 that the countries of the second category (100 to 1000 billion tce) each have coal resources equivalent to or greater than total global oil reserves; however, some of them consider themselves generally "energy poor." (Such comparisons must, of course, be handled with care, since resources in the ground are very different from recoverable reserves.)

New exploration is expected to increase the number of countries in the third and fourth categories shown in Table 2-3, especially with respect to the developing countries. This would not necessarily change the total global coal resources appreciably, but it could influence the energy balance of these developing countries and possibly the potential global energy trade.

Table 2-4 gives the distribution of global coal resources and reserves among the seven IIASA world regions[c] calculated from WEC (1978a) data.

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[c] See Figure 1-3 for a definition of these regions and Appendix 1 A for a list of the countries in each of these regions.

Table 2-3. World distribution of coal resources (in 10^9 tce).

Greater than 10^{12} tce (1000×10^9 tce)		*Between 10^{11} and 10^{12} tce (100 and 1000×10^9 tce)*		*Between 10^{10} and 10^{11} tce (10 and 100×10^9 tce)*		*Between 10^9 and 10^{10} tce (1 and 10×10^9 tce)*	
USSR	4860	Australia	262	India	57.0	GDR[a]	9.4
United States	2570	FRG	247	South Africa	57.0	Japan	8.5
China	1438	United Kingdom	163	Czechoslovakia	17.5	Columbia	8.3
		Poland	126	Yugoslavia[a]	10.9	Rhodesia	7.1
		Canada	115	Brazil	10.0	Mexico	5.5
		Botswana	100			Swaziland	5.0
						Chile	4.6
						Indonesia[a]	3.7
						Hungary[a]	3.5
						Turkey	3.3
						Netherlands	2.9
						France	2.3
						Spain	2.3
						North Korea	2.0
						Romania	1.8
						Bangladesh	1.6
						Venezuela	1.6
						Peru	1.0

[a] Mostly lignite.

Source: Based on data from World Energy Conference (1978a).

Table 2-4. Coal resources and reserves for the seven IIASA regions (in 10^9 tce).

Region	Coal Resources			Coal Reserves		
	Hard Coal	*Brown Coal*	*Total*	*Hard Coal*	*Brown Coal*	*Total*
I (NA)	1286	1400	2686	122	65	187
II (SU/EE)	4127	892	5019	107	41	148
III (WE/JANZ)	683	80	763	117	29	146
IV (LA)	25	9.3	34.3	4.9	5.9	10.8
V (Af/SEA)	179	4.9	184	43	1.9	44.9
VI (ME/NAf)	0.4		0.4	0.2		0.2
VII (C/CPA)	1427	13.4	1440	99	NA	99
Total[a]	7727.4	2399.6	~10,127	493.10	142.8	635.9

[a] Regional figures do not sum to totals because of rounding.
[b] NA–not available.
Source: Based on data from World Energy Conference (1978a).

In general, we have considered two cost categories for coal—less than \$25/tce and between \$25 and \$50/tce. It seems that in many regions large amounts of coal can be produced at these costs. This includes IIASA region III (WE/JANZ); it is known that some production costs in Europe are already higher than the upper limit of \$50/tce (France and the FRG, minimum \$75/tce; Belgium, \$100/tce), but this region also includes South Africa, Australia, and the United Kingdom, with reasonable to very low production costs.

The "economically recoverable" reserves have been put in the first category (except for region III, because of the above comments) and part of the resources remaining to be identified in the second category. For the USSR, the United States, and China, only 10 percent of resources have been considered. However, the figures are already sufficiently high so that including more would not change very much—at least with our time horizon of 2030. Moreover, for these countries, and probably also for others, the possibility that some of the reserves may finally appear in the higher cost category is not excluded, but some of the resources remaining to be identified can replace them in the lowest category. These assumptions are not contradictory to the WEC experts' assumption of increasing total global coal reserves to 1200 billion tce by about 2020. Because these figures—1200 or 1500 billion tce—are already very large, we did not make supplementary assumptions about the ultimate recoverability factor (estimated at 50 percent by some experts) of total global resources.

Because of the threatening "shortage" of oil and because of the very big differences in coal resources among various regions and even more so among various countries, the subject of a global coal market is heard more and more frequently.[d] Although it is somewhat outside the scope of this chapter, we

[d] According to WEC (1978a) the existing international coal market was given as 7.7 percent of total global coal production in 1975. Because at the time of the WEC study no clear trend was apparent toward a larger world coal market , only small prospects for such a potential world coal market were given—8.9 percent of total output (i.e., about 788 × 10^6 tce) in 2020.

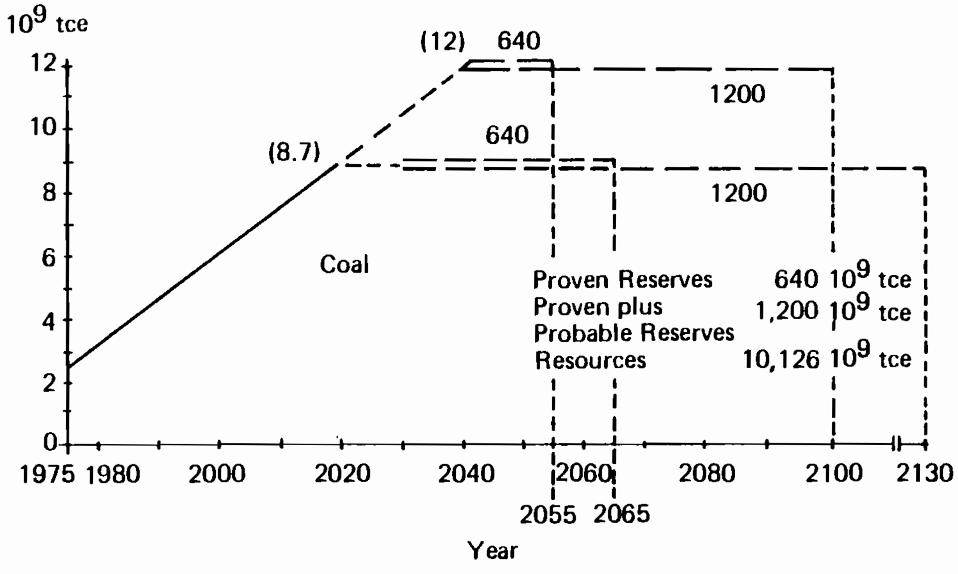
comment briefly on this subject here. One major question relates to the possible supply role of the three coal giants (the USSR, the United States, and China), which have tremendous resources but also very large domestic energy requirements. It is not clear whether these countries would be willing and/or able to manage additional capacity for an export market, although this may serve political or economic purposes. Potential customers could also be reluctant to increase their "energy dependence" on these political giants. Finally, there are only a few countries that have both large energy requirements and few coal resources and as such could be major coal buyers—Japan and some countries of southern Europe are examples.

Illustrative Coal Production Levels

Figure 2-1 shows the possible coal production curve for the world proposed by the WEC (1978a) study. For our purposes, the production curve has been extrapolated according to the following two assumptions:

- From 2020 onwards, production would stabilize at the maximum level of 8.7 billion tce per year. This level could be maintained until 2065 if proven reserves were to remain at the 640 billion tce level, but it could be maintained until 2130 if the reserves were to be increased, as suggested by the WEC experts, to 1200 billion tce.
- Production could possibly continue to increase up to a maximum of 12 billion tce per year, which would be reached around 2040, assuming the

Figure 2-1. Coal: possible production and lifetime of global reserves. Solid line based on data from WEC (1978a); dashed line is IIASA extrapolation.



> continuation of the previous rate of growth. Thereafter, production of 12 billion tce per year could continue until 2055 with reserves limited at 640 billion tce or until 2100 if the reserves were to be raised to the 1200 billion tce level.

The various extensions of the production curve shown in Figure 2-1 are useful for illustrating roughly the possible continuation of global coal production, based on present known reserves or on reasonable assumptions about their potential increases. These extensions are based on estimates of reserves and resources; the WEC experts were aware of the political, sociological, and environmental problems associated with such production levels. We do not repeat their arguments here. Also, such production levels raise the question of a possible carbon dioxide problem, which will be discussed in Chapter 10.

OIL RESOURCES

Because of the present and future major role of oil, knowledge of "apparently" limited oil resources is of crucial importance. Unfortunately, efforts to improve such knowledge have not been commensurate with the importance of the problem. One reason for this may be that although the final exhaustion of oil resources has been forecasted periodically, new discoveries have periodically postponed this. As a result, there is popular faith in infinitely new oil discoveries.

From Historical to Delphi Estimates

Over the past thirty-five years, there have been about twenty-five estimates (less then one per year) of ultimate recoverable global oil resources (defined as past cumulative production and proven reserves plus recoverable oil remaining to be discovered). These twenty-five estimates are, in fact, not independent. M. King Hubbert has contributed two estimates; Moody (from Mobil Oil Company, United States), three; and Weeks (from Weeks Natural Resources, United States), eight; and Klemme (of Weeks Natural Resources, United States), one. Because of the mutual influence of some estimates (such as the very good one from Moody presented at the Eighth World Petroleum Congress in 1975 [Moody and Esser 1975]), there are some half-dozen independent estimates.

In the course of time, these estimates have shown a general trend toward increasing values; this trend was somewhat reversed in the first half of the 1970s and was followed by some convergence in 1975 and 1976 around Moody's estimate (232 billion tons of oil remaining to be produced, plus about 45 billion tons already produced). It is also interesting to observe that the dispersion of estimates was about the same between 1945 and 1950 as

Table 2-5. Historical world oil resource estimates.

Year	*Name*	*Company*	*Estimate ($\times 10^9$ bbl)*	*Estimate ($\times 10^9$ tons)*[a]
1946	Duce	Aramco	500	68
1946	Pogue		615	84
1948	Weeks	Jersey	617	84
1949	Levorsen	Stanford	1635	224
1949	Weeks	Jersey	1015	139
1958	Weeks	Jersey	1500-3000	205-411
1959	Weeks		2000-3500	274-479
1965	Hendricks[b]	USGS	1984-2480	272-340
1968	Weeks	Weeks	2200-3350	301-459
1969	Hubbert	USGS	(1350-2000)	(185-274)
1970	Moody	Mobil	1800	247
1971	Warman	BP	(1200-2000)	(164-274)
1971	Weeks	Weeks	2290-3490	314-478
1972	Jodry	Sun	1952	267
1973	Odell	UNIV.	4000	548
1974	Kirkby, Adams	BP	(1600-2000)	(220-274)
1975	Moody	Moody	(1705-2030-2505) 95% 5%	(234-278-343) 95% 5%
1976	Grossling	USGS	(1960-2200- 3000-5600)	(268-301- 411-767
1976	Klemme	Weeks	1600	219
1977	Parent, Linden	IGT	2000	274
1977	Delphi	IFP	2200-2500	305-350
1978	Moody	Moody	2030	278
1978	Nehring	Rand (CIA)	(1700-2000-2300)	(233-274-315)

[a] Rounded figure.

[b] Estimated oil in place. The two values correspond to the two different recovery rates.

that occurring twenty-five years later (between 1970 and 1975), as can be seen in Table 2-5 and Figure 2-2.

Table 2-5 lists the global oil estimates that we considered, excluding those not formally presented or referred to as private discussion. Most of the original values were given in barrels of oil (column 4) and have been converted into metric tons (using 7.3 barrels per ton, column 5). When two values are given with a slash, they refer to two values actually given by the estimator, such as Weeks' two different assumptions on type and value of recovery. When two or more values are given in brackets, they refer to a range of values, with or without a proposed average. In the case of Delphi, the values given are the two averages selected by the estimator.[e] All these values have been put on the graph in Figure 2-2.

A major oil resources assessment was made in 1977 by a group led by

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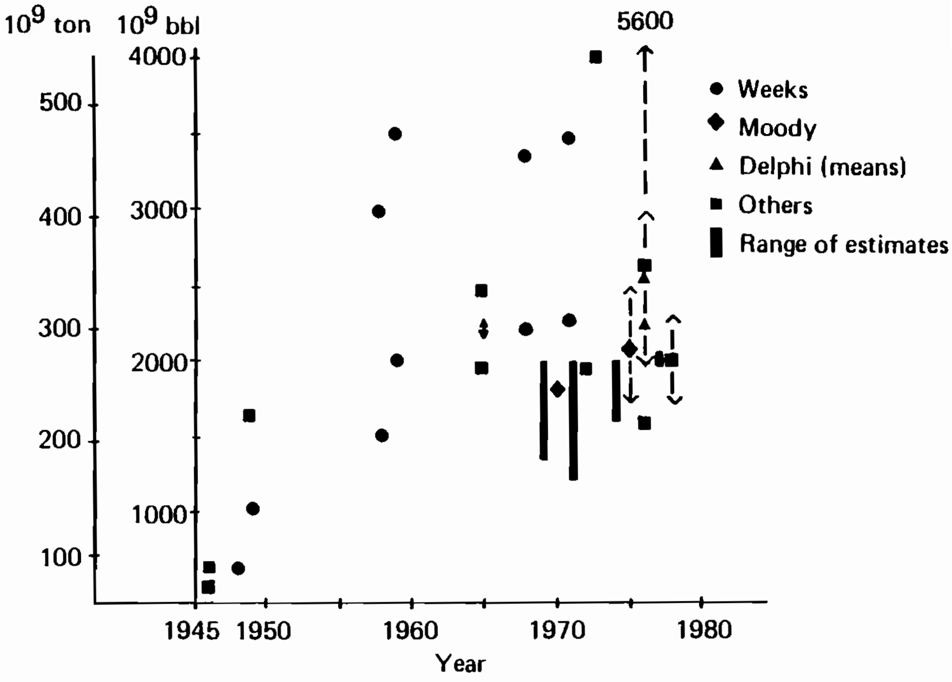
[e] If we take a higher value, 300×10^9 tons remaining to be produced, and add past cumulative production, we get 345×10^9 tons, or about 2500×10^9 barrels, which is one-eighth higher than the often quoted value of 2000×10^9 barrels.

Figure 2-2. Evolution of ultimate world oil resource estimates.



Desprairies (1977), under the sponsorship of WEC. Some thirty experts worldwide contributed to the study, which to our knowledge was the first time that the Delphi method was used for assessing oil resources. The aim was to reach a consensus among these experts.[f]

This Delphi study is undoubtedly one of the best sources of information—data plus accompanying comments. By making these comments available, Desprairies has invited those interested to form their own opinion. We have done just that.

Figure 2-3 interprets graphically the data of the main table of this Delphi study. An assumption imposed on the participating experts was that production costs (excluding taxes and profit) must not exceed \$20 per barrel (1976 U.S. dollars) by 2000. (Recall that in 1976 more than 50 percent of the world's oil probably was produced at less than \$2 per barrel.) With this limitation—which some experts considered a constraint for deep offshore and polar areas—it may be seen that the answers covered a broad range, from a low 173 billion tons to a high 550 to 950 billion tons of oil (averaged in Figure 2-3 as a single 750 billion tons of oil value). More then 90 percent of the experts considered that the ultimate resources remaining to be pro-

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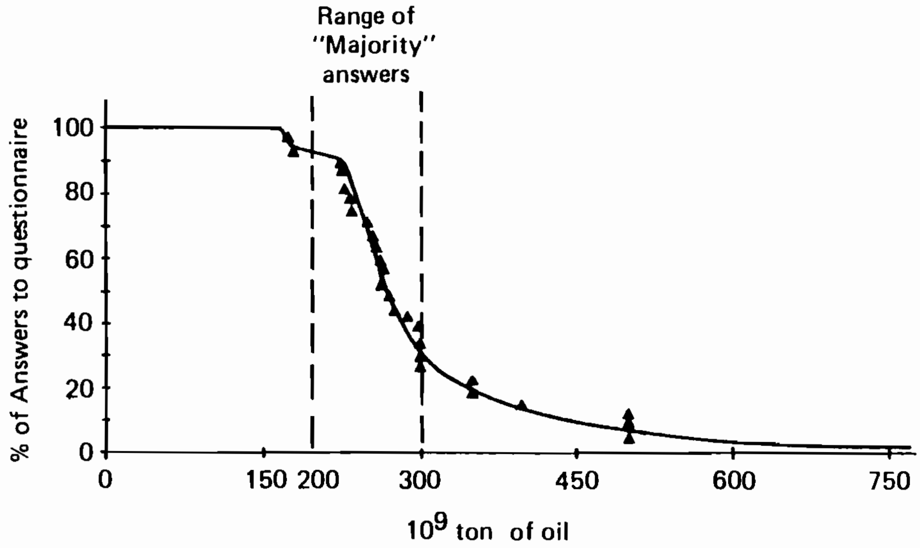
[f] This objective was not really achieved, as three opinion groups emerged—pessimistic, moderate, and optimistic. Anyhow, consensus is not proof. And history is full of examples where all (or a large number) of experts were wrong at the same time.

duced would be higher than 225 billion tons (compared to 1977 reserves of 88 billion tons); 25 percent of this group predicted that ultimate resources remaining to be produced would be higher than 300 billion tons; while the "majority" (about two-thirds) estimated resources to be between 225 and 300 billion tons.

Based on the assumption that the recovery rate of the oil originally in place would increase worldwide from the present 25 to 40 percent toward the end of the century, Desprairies estimated the ultimate recoverable oil resources remaining to be produced (as of 1977) at 300 billion tons, including deep offshore and polar areas. We note that the author of this Delphi study has a slight tendency to exclude deep offshore and polar areas (reducing ultimate resources to 260 billion tons if all of the estimates are included and to 240 billion tons for the central, majority opinion, which is very close to the 232 billion tons of Moody's value). Nevertheless, we generally prefer to retain these areas and to keep the 300 billion ton value. Our time horizon, up to 2030 or longer, is also greater than that of Desprairies (2020).

The authors of the Delphi study noted that between now and the end of the century exploration costs may double; development costs would probably also increase, but at a slower rate than exploration costs. The opinions (or the "educated guesses") of the experts were that 36 percent of these 300 billion tons of oil could be produced at less than \$5 per barrel, 26 percent between \$5 and \$12 per barrel, and 38 percent at more than \$12 per barrel (all prices in 1976 U.S. dollars).

Figure 2-3. Oil resources remaining to be produced. *Source:* Based on data from Desprairies (1977).



Regional Distribution of Ultimate Oil Resources

Whether we consider all of the estimates of the Delphi study or only the central ones—say, the eighteen answers between 200 and 300 billion tons of oil remaining to be produced—we can observe very broad variations in the regional attributions of oil resources, which makes the selection of a single regional distribution very difficult. For deep offshore and polar areas, for instance, the experts' estimates vary from 0 to 180 billion tons (all of the experts)—that is, from 0 to about twice today's proven reserves—or from 0 to 50 billion tons of oil (the "majority" of experts). Even for North America, which is the most extensively explored region (with more than 2.5 million oil and gas wells), assessments still vary broadly—6.2 to 50 billion tons if all estimates are considered and 15.6 to 45 billion tons (which is still a factor of three) for the eighteen values in the 200 to 300 billion ton range. These values for North America (which includes the United States and Canada) can be compared with the values estimated in 1975 by Miller et al. (1975) for the United States—(minimum) 37.4 billion tons (95 percent probability); (maximum) 59.6 billion tons (5 percent probability).

Table 2-6 gives the distribution of the ultimate oil resources remaining to be produced (derived from the Delphi study) among the seven IIASA world regions and, for comparison, the proven reserves as of 1 January 1978 (*International Petroleum Encyclopedia* 1978). It can be seen that the share of the Middle East and North Africa resources (mostly those of the Middle East) remains very important, although this share is somewhat less than that for proven reserves.

We judge that the resources of three geographical areas—South America, Africa, and East and Southeast Asia—have been underestimated in the Delphi study, considering their prospective areas. Aggregated data according to the IIASA world regions are also given in Table 2-6, together with total, cumulative drilling activities (Grossling 1976). Prospective areas have been calculated onshore and offshore up to a depth of 200 meters—that is, they do not include the deep offshore areas referred to in the Delphi study. We note, however, that the outline of the prospective area changes with time and depends on the author and the criteria being used.[g] The last column of the table gives the drilling densities or the number of wells per thousand square kilometers of prospective areas.

There is no doubt that these figures, as pointed out rightly by Grossling, show a "drilling gap" (i.e., very large differences in the drilling densities for various regions). Curiously, the two lowest figures are for region VI (ME/NAf) and for region V (Af/SEA). The two cases differ completely and illustrate the need for care in addressing world oil perspectives. Region VI has been drilled very little, but with exceptional success. The area of region V is very large (12,169,000 km^2 onshore and 5,560,000 km^2 offshore, the

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[g] Unfortunately, it is not always easy to distinguish in the statistics between exploratory and development drilling. Moreoever, these prospective areas have recently been "challenged" as being too large. Although interesting, the statistics should be used with caution.

Table 2-6. Oil resources, reserves, and drilling densities for seven IIASA regions.

Region	*Resources*[a] *(10^6 t)*	*Reserves*[b] *(10^6 t)*	*Prospective Areas*[c] *(× 1000 km²)*	*Total Number of Wells*[c] *(end of 1975)*	*Drilling Density (total wells/ 1000 km²)*[c]
I (NA)	28,000	4857	12,928	> 2,575,000	202.75
II (SU/EE)	46,730	10,670	9797	542,325	55.36
III (WE/JANZ)	16,020	4021	11,030	34,737	3.15
IV (LA)	23,000	5521	12,444	103,359	8.31
V (Af/SEA)	21,150	6176	17,729	28,281	1.60
VI (ME/NAf)	109,100	54,363	8212	12,501	1.52
VII (C/CPA)	12,730	2736	2831	8500	3.00
Total	257,230	88,344	~75,000	> 3,300,000	44.00

[a] Based on data from Desprairies (1977).
[b] Based on data from *International Petroleum Encyclopedia* (1978).
[c] Based on data from Grossling (1976).

majority of this in the Western Pacific countries). Some of the countries of region V are among the oldest oil countries (e.g., Pakistan, Borneo), but for many reasons (very often political ones), they have known only scarce and irregular drilling activities over the last few decades. The argument that these countries are not promising in terms of oil does not seem to hold, except that they have up to now provided a low share of giant fields (almost none in East Asia and Southeast Asia and very few in Africa, outside Algeria and Libya).

It is well known that giant fields are the preferred objective of oil companies. But views and attitudes may change, and it is hoped that, along the lines now explored by the World Bank, more exploration and oil activities will take place in regions IV and V, which together represent more than 30 million km² of prospective area (almost 50 percent of the 62.5 million km² total excluding the Middle East). The Delphi study value for these areas—only 44 billion tons of ultimate oil remaining to be produced (about 30 percent of the expected 148 billion tons total excluding the Middle East)—probably is too low. In fact, at the end of 1975, less than 0.86 percent of total world drilling had been performed in region V.

Perspective on 300 Billion Tons of Oil

To put such a figure of 300 billion tons of ultimately recoverable conventional oil in perspective, we shall examine briefly the various possibilities of downward or of upward revisions. The following observations are made for possible downward revisions:

- Discovery rates (expressed, for instance, in barrels of recoverable oil discovered per foot of drilling) could decline because most of the giant and supergiant fields have already been discovered and are increasingly difficult to find. (Recall that this seems to be especially true for oil, but not yet true for gas.) Although current trends of discovery rates are being debated, there is no evidence that they are decreasing worldwide, if the Middle East is excluded.

- The hopes of increasing recovery rates by 50 percent worldwide—that is, from 25 to 40 percent—may not be realized.
- Exploration and production costs could continue to increase, making oil too costly and possibly less and less competitive with cheap coal.
- The potential of the Middle East and of western Siberia may have been overestimated.
- The international climate may continue to deteriorate, and international oil companies, which have the know-how, may be progressively pushed outside the oil business. Thus the tools for oil exploration would be missing or would be dramatically reduced.
- Deep offshore and polar areas may turn out to be very disappointing with respect to their estimated potential; they may be reduced from 13 percent of the total Delphi estimate to, say, a few percent.[h]

Possible upward revisions may be the result of the following:

- Discovery of a new "Middle East." The possibility cannot be completely excluded (deep offshore, Antarctica, offshore China?). The chances are generally thought to be very small. Recent discoveries in Mexico (Reforma, Campeche, Chicontepec) provide arguments for the optimists.
- Deep offshore is a very poorly known area (continental slope and rise). There could be an agreeable surprise.
- New types of deposits. Up to now, 95 percent of oil fields, whether giants or not, have been found in anticlines (a theory that was laid down some one hundred years ago). Stratigraphic traps have yielded only small deposits (except in East Texas).
- Progress in exploration, in drilling, and/or in production technology. For instance, "bright spot" techniques have helped to discover previously hidden (gas) fields; the possibility of changing the drilling head without removing all the strings may decrease drilling costs; new offshore production technology (as explored by Shell at the Castellon's field off the shore of Spain) may eliminate the need for expensive platforms, for example. All of these possibilities point also to a potential growing role of medium or even small deposits.
- Enhanced recovery (which is at its initial phase) may be more promising than expected. This may be especially true for large amounts of heavy oil for which thermal methods can dramatically increase the rate of recovery (from a low 5 percent to a high of 40 percent or more in some

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[h] Some recent studies in 1978 and 1979 point in this direction. Even normal offshore exploration has given some discouraging results (such as Baltimore Canyon, as of mid-1979). We consider it too soon for a definite statement.

cases); many of these resources are not included currently in the reserves or only to a small degree. Recall that a 1 percent increase in the recovery rate, say, from 40 to 41 percent for 300 billion tons of recoverable oil is worth 7.5 billion tons of oil.

- As mentioned above, some of the regional estimates may have been somewhat underestimated. (In fact, some experts say that the Middle East is underestimated.)

Unconventional Oil Resources

Critics are fond of saying that unconventional oil resources have been expected for more than fifty years and always seem to cost \$3 or \$5 more than conventional oil, regardless of the cost of the latter. Certainly, unconventional oil is a "difficult" resource and, thus, expensive. But these resources are very large, and only a very small part of them is presently known.

These unconventional oil resources (which include heavy crude oils, tar sands, and oil shales) were extensively reviewed during the Second IIASA Conference on Energy Resources, jointly organized by UNITAR and IIASA (Meyer 1977). Most of the results of this conference were accepted and adopted, with minor modifications, by WEC (1978b), which refers only occasionally to unconventional oil resources and did not include them in its study.[i]

According to recent theories of oil formation and migration, there is an interesting continuity among the various hydrocarbon categories (see Figure 2-4). In brief, the burial of organic matter has led to the formation of kerogen—that is, to oil shale formation. If this were to remain near the surface, it would form the oil shale deposits that are currently known. But usually, the organic layers have been buried under additional layers of sediment and have crossed the "petroleum window" (about 65°C to 150°C) where the kerogen has been transformed into oil and into gas if the burial has continued deeper and deeper. Often, the fluid oil has migrated into an entrapping reservoir. Finally, if this oil were to come back near the surface through upward tectonics and/or if it were chemically (oxidized) or microbiologically altered, it would result in tar sands or heavy oil deposits. The recent understanding of these dynamic phenomena serves as a guide for new kinds of oil exploration that could pave the way to new discoveries.

Heavy crude oils and tar sands are very closely related. In fact, there has not been, to date, any general agreement on their definition. In broad terms, *heavy crude oils* have 10° to 25° API densities and can flow (although possibly very slowly); *tar sands* have between 7° and 10° API densities and

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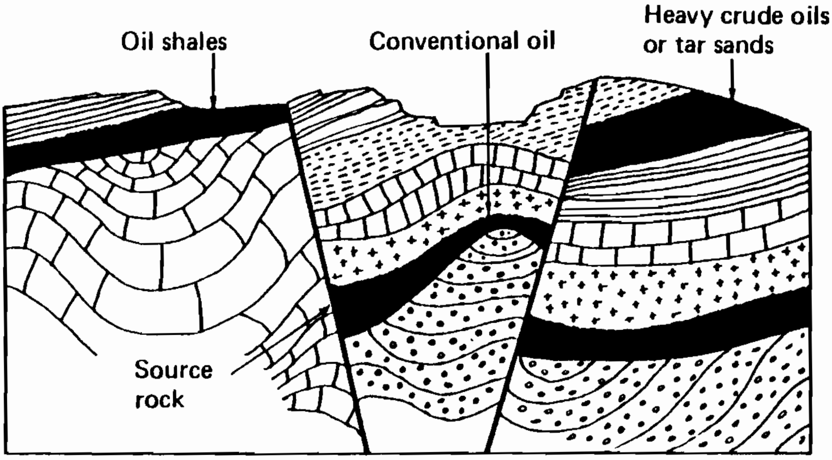
[i] As a followup to this IIASA-UNITAR conference in 1976, UNITAR organized the First International Conference on Heavy Crudes and Tar Sands in Edmonton (Canada) in 1979. Although the discussions were much of a technical nature, there were no important revisions or updating of the data on world resources. IIASA, for its part, has launched an independent assessment of world unconventional oil resources.

Figure 2-4. Continuity of oil resources.



cannot flow under normal conditions. About 90 percent of the currently known worldwide tar sand/heavy oil resources can be found in three countries—Canada, Venezuela, and the USSR. Nehring (1978) has pointed out that the supergiant deposits of tar sands (Alberta), oil shales (Colorado), and heavy crudes (Orinoco) belong to an "oil ring" (on the Pangea, 180 million years ago, before the continental drift) that also contains the giant and supergiant oil deposits of Alaska, Texas, Mexico, North Africa, the Middle East, and Western Siberia.

In some respects, the worldwide distribution of tar sands and heavy oils (and oil shales as well) would seem to resemble that for coal, with a broad geographical distribution dominated by a few giants:[j]

- Approximately 300 billion tons of heavy oil and tar sands (oil in place)—as much as the Delphi study estimate for recoverable conventional oil—are divided among four giant fields—Orinoco (Venezuela, 100 billion tons)[k]; Athabasca (Canada, 86 billion tons); Olenek (USSR, 86 billion tons); Cold Lake (Canada, 23 billion tons).
- Approximately 27 billion tons are contained in eight large fields (two in Canada, five in the United States, and one in Madagascar).

The technology for recovering bitumen and heavy oil falls into two general categories—surface mining and in situ recovery. Only 5 to 10 percent of

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[j] Note that these unconventional oil resources are found in unconventional types of deposits—namely, stratigraphic as opposed to structural traps for oil.

[k] According to some experts, this estimate is rather low and could possibly be doubled, or more. And Columbia probably also has very rich deposits.

the currently known resources are potentially recoverable by the surface mining method (with a reasonably high recovery ratio)—that is, 15 to 30 billion tons. The remainder would be recovered by in situ techniques (with an estimated recovery rate of between 30 and 50 percent).

In recent years, progress has been made in the recovery of heavy oil and tar sands, mainly in Canada, Venezuela, and the United States. The Syncrude plant (Syncrude Canada Ltd. 1978), with 6.25 million tons of oil per year, went into operation in 1978, and government incentives are progressively leading to other plants of this type. A growing number of pilot processes for in situ recovery are under development in Canada (more than twenty by mid-1979, most of them to be completed between 1980 and 1982), with the incentive that each future facility could possibly produce more than 6.25 million tons, which constitutes the present optimum figure for surface mining and surface processing. (Because surface operations are capital and labor intensive, it is understandable that the penetration of this new technology will not start soon.)

More than 420 billion tons of oil shale resources have been identified, two-thirds of them in North America. Here, also, 5 to 10 percent are considered recoverable under present conditions. Pilot plants are being developed, with a growing interest in the Garrett-Occidental modified in situ process. In mid-1979, oil shales became a major objective of the Synfuel Program proposed by President Carter to decrease U.S. oil imports.

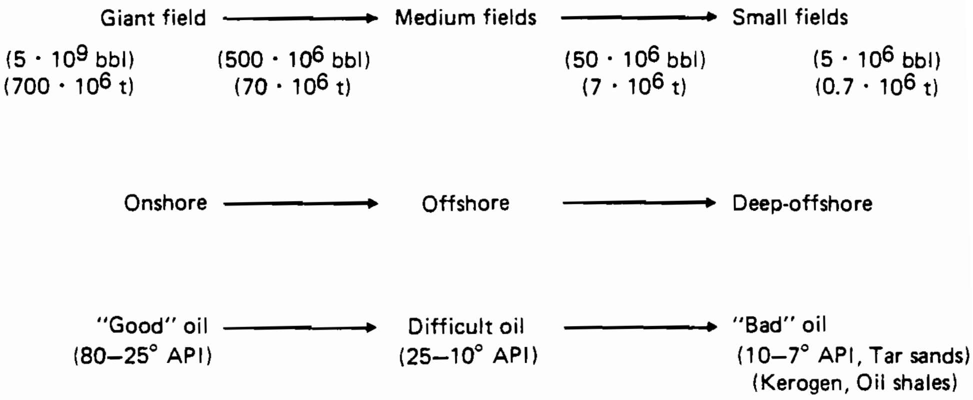
It is difficult, if not impossible, to make realistic forecasts of how and when these unconventional oils would enter the market. The Delphi study mentions that they can be progressively phased in after 1990. We share this opinion. The events of 1979 in Canada and the United States point in this direction. Production costs for upgraded syncrudes are given (1978 U.S. dollars) from \$12 to \$15 per barrel (Orinoco) to \$12 to \$20 per barrel (Athabasca) and up to \$20 to \$25 per barrel (Colorado oil shales), although these costs could be lowered through price guarantees and government-sponsored research and development programs.

The Three Paths to Costly Oil

Summarizing and synthesizing these findings, we see that we are heading for "costly oil." (By costly oil we mean the cost of producing oil and not the price of oil.) There are three paths to costly oil, as shown in Figure 2-5.

First, the oil industry, especially onshore, would shift progressively from supergiant oil fields (larger than 5 billion barrels or 700 million tons) and giant oil fields (larger than 500 million barrels or 70 million tons) to medium-sized fields and, finally, to small fields. Note that these supergiant and giant oil fields are now the most profitable and still account for more than 70 percent of global oil production. In the United States, small fields already account for 15 percent of production. As mentioned above, according to the Delphi study, most of the oil remaining to be produced (say, more than 60 percent) could be produced probably at less than \$12 per barrel or

Figure 2-5. Three paths to costly oil.



with investments of less than $6000 to $10,000 per barrel per day capacity. We judge that this oil will increasingly be the choice objective of the many national oil companies to feed their national requirements. This is what we call exploring the prospective areas "with a fine tooth comb." Natural gas would probably also be found and would contribute greatly to regional industrial development.

The second path to costly oil is from onshore to offshore, and, progressively, to deep offshore. Technology has progressed considerably (the North Sea has contributed much to this development), but costs have also soared. Because of these higher costs, development projects presently concentrate on giant fields. Investment costs for offshore can reach as high as $10,000 per barrel per day capacity and soar to $20,000 per barrel per day or more for deep offshore. Because of these costs, the associated high risks, and the advanced technology required, the largest projects are presently reserved for the biggest international oil companies (and/or consortia of many companies), who would thus continue to play their role as pioneers.

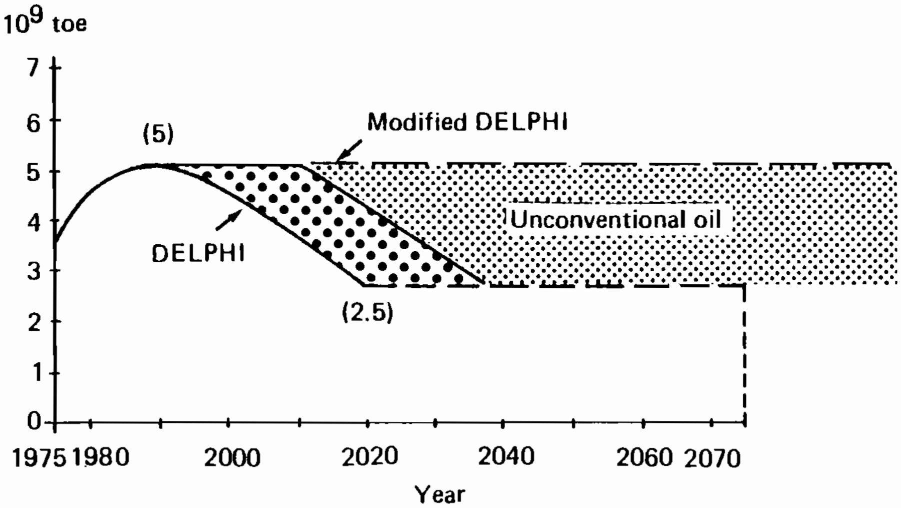
The third path goes from "good" oil to oil shales, through "difficult" oil. The trends are the same as for offshore to deep offshore, and investment levels are comparable, from $15,000 to $30,000 per barrel per day for tar sands and oil shales (and production costs between $15 and $20 per barrel). And also, for the same reasons (investments, risks, and technology), we judge that this frontier would be reserved initially for the large oil companies, or pioneers, or for governmental organizations. Incidentally, this points to the important contribution major oil companies continue to make to future oil supply, assuming that they are allowed, and even encouraged, to to do so. If this is the case, the physical continuity of oil resources illustrated in Figure 2-4 would be matched by the industrial continuity of the three paths to costly oil, to ensure a lasting oil supply.

Illustrative Production Levels

As a means of synthesizing these various considerations, we propose a production curve derived from the Delphi study, but with a major difference. We judge that the classical bell shape—popularized by Hubbert but since challenged—is not necessarily the only solution. Discovery rates could possibly be maintained—at a cost—at a more or less continuous level for a few more decades. Moreover, the Delphi curve assumes a constant reserve-to-production ratio over time for the various regions. It could be accepted that this ratio would decline slowly for other regions, as it did for the United States, allowing production to be kept constant over a longer period. Both factors would maintain a longer production plateau and provide more time for the progressive phasing in of unconventional oil (Figure 2-6).

The curve proposed by the Delphi study would decline from a maximum of between 4 and 6 billion tons per year around 1990 to a level of about 2.5 billion tons per year in 2020 and would continue to decline to lower levels over a long period. In fact, according to such a curve, and starting from 300 billion tons of oil, some 120 to 130 billion tons of oil would still remain in 2020 or about 250 billion tons in the early 1990s. Such an amount could (and must) be large enough to sustain a production plateau for a few

Figure 2-6. Oil: possible production and lifetime of ultimately recoverable global resources (conventional oil only; 300 X 10^9 tons). The right side of the figure shows the theoretical extension of the oil production level and not a possible real production curve. The semishaded area between the "Delphi" and the "Modified Delphi" curves represents a possible stretch of conventional oil production before a planned but delayed decline. *Source:* Delphi estimates based on Desprairies (1977).



decades before the actual decline phase begins. If the growth rate of oil production and consumption continues to average 3 to 4 percent per year or less (as opposed to 7 to 8 percent per year previously), and if new producers come progressively into the market to maintain a "fluid" supply in the next decade, there is no urgent need to introduce the most expensive unconventional oil resources, except in a few countries and for political reasons. In fact, this is true for new fuel supplies from Alaska and the North Sea and would probably continue to happen in the early 1980s in other countries such as Mexico, Egypt, Brazil, and Malaysia. Penetration could begin in the 1990s, with the cheaper unconventional oil resources. Note that this has already begun in Canada with Lloydminster and Cold Lake heavy oils and with the Syncrude project and its followers. Valuable progress can be expected in these fields over the next ten or fifteen years, as for example the oil shale projects in the United States.

GAS RESOURCES

There are many similarities between oil and gas resources, but also some major differences. Until recently, interest in gas resources was much less strong and came much later than for oil resources. Not long ago, finding a dry gas field somewhere outside the United States was considered a catastrophe. The rapid growth of natural gas consumption really started in the United States only after the Second World War and in Western Europe only over the last decade after the discovery of the Italian, French, and especially the Dutch gas fields. At the least, development has been impressive, so much so that natural gas now holds the share in Western Europe that was foreseen, in postwar energy forecasts, for nuclear energy.

Yet despite the very rapid increase in natural gas consumption, the industry is still quite young. Less than 8 percent of total estimated gas resources have been consumed up to now (unfortunately, a good part of it has been flared), as opposed to almost 15 percent or more for oil. Gas reserves are expanding continuously through revision of old estimates (of associated gas, mainly) and through many new discoveries of dry gas deposits. The ability to drill deeper and deeper is favorable to gas findings more than to oil. Anadarko Basin and Tuscaloosa Trend are two of the important recent developments in deep gas discoveries. And there is no slackening of the rate of finding new giant or supergiant gas deposits.

There is a strong consensus among world petroleum experts that natural gas consumption and production worldwide will continue to increase over the next decades, possibly until the beginning of the next century, because of the attractive properties of natural gas utilization and the growing sources of supply. However, the developed countries—especially those in Europe—seem to be approaching a limit for regional gas trade operable through land pipelines, and they will have to resort either to sea gaslines (e.g., the project across Sicily from Tunisia) or to expensive and still difficult LNG (liquefied natural gas) maritime transportation between conti-

Table 2-7. Estimates of ultimate gas resources remaining to be discovered and world gas reserves for the seven IIASA regions (in 10^9 m^3).

Region	*Reserves (as of 1 January 1977)*[a]	*Resources Still to be Discovered*[b]
I (NA)	7763	43,500
II (SU/EE)	22,654	59,000
III (WE/JANZ)	5061	14,500
IV (LA)	2695	15,000
V (Af/SEA)	3560	12,000
VI (ME/NAf)	21,157	78,000
VII (C/CPA)	594	10,000
Total[c]	63,484	232,000

[a] Based on data from *World Oil* (1978).

[b] Based on data from World Energy Conference (1978b).

[c] The two values do not add up to the ultimate value of 280,000 billion m^3 given above because of differences of dates and of origins of the data.

nents. A balance must be found between these constraints and the large availability of associated natural gas, mainly in the Middle East, relative to the high oil production. Rightly, producers, especially from the member countries of the Organization of Petroleum Exporting Countries (OPEC), are exerting strong pressure to avoid technical and/or economical losses of this precious resource.

There are still far fewer estimates of ultimate global gas resources than of oil resources, although efforts to improve this situation are taking place. Estimates of ultimate oil resources and of gas resources differ in several ways. Because gas recovery is already high (80 to 90 percent), there is not the same potential mechanism of additions to reserves by shifting from identified resources. Additions to conventional gas reserves must thus come from revisions of known reserves and, principally, from new discoveries.

The selected value—adopted by the WEC (1978b) and by the American Gas Association from an assessment by the U.S. Institute of Gas Technology (IGT)—is about 280,000 billion m^3 of gas remaining to be produced worldwide after 1 January 1976.[l] A tentative distribution of the gas resources amng the seven IIASA world regions is given in Table 2-7,[m] together with calculated gas reserves, using *World Oil* (1978) data (as of 1 January 1977). According to WEC (1978b), probably as much as 75 percent of these gas resources could be produced at less than $14 per barrel of oil equivalent (1974 U.S. dollars) by 2000 or later and the remainder at less than $20 per barrel of oil equivalent.

[l] The value given in the WEC (1978b) study is 10,508 EJ or Exajoules—that is, 279,000 billion m^3 (assuming 9,000 kcal/m^3). This value was derived from the range of values 9960 to 10,395 EJ—that is, 264,000 to 276,000 billion m^3 of the Institute of Gas Technology.

[m] It was necessary to make some special assumptions for this distribution because the gas regions considered by IGT and WEC are different from the oil regions.

During the Second IIASA Conference on Energy Resources (Meyer 1977) there were extensive discussions of "unconventional" gas resources—that is, gas in geopressure zones, gas in tight formations (sandstone, Devonian shales, etc.), and methane from coal fields, landfill gas, gas hydrates, and so forth, not to mention syngas from coal. There was some consensus that these resources are probably very appreciable, each perhaps equivalent to or even one order of magnitude greater than conventional resources, but that it is presently impossible to make a global estimate. Because of the youth of the industry and of gas consumption, and because of the sufficient supply of conventional gas at reasonably low cost, there has been little incentive to look for these new, technologically difficult and economically more expensive, gas resources. The United States is the only country that faces a possible gas shortage; and indeed, it is only for the United States that preliminary data are available and that the technology is being seriously explored. (In fact, depending on price policies and incentives, the situation in the United States could evolve between shortage and excess supply, as experienced in recent years.)

In Table 2-8 data on additional gas resources in the United States are given. These are large resources. Experiments are being carried out on coal bed degasification. Gas in Devonian shale and in tight formations is being produced on a small scale and is awaiting progress in fracturing technology. In 1979, a pilot well was drilled in Texas to assess gas in geopressure zones and, especially, to determine which possible share of estimated volume in place could be recovered: a low 5 percent would lead to recoverable reserves of 4000 to 70,000 billion m^3, the latter figure being equivalent roughly to present total global gas reserves.

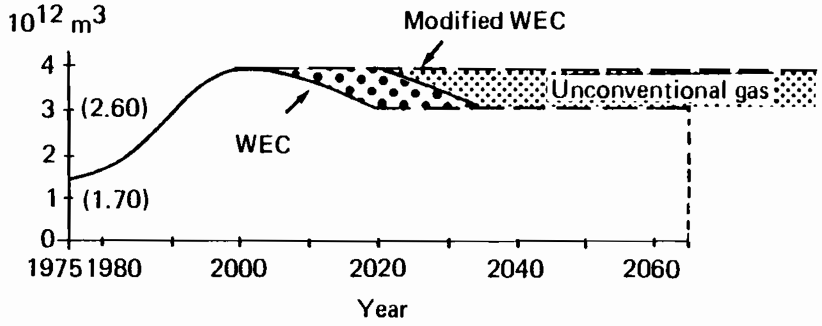
Turning to possible production levels, as shown in Figure 2-7, we see that (adopting WEC assumptions) gas production could increase to a level of around 3700 to 4000 billion m^3 per year between 2000 and 2010 or 2020. With the same reasoning as for oil, we judge that a constant level could be maintained for a few decades, instead of beginning to decline as soon as the maximum level has been reached. It is also worth mentioning that the present reserves-to-production ratio for gas is higher (around a value of fifty years) than for oil. In the year 2000, the remaining global gas resources would still be about 160,000 billion m^3, a sufficiently high value to allow constant production to be maintained for a few decades (possibly accepting

Table 2-8. Estimated additional gas resources, United States.

Source	*Estimated Volume in Place (10^9 m^3)*
Coal bed degasification	8630-23,100
Devonian shale	14,470-17,260
Tight formations	17,260
Geopressured gas	85,000-1,444,400

Source: Based on data from World Energy Conference (1978b).

Figure 2-7. Gas: possible production and lifetime of ultimately recoverable global resources (conventional gas only; 280,000 m^3). The right side of the figure shows the theoretical extension of the gas production level and not a possible real production curve. The semishaded area between the "WEC" and the "Modified WEC" curves represents a possible stretch of conventional gas production before a planned but delayed decline. *Source:* Based on data from WEC (1978b).



a progressive decrease of the reserves-to-production ratio) and to provide time for a progressive phasing in of new, unconventional resources.

OBSERVATIONS AND CONCLUSIONS

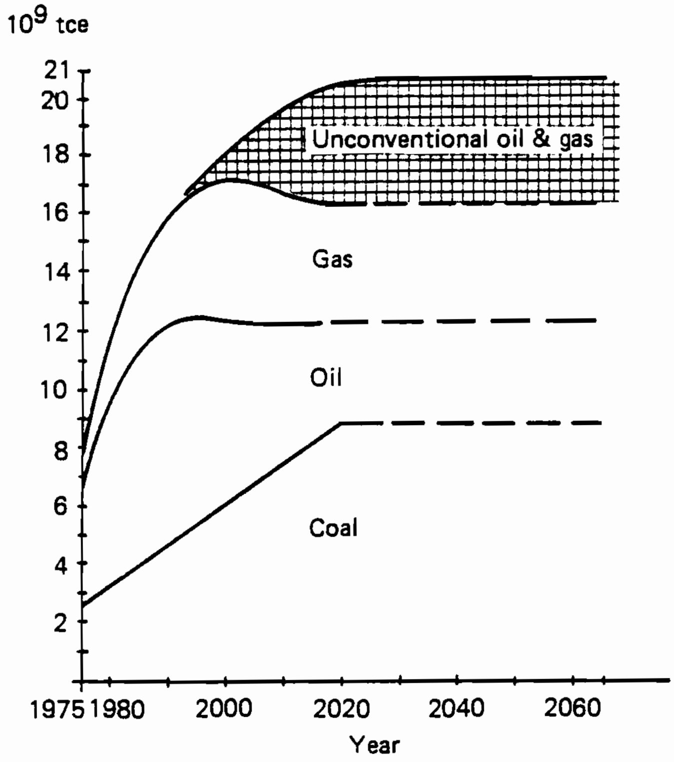
Figure 2-8 shows the various fossil fuel production levels proposed in this chapter. Again, these are possible maximum production levels, assuming that decisions are taken in time and that there are no political restrictions—that is, no political embargoes but not excluding a ceiling on future production. For fossil fuels, a level of about 20 billion tce could be reached in 2020 and could continue for many decades if necessary—that is, assuming the demand for fossil fuels will be this high (which seems improbable to us) and/or that no new, cheap, and plentiful energy source will be available shortly (which seems more probable to us). This, in our opinion, would allow sufficient time to achieve a smooth transition from fossil fuel use.

We have shown the "continuity" of oil resources and of the oil industry (Figures 2-4 and 2-5). We consider it worthwhile to extend such considerations to include fossil fuel resources as a whole, especially within the framework of our fifty-year time horizon, while recognizing the problem of predicting the future.

Looking back fifty years to around 1930, we see that coal was the prime energy source: its annual production level then was about 1300 million tce. Coal technologies have progressed since that time, and surface coal mining is presently the fastest developing coal production technology.

Oil production in 1930 was about 200 million tons, of which 6.4 million tons came from the Middle East. The Arabian fields had not yet been dis-

Figure 2-8. Fossil fuels: possible production levels and lifetimes. This is a theoretical curve, aiming to show the potential leveling of fossil fuel production.



covered; water injection was at a start; and the first offshore platform would not appear for another twenty years. In 1930, more than 95 percent of the natural gas was simply flared, with annual production around 50 billion m^3.

Because of the progress of coal technologies and especially of oil and gas technologies, we can view the task facing the fossil fuel industries courageously. In this context, we offer the following comments on the growing industrial continuity of apparently very different fossil resources.[n]

Figure 2-9 illustrates some of the technological exchanges between coal and petroleum industries in the field of extraction. Similar diagrams could be made for downstream steps, refining, conversion, and so forth. In other words, any carbon fuel can now be technically converted into any other (coal → gas → methanol → gasoline → and so on).

As to the extraction process, perhaps over the next few years it would be simpler to speak of "mineable" carbon compounds (coal, tar sands, and oil

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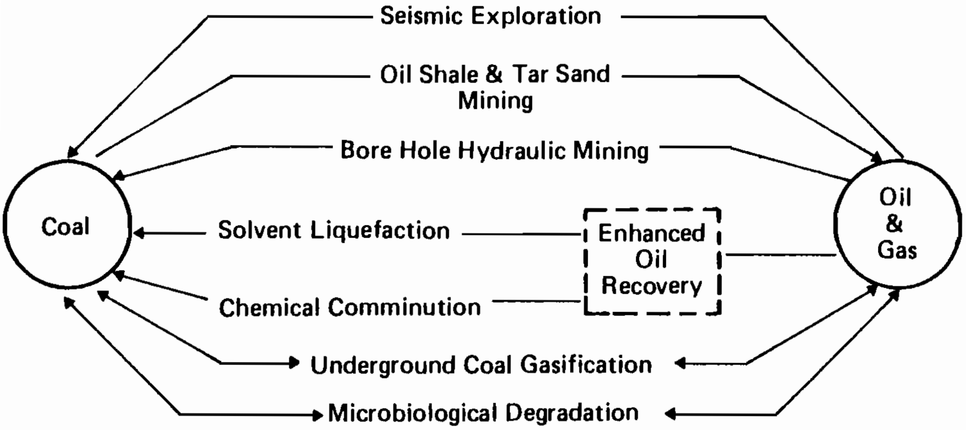
[n] Note that physical continuity has been shown by some authors, extending the considerations and similarities of Figure 2-4 to all carbon compounds.

Figure 2-9. Integrated fossil extraction industry. Arrows indicate technological exchanges between the two industries.



shales recovered through surface or underground mining) and of "drillable" carbon compounds (oil, heavy crude oils, gasified coal, in situ tar sands or oil shales, and gas recovered through drilling and fluid handling). Indeed, this would require a change in the vocabulary of coal people, since they continue to speak of "bore hole mining," "solution mining," and so forth. Some of these drilling operations seem to be at hand (e.g., enhanced oil recovery or steam-driven heavy crude production), while others seem further away, but all of these will benefit from common technologies (e.g., drilling, fracturing, fluid control) that we believe can potentially be developed by the year 2030.

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3 THE COAL OPTION

INTRODUCTION

The technically accessible resources of coal are very large and dwarf most of the other relevant fossil energy resources. In view of likely limitations on the adequate supply of crude oil and natural gas, we have analyzed the potential role of coal as a global long-term energy option.

The fact that, compared to oil and gas, coal is a vast resource could tempt us into considering it an infinite resource. It is not. While solar energy will last for billions of years and nuclear power for at least millions of years, the "vast" supply of coal can be measured in centuries of human use. So as not to lose the impact of this important matter, our analysis of the coal option goes beyond 2030, the nominal end point of our energy study, and up to 2100.

Modern energy systems began with coal and made the fundamental transition to oil and gas as these resources started to compete successfully. The system infrastructure shifted more and more to an emphasis on amenity and convenience, using secondary energy forms such as electricity, gasoline, district heat, and towngas. Thus, if coal is to be used as a principal energy resource in the future, it must contribute uniquely to supplying these secondary energy forms. The function of coal must be seen in terms of its capability to provide the raw input for the production of synthetic liquid fuels, which, over the next fifty years, could constitute an indispensable component of the total demand for energy.

However, the reserve and resource situation, as well as the global environmental implications, suggest that coal cannot be exploited again as the dominant source of primary energy, as it was from the early nineteenth century until the 1920s. This is because such a dominant role could have only a brief run in the longer theater of history. Only if we are frugal in our use of coal will it last for many centuries. The fact that the carbon in coal is in a chemically reduced form makes it an important exception to the generally oxidized state of most of the earth's carbon. A too rapid release of carbon into the atmosphere in the form of carbon dioxide, the combustion product of coal, could have serious global environmental consequences.

Nevertheless, a substantial increase in the existing supply capacity of coal appears to be a prerequisite for the transition from the use of clean oil and gas supplies to the use of dirtier fossil fuels and ultimately to the use of nonfossil fuels (e.g., hydrogen) during the twenty-first century. Therefore, the possibilities of a coal revival via new coal conversion technologies are analyzed in this chapter. Two case studies are discussed that demonstrate that modern coal liquefaction and gasification techniques could serve over the short term as a basis for the longer term transition.

To repeat a salient point: if a more dominant path for coal were chosen than that outlined here, the results would be the depletion of the world's fossil resources at the same time that an imprudently large amount of carbon dioxide would be dumped into the atmosphere.

A HISTORIC REVIEW OF COAL

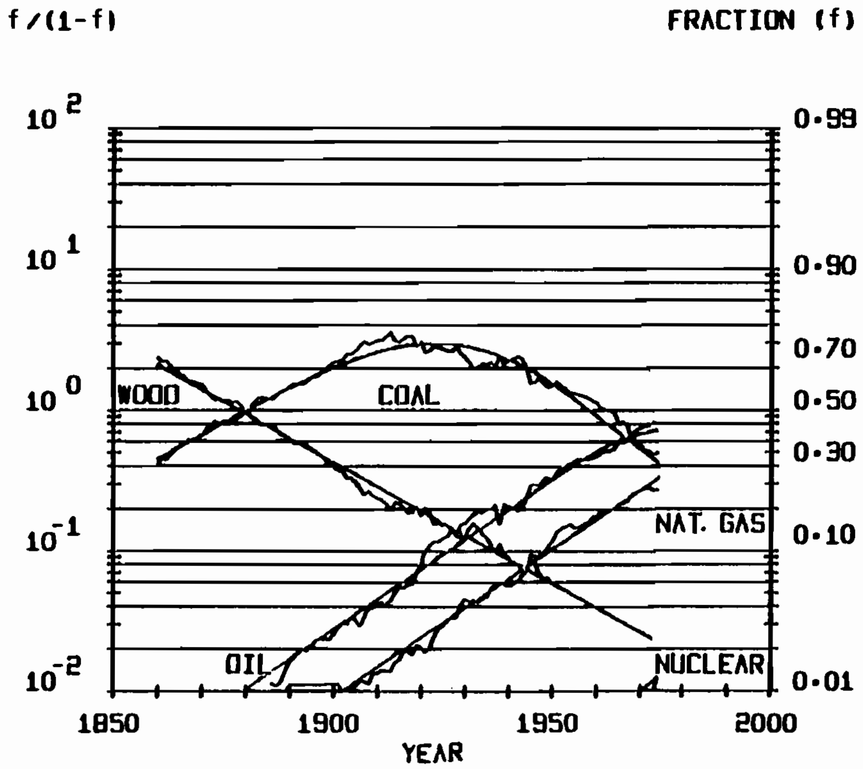
Modern energy systems depend on crude oil and natural gas, yet they have supported an extension of a technical system that evolved on the basis of coal. By plotting the share that each of these primary energy forms has contributed over time to the global energy balance, a remarkably simple and rigid process becomes visible. Figure 3-1 illustrates the contribution of various primary energy sources by means of a logarithmic scale that is suitable for displaying market substitution mechanisms.

Over the past several decades, oil and gas have expanded their market shares at the expense of coal. This substitution process followed an earlier substitution of coal for the renewable energy source, wood. It is tempting to extrapolate the lines of fate that Figure 3-1 seems to suggest. Before any projections can be made, however, it is important to distinguish between causes and effects of the past evolution. We therefore consider the general conditions of the past within which coal use matured and then gave way to the uses of oil and gas.

From Wood to Coal

The use of coal dates back some 2000 years, with coal remaining on the sidelines with respect to energy deployment throughout the Middle Ages. The depletion of forest reserves in many industrializing countries, giving

Figure 3-1. Global primary energy substitution. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



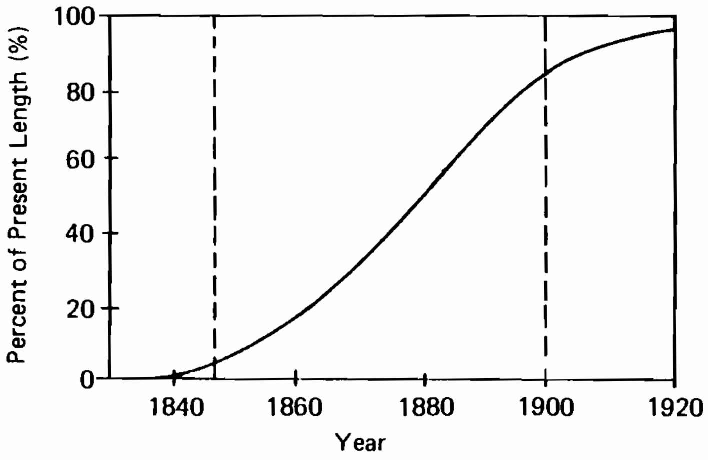
rise for example to the fuelwood crises of the nineteenth century, created an energy demand that could not be met at a local level. Coal was able to fill this market gap.

Coal's potential was realized once a sufficient centralization of demand in towns matched the possible centralization of supply in mining districts. Centralization at each end of the supply chain favored long-distance bulk transportation of coal—a capability readily offered by the railroad systems. Coal was favored for a number of reasons: the railroads benefited from the transportation of this new, high quality fuel; more railroads meant more steel; more steel meant more coal.

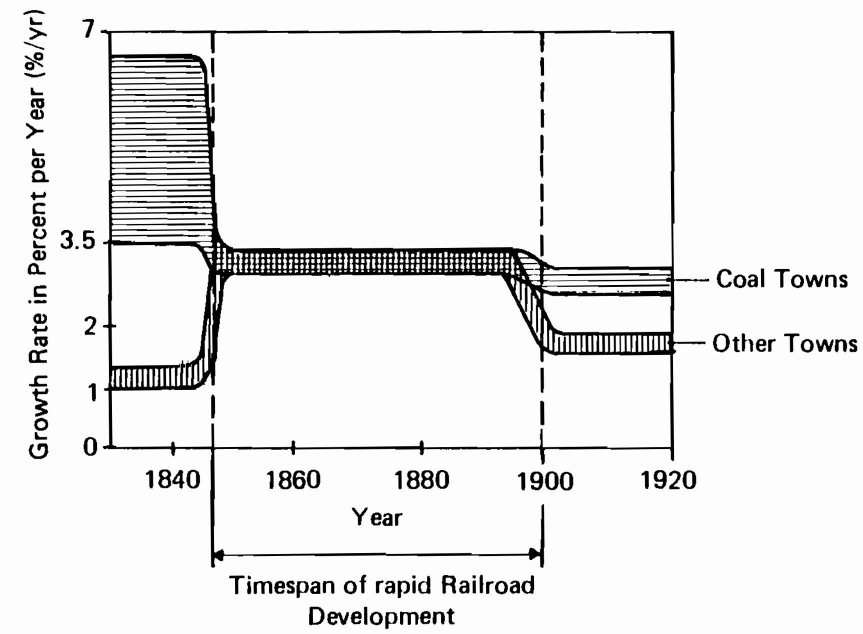
Within a period of roughly eighty years (1840-1920), the countries of the West completed a transition from wood, the age-old energy source, to coal, the prototype fossil resource. This transition occurred at the same time as the even more fundamental transition from a civilization based on agriculture to one based on industry. Figure 3-2 illustrates this transition for the case of the nation of Germany during the period 1840-1920. The rapid

Figure 3-2. Transition to a coal-based economy for Germany over the period 1840 to 1920. *Note:* The unique growth rate of 3.5 percent per year for both coal towns and all towns between 1850 and 1900 was possible because of the then available railway system.

Development of Railroad Systems in Germany



Growth of towns * in Germany



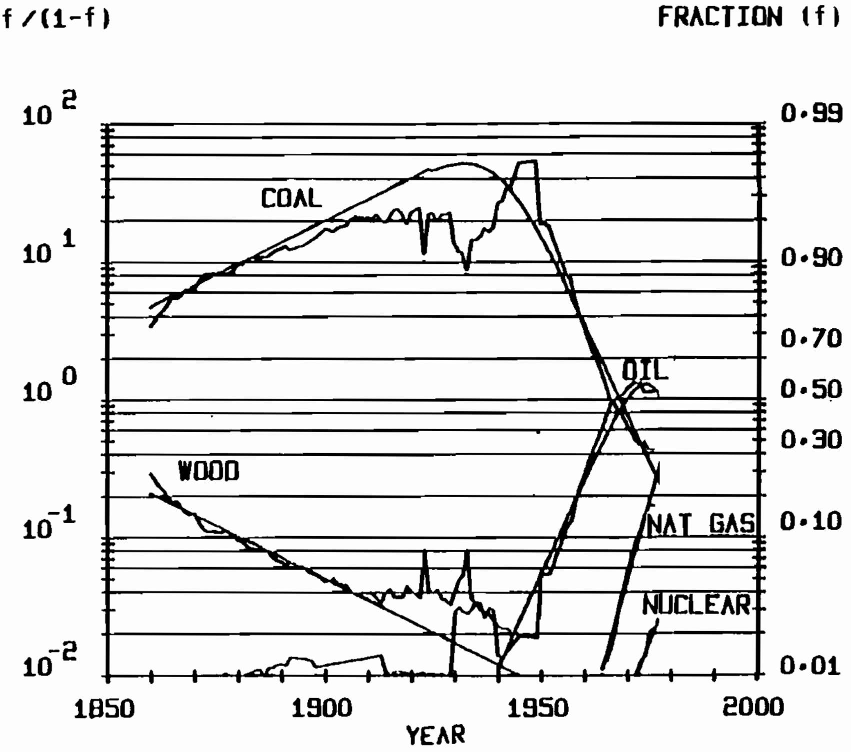
* All towns with more than 50,000 inh. in 1850

buildup of the railroad system between 1850 and 1920 coincided with the increased population concentration in major cities. The rapid rate of population growth in the larger towns and cities in the coal districts during the initial phases of the railroad era and their extended growth after the completion of that basic transport infrastructure point to the centralization of both demand and supply of energy that went along with the transition from wood to coal.

From Coal to Oil and Gas

What led, after such a convincing development in favor of coal, to its stagnation and relative decline in the primary energy market, which began around 1920 on a global scale? Figure 3-3 illustrates the dramatic speed of this process for Germany. (The market shares are plotted for the nation of Germany from 1850 to 1945; the figures for the Federal Republic of Ger-

Figure 3-3. Contribution of primary energy sources to the energy balance of the FRG, 1860-1975. Logarithmic plot of the transformation *f*/(1-*f*) where *f* is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



many are used after 1945.) In this traditional coal country, with an active coal industry and negligible indigenous oil and gas reserves, coal lost some 50 percent of its primary energy market share during the period 1935-1960. Although coal's market decline was delayed during the Second World War, thereafter coal lost its share of the market at a faster rate than had occurred at this time in, for example, the United States.

The roots of the shift to oil and gas reach back to the beginning of the coal era. The evolution of urban lifestyles led to a strong demand for more sophisticated forms of energy than raw coal could provide. Around 1825, the first gas lights appeared. Coal was converted into towngas, and pipeline networks grew—slowly at first, as they had to penetrate already builtup areas. By 1875, electricity grids offered a more appropriate means for lighting towns. Gas grids were used principally for the convenient supply of domestic heat for cooking and heating. District heating appeared at the end of the nineteenth century. Increasingly, secondary energy forms—towngas, electricity, and hot water—were supplied by means of grids that in turn depended on coal; hydropower, when available, was the only other source of electricity.

When oil and gas began their rally into the energy market sometime around the turn of the century, they followed a demand for quality energy that processed coal had stimulated and supported over a period of some eighty years. The replacement of coal by oil and gas was not a matter of fuel price, nor was it stimulated by a shortage of coal reserves. Oil was an internationally available energy form that could be moved inexpensively around the globe in a way that was not possible with coal; in a sense, oil "deregionalized" energy. And of course, the development of oil-based automobiles and airplanes, and especially of modern agricultural technologies, strengthened oil's position in the market. Gas, which could be supplied by networks, freed the consumer, both domestic and industrial, from the need to maintain a private fuel storage capability and to arrange for periodic resupply. Towngas was never seriously challenged by oil and was supplanted only by natural gas, whose network potential was greater. So strong were the convenience features of oil and gas that even the electric utilities in locations far from coal supplies relied more and more on oil and gas: convenience to a small customer translates into nonfuel economies for a large one—namely, capital and labor savings, process simplifications, and environmental and aesthetic benefits.

In summary, the ability of oil and gas to meet increasingly sophisticated consumer demand, at both the private and the industrial level, is the basic reason why coal was forced into retreat so quickly. Even the railroad system switched to other forms of locomotion (fuel oil and electric traction) for reasons of fuel and labor efficiency and of pollution abatement in urban complexes.

These patterns describe the rise and fall of coal use in the more industrialized countries, where development took place mainly during the era of coal dominance. Also, coal was then abundant in these countries. However, those countries whose industrial development is taking place now are not likely to experience a coal era of this sort. These developing economies depend principally on fuels that can be transported inexpensively over great distances. Oil satisfies this condition far better than coal and is the fuel of choice because of practicality and convenience.

A GLOBAL RETURN TO COAL?

The possible limitations on the adequate supply of conventional oil and natural gas, together with a growing politization of the limitations of nuclear energy and the economic constraints of large-scale hard solar, cloud the outlook for adequate energy supplies. It therefore seems appropriate to question whether coal could make a comeback as a global primary energy resource. To explore this possibility, we have developed a hypothetical high coal consumption case, which we will describe later in this section. First, it is useful to examine the various factors affecting the use of coal.

Coal Resources

There are abundant coal reserves in the ground. But how much of it can ultimately be produced? In Chapter 2, we touch upon the difficulties inherent in the concept of resources. Because of the different genesis of fossil energy resources and the widely differing technologies for their exploitation, comparisons of coal, oil, gas, and other fossil hydrocarbons lead to considerable ambiguities. But quantitative differences outweigh qualitative and conceptual inconsistencies. There is more energy in coal, accessible with demonstrated mining technologies, than could be obtained from known oil and gas fields using present and anticipated technologies.

According to data given in Chapter 2, the ultimately recoverable resources of conventional and unconventional oil and natural gas worldwide are estimated to be of the order of 1250 TWyr. (This estimate includes 420 TWyr of heavy crude oil and tar sands and 60 TWyr of shale oil.) The resource base of heavy crude oil is larger than has been estimated here and is very much larger for shale oil. Nevertheless, allowing for improved technology, this is all that seems to be producible at prices competitive with coal. This estimate of 1250 TWyr—which is more than four times the value of the economically producible reserves demonstrated in 1977—takes into account new discoveries of conventional oil and natural gas, a significant increase in the percentage of oil and gas that can be extracted from in situ amounts, and a substantial increase in the cost of production.

By contrast, economically recoverable reserves of coal worldwide have been estimated at 600 TWyr. This amount of coal could be mined with present technologies and without substantial increases of production costs. The 600 TWyr of coal reserves currently account for 6 percent of the geologically prognosticated world coal resource base of an energy equivalent of 10,000 TWyr. Roughly 30 percent of the prognosticated coal resources—

3000 TWyr—were identified in explored geological formations (Fettweis 1976).

For technical reasons, only a fraction of the 10,000 TWyr of coal resources could ultimately be produced. Nevertheless, further exploration and development of production technologies might extend the potential of coal reserves considerably. Even the resource figures might increase. The World Energy Conference (1978) pointed to the real possibility of a doubling of world coal reserves of 600 TWyr within the next forty years. It therefore seems inevitable that longer term fossil energy opportunities are more dependent on coal than on all other types of hydrocarbons considered together. But coal, like oil, is not distributed uniformly. Roughly 85 percent of the resources are in the United States, the USSR, and China or, in our terminology, in regions I (NA), II (SU/EE), and VII (C/CPA).[a] This has severe implications. It is by no means clear that these regions would assume a supplier role, as region VI (ME/NAf) does and is expected to do for oil.

Astakhov (1980) estimated the economically recoverable coal resources at between 2400 and 3700 TWyr. This estimate goes beyond what we have given for coal in Chapter 2, because Astakhov additionally considered what is feasible over the entire twenty-first century. However, his range is well within what we have considered in Chapter 2 and is therefore not inconsistent. Here, for our purposes, we adopt the estimate of 2400 TWyr of recoverable coal resources.

Global Coal Resource Economics

As long as mankind can choose among various energy sources, cost differentials will greatly influence such choices. In order to determine the role that coal could play over the next fifty years, we assessed the supply costs for a large amount of coal. Any such undertaking rests ultimately on assumptions about technical and political circumstances affecting access to the physical resources and, equally important, on the supply situation of alternative energy forms. Unlike oil, there is currently no global reference price for coal. Moreover, there are different types of substances referred to as coal that differ over a broad range of physical properties and in their content of hydrogen, water, and minerals. These properties in turn affect the usefulness of the various coal types for specific applications, their transportability, and thus their value.

The price of coal is only in part influenced by its recovery cost. As is true for oil and gas, the price of coal is influenced greatly by the demand for the product. Thus good quality anthracite—a high grade carbon in great demand by the metals industries—commands a premium price, far greater than its recovery cost would suggest. In recent history, the price of coal has followed the price of oil upward at a discrete differential, maintaining a significant

[a] See Figure 1-3 for the definition of the IIASA regions and Appendix 1A for the list of the countries in each of these regions.

price advantage on a cost per thermal energy content. This demonstrates that oil remains the world's reference fuel and that when and if coal achieves this position, its price would be greatly affected by the history of the oil domination of the energy market.

Nevertheless, we need a point of reference for the evaluation of coal. We have considered \$20 (1975) per ton of coal equivalent (tce) at mine mouth as the best orientation for coal fed as a base supply to global needs. Thus \$20 is a price at which the system would accept large amounts of coal. The cost of producing coal at this price is much more difficult to calculate, since it is dependent on land values, labor rates, and other factors that vary widely among regions.

Transportation and Delivered Prices

Again, coal is unevenly distributed, and its transportation is therefore an essential element of the overall coal picture. The traditional methods of transporting coal have been by railroad and ship, both of which are labor and energy intensive; as the value of these inputs increases, their costs generally escalate. For coal with high water and ash content (e.g., brown coal), transportation problems are especially severe. The additional weight increases the already costly transportation operation. Unfortunately, most of the least expensive coal in the world (e.g., that in the northern Rocky Mountains in the United States) falls into this category. Most lignites and brown coal cannot be transported at all at acceptable costs. The differential between a price of \$20 to \$30 per tce for coal at the mine mouth in the northern Rocky Mountains and a price of about \$50 per tce for coal delivered to an east central U.S. customer (in Illinois) illustrates the magnitude of the coal transportation problem using railroads (Corey 1977).

Long-range transportation of coal by bulk carrier is also a possibility. Again, the transportation costs for coal are much greater than those for oil. Coal cannot be transported entirely by ship; if either the deposits or the consumers are located inland, the coal must be transported by other means before it can be shipped. The loading and unloading of coal is more labor intensive than is oil. Since coal is bulkier per unit of energy content than oil, even large colliers cannot achieve the economy of scale of the supertankers.

One way of reducing transportation costs is by preprocessing the coal at the mine mouth into more transportable products. For example, coal could be pulverized, thereby discarding some of the inclusions, and transported by slurry pipelines. However, this substitutes the cost of a new infrastructure (e.g., the pipeline) for the greater continuous costs of railroad operation. Coal slurry pipelines are not without their own problems, since the slurrying often requires that coal be further processed at the delivery end.

Currently, the easiest and most economical way to convert coal into a transportable product is to use it for generating electricity at the mine mouth. Here, the cost of electrical transmission is offset in part by the need to maintain large-scale transmission networks for balancing continental loads and for providing interregional reserve capacity. That is, the capital structure of electrical networks is not an intrinsic limit. More constraining is the fact that economical transmission systems have losses—of the order of 1 percent per 100 km—which limit mine-mouth generation to a regional capability. And of course, mine-mouth generation leads to problems of environmental equity, since the population in the mining area must deal with the environmental costs of coal extraction as well as with the added air pollution from burning coal. The well-known case of the Four Corners Power Plant in the southwest United States, where the smoke plume was clearly visible by eye from orbiting spacecraft, illustrates the problem.

A Hypothetical High Coal Consumption Case

For heuristic purposes let us now assume that problems arising from the geographical distribution of coal resources can be handled successfully. Does coal become a global primary energy option somehow in parallel to nuclear and solar power? How large is a potential of 2400 to 3700 TWyr of coal resources when looking at it operationally?

In order to assess the basic assumptions and limitations of coal as a primary global energy resource, we consider its role in terms of global energy demand. The basic method used to calculate the exhaustion time of a resource is to divide known quantities of resources by present or expected future consumption rates; however, this does not take into account the intrinsic inertia of the energy system. Any return to coal as the main primary source of energy would be a gradual process. In line with the dynamics of past market substitution processes (as will be discussed in Chapter 8), we developed a hypothetical high coal consumption case up to the year 2100, quantified in Figure 3-4 and summarized in Table 3-1. It is meant to demonstrate a limiting case for coal.

The following assumptions were made for the hypothetical coal case. The coal revival begins in 1980, with a market penetration time identical to that of oil in the global market of the past (see Figure 3-1). A high—40 TWyr/yr—global demand for secondary energy by 2030 provides a target for deriving total energy demand. This demand is held constant after the year 2030. Primary energy demand is adjusted in Figure 3-4 for increased conversion losses as the substitution of coal-derived synthetic liquid and gaseous fuels for oil proceeds; thus eventually more than 40 TWyr/yr of primary energy is needed.

Based on these considerations, we conceive that the present downward trend of the market share of coal would be reversed and that coal consumption would increase to 40 TWyr/yr around the year 2080. This level would, at that time, be some 80 percent of the total primary energy, a share previously held by coal around 1870. However, the price of this concentration of primary energy is a significant resource depletion rate. We therefore made one more assumption to complete the picture: in 2080, an unspecified addi-

Figure 3-4. Primary energy consumption in a hypothetical high coal consumption case.

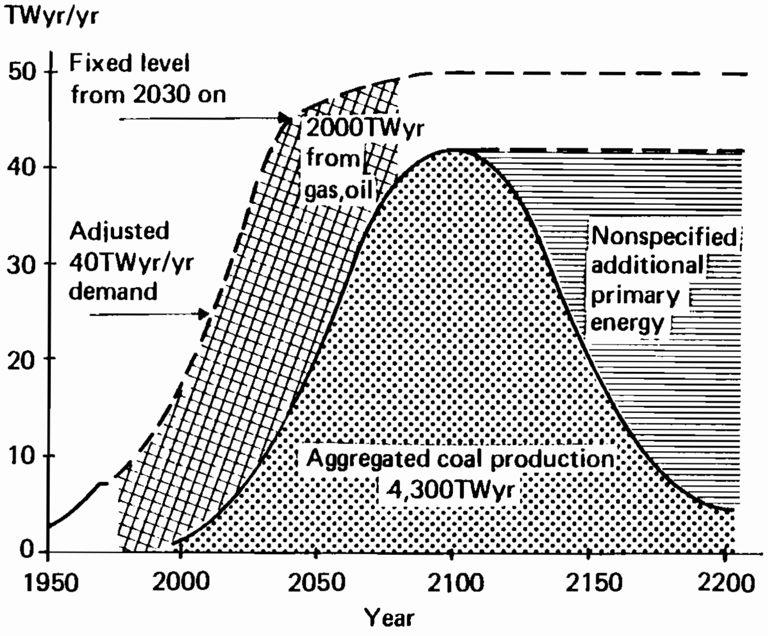


Table 3-1. Hypothetical high coal consumption case (to 2100).

Assumptions

- Coal revival begins in 1980
- Secondary energy demand is 40 TWyr/yr in 2030 and thereafter
- Primary energy demand is more than 40 TWyr/yr in 2030
- Coal consumption is 40 TWyr/yr (or 80 percent of primary energy demand) in 2080
- An unspecified additional primary energy source is introduced in 2080 and begins to phase out coal

Implications

- Forty-three percent of stated coal resources required; because coal recovery is only 50 percent efficient, total coal resource base is used up in 100 years
- Oil and gas fill supply gap until 2080; however, oil and gas resources will be used up before 2050
- Increased CO_2 atmospheric levels above prudent level due to coal combustion
- Large-scale mining and handling operations

Conclusions

- A global energy strategy based entirely or even primarily on coal and other fossil fuels would mean that these resources would be used up in about 100 years and prudent environmental constraints would be violated.

tional primary energy source is introduced that phases out coal at the same rate as coal was forced into the global market initially.

A number of systemwide problems were considered in the hypothetical coal case. Some 4300 TWyr of coal, or 43 percent of the geologically prognosticated resources of coal, would have to be ultimately produced. If only 50 percent of the resource is capable of ultimately being recovered, then according to our hypothetical coal case, the total resource base of coal would be practically consumed in about one hundred years. Further, we have assumed virtually no solar or nuclear contribution before 2080 and the use of additional energy from oil and gas to fill the gap between energy demand and supply during the period when coal supply is gradually increasing—that is, up to the year 2100. In the twenty-first century, the total global energy needed above and beyond that produced by coal would be about 2000 TWyr. However, the resources of oil and natural gas, including highly speculative unconventional forms (see Chapter 2) amount to about 1350 TWyr. Of course, if solar and/or nuclear power would be introduced earlier than 2080, they could fill this gap of a complementary primary energy source.

Environmentally, this hypothetical case implies many problems, including the potentially serious environmental effects of high atmospheric carbon dioxide levels. Chapter 10 discusses the carbon dioxide problem in depth; here, we repeat the conclusions that the present scientific basis does not yet warrant a curtailment of fossil fuel use, while at the same time policies emphasizing the use of coal are at present equally unjustified. These statements refer to near-term policies at the scale of current global primary (commercial) energy consumption, which is some 8 TWyr/yr.

There are other systems problems of producing and consuming up to 40 TWyr/yr of coal—that is, 45 billion to 60 billion tons of coal per year depending on its average calorific value. Consider the present problems of mining, transporting, and converting roughly 3 billion tons of coal (2000×10^6 tce) per year. The difficulties of embedding twentyfold larger technical operations in the ecosphere of an increasingly populated globe are enormous. Local pollution and/or social conditions are likely to limit the deployment of coal on such a scale in those coal countries that have other energy options, and conservation efforts might constrain coal production in areas where coal is the only or the main national energy resource.

Here, we recall the purpose of this heuristic exercise—to shed light on the possibility of a global return to coal. Based on the above considerations, we conclude that a global return to coal as a primary fuel is impossible.

THE STRATEGIC ROLE OF COAL IN FUTURE ENERGY SYSTEMS

Having demonstrated a limiting case for coal globally, we now turn our attention to how this major resource can be used prudently. As we see it, the strategic function of coal is to fill the liquid fuel gap created by the transition from clean oil and gas to dirty oil and gas and, ultimately, to nonfossil fuels. It is not difficult to foresee in the long run—perhaps beyond the year 2100—a global energy system in which nuclear and solar power supply unlimited amounts of primary energy. Still, these primary energies would have to be converted into a viable secondary energy form. Electricity and hydrogen are these forms; in Chapter 22 we refer to them as secondary energies of an "electronic" and "protonic" nature. With coal, the chemical properties of the carbon atom come into play—namely, its ability to bind and thereby to carry hydrogen. By means of both allothermal liquefaction and allothermal gasification, exogenously produced hydrogen from nuclear or solar can be used along with coal to produce methanol or methane or other synthetic hydrocarbons. Allothermal coal liquefaction, using, for example, the molten iron bath technique, offers great potential, and is therefore discussed in detail in Chapter 22. Here, we note that allothermal liquefaction, as opposed to autothermal liquefaction, should be the preferred technology since it requires less coal.[b]

By considering the prudent use of coal, we are turning from a consideration of primary energy to that of secondary energy. This, then, leads us to a consideration of the existing and the future energy infrastructure.

Coal Within Today's Energy Infrastructure

Currently, coal is a major energy source for the steel industry and for electricity production. Based mainly on these two applications, coal provides some 30 percent of the global primary energy needs. Consequently these powerful industries worldwide provide the demand for coal mining, coal transportation, and the continual improvement of coal technologies; most important, in many countries coal is a socially accepted reality in spite of its side effects and risks.

Coal industries in many countries face strong competitive pressures. This is not merely the consequence of cost-price relations. Even after the substantial price increases of crude oil between 1972 and 1974, and in spite of national policies favoring coal in many countries, the future of coal in the energy market is unclear.

As mentioned above, labor problems and environmental constraints both for large-scale mining and for the conversion of coal, as well as the difficulties of transporting solid fuels, make it necessary to view each coal deposit individually. But these are only a few of the difficulties of embedding increased large-scale coal deployment into the global energy system. Between the beginning of the oil era and the present, the infrastructure built initially around coal has been transformed. More specifically, coal as a commodity has been displaced not so much by oil as by secondary energy carriers. It is significant that the chief consumer of coal—the electric utility industry—has carried out this transformation.

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[b] For the autothermal method, the process heat comes from the coal itself, while for the allothermal method the process heat is supplied exogenously.

The Growing Need for Secondary Energy

Energy systems are linked to our civilization more intimately than the environmental and resource issues might indicate. This fact becomes clear as we examine the relationship between primary and secondary energy carriers. Indeed, the availability or the nonavailability of secondary energy carriers is currently a more critical matter than the availability or the nonavailability of a specific primary source of energy. For example, a country could find itself in great difficulty if its supply of crude oil were suddenly cut off; given an appropriate time for adjustment, it could cope by switching to the use of more coal and natural gas, for example. Nevertheless, it is almost inconceivable for a modern economy to operate without gasoline and even more so without electricity. Indeed, the secondary energy balance of a country or a region, rather than its primary energy balance, is a useful aggregate indicator of individual lifestyles and settlement patterns within the framework of climatic and environmental circumstances.

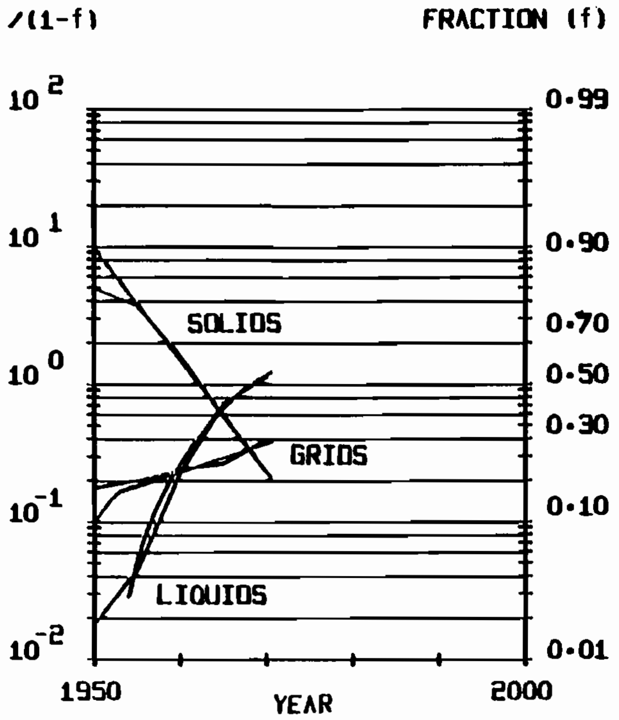
Several criteria determine the success or failure of a specific secondary energy form—technical suitability for the final consumer; effective conversion, transportation, and distribution systems; and concentration of side effects at the supplier end rather than at the consumer end. The first criterion was responsible for eliminating most of the "exotic" forms of secondary energy (e.g., mechanical cable transmission and hydraulic grids) in the early phase of the industrial revolution. The second criterion has been most actively used throughout the twentieth century and is responsible for the success of liquid fuels and electricity in the secondary energy market. The third is likely to be applied more vigorously in the future.

How did the demand for secondary energy evolve? Recent changes in the secondary energy balance of the FRG are shown in Figure 3-5 in terms of market shares of secondary energy delivered to the various energy consumers in both solid and liquid forms and through grids. Grid supply comprises district heat, pipeline gas, and electricity. Energy for the transportation sector and coke for the steel industry were excluded, since for these specific markets consumers have no other energy alternative. Similar patterns have evolved in many other countries, in spite of marked differences in the availability of indigenous primary energy sources.

Two independent substitution processes took place in the FRG during the period 1950-1975, as can be seen in Figure 3-5. The first is the very rapid transition from solid fuels to liquid fuels for heating purposes; this corresponds to the shift during this period from wood and coal to crude oil in the primary energy balance of this country. A slower, but very distinct, substitution process that began in the nineteenth century is indicated in the figure by the ever-increasing share of energy supplied by grids. This reflects the gradual shift from individual handling of "dirty" fuels to centralized supply of clean, automatically controllable forms of energy.

For economic and technical reasons, the buildup of supply grids depends on sufficiently high energy demand densities and thus on the process of urbanization. (The relationship between energy densities and human settlement patterns is discussed in depth in Chapter 23.) Similarly, congestion

Figure 3-5. Secondary energy supply, FRG, 1950-1970. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; straight lines show the logistic model substitution paths; model estimates follow historical data and are therefore not easily distinguishable on graph.



and local pollution because of urbanization gradually constrain the operation of less sophisticated individual energy conversion systems based on solid and liquid fuels. Two independent observations underline this fact. First, the saturation effect in the market share of liquid fuels (Figure 3-3) occurred before the oil crisis of 1973-1974, at a time when oil was the cheapest of all forms of energy available to the consumer. Second, the fraction of secondary energy supplied by grids depends strongly on the size of towns. In the large urban complexes of the FRG, up to 75 percent of the stationary energy demand is currently met by the use of grids; this amount is some 20 percent or less in small towns and villages. Urban planners for large cities have favored district heating systems on environmental grounds. The positive effects are well documented by the urban pollution-monitoring systems. But while the demand for energy supplied by grids will certainly increase, networks cannot supply all the final energy that will be required.

Within tomorrow's energy infrastructure, coal must be used prudently—that is, it must be adapted to suit the specific features of secondary energy requirements. As we shall discuss below, these requirements center around the need for secondary liquid fuels.

Secondary Liquid Fuel Requirements

The demand for liquid fuels is almost irreducible. Globally, some 40 percent of the secondary energy currently supplied is met by liquid distillates and derivatives of petroleum (e.g., gasoline, kerosene). In industrialized societies, some 20 percent of the total demand for secondary energy is for liquid fuels for transportation purposes. Currently, liquid fuels appear to offer an indispensable combination of energy density, portability, and direct applicability to the task. In these societies there are also demands from discontinuous operations (e.g., diesel generators for shift operations in industrial plants) of smaller consumers in outlying districts of urban areas and even higher demands in small towns and villages. In less industrially developed countries, liquid fuels are of even greater importance: indeed, in most countries such fuels are the only forms of high quality commercial fuel available to consumers, particularly those in rural areas.

Here we estimate that for the world of 2030 and beyond some 10 TWyr/yr of liquid fuels would be needed. Our reasoning is that a low energy demand world (of about 25 TWyr/yr of primary energy) would not bring much change in end use patterns from current patterns; 10 TWyr/yr of liquid fuels is some 40 percent of the current contribution to secondary energy supply. A high energy demand world (of about 40 TWyr/yr of primary energy) would involve very different circumstances, and there would be more opportunities for substitution as a result of both greater innovation and greater necessity. In this high demand estimate, 10 TWyr/yr of liquid fuels is only a little more than the amount that would be needed by the transportation sector. But this 10 TWyr/yr could be supplied from petroleum and from allied fuels for only a limited period of time. Thereafter, liquid fuels would have to be derived from other sources.

What alternatives exist, other than liquid fuels from fossil carbon—from coal? The only possible competitor appears to be certain heavy oil—for example, shale oil. However, since these oils must be recovered from rocks in which there is only a small amount of this material, they may not be as acceptable, both for economical and environmental reasons, as coal.

So we observe that coal-derived liquid fuels are probably the most appropriate means for meeting these secondary liquid fuel requirements, with the caution that this observation, while plausible, is not absolute. Still it points to the prudent use of coal.

Environmental Considerations of Carbon-Based Liquid Fuels

As far as time is concerned, we judge that liquid fuels derived from coal would be needed for about one-hundred years or perhaps even more. This period is long enough for us to hope, with some confidence, that hydrogen or other noncarbon energy carriers would be able to fill the need for liquid fuels or that technologies will be developed for deriving carbon from limestone or atmospheric carbon dioxide. With the exception of the problem of high carbon dioxide levels in the atmosphere (see Chapter 10), other effects of carbon combustion appear to be minimal; after all, mankind has been experimenting with fuel combustion for some time.

As is suggested in Chapter 10, deriving 10 TWyr/yr from the direct combustion of coal might be an imprudent action if carried out over a long period. On the basis of admittedly limited data and knowledge, it is conceivable that such actions could ultimately cause global climatic changes too quickly for mankind to adjust to. Using the same data base, it is also possible to suggest that 5 TWyr/yr of coal combustion, causing a little more than present carbon dioxide emissions, would bring about changes at a rate accordingly slower to permit adjustment. Deriving 10 TWyr/yr from petroleum would thus lead to an annual release of carbon dioxide into the atmosphere equivalent to that of some 5 TWyr/yr of coal combustion; the remaining 5 TWyr/yr in this instance would result in the emission of water. Deriving 10 TWyr/yr from methane would produce the same level of carbon dioxide emissions as would be derived from 3 TWyr/yr of coal combustion. Thus, 10 TWyr/yr of energy from liquid fuels—be it a synthetic olefin or an alcohol—appears to be a prudent approach because it still allows for adjustments to be made of the coal and hydrogen shares, as well as for flexibility.

Ideally, what is needed is an asymptotic 10 TWyr/yr carbon-based liquid fuel supply whose internal energy is not derived at all from fossil fuel combustion. Under these circumstances, the use of coal as a raw material for the synthesis of liquid fuels would not increase carbon dioxide emissions over present amounts. In fact, this means recycling and thus investive uses of the coal resources. (See Chapter 21 for a discussion in detail of investive uses of resources.) Of course, it will turn out that this approach is probably too cautious. Nevertheless, it is commensurate with the current level of concern about the problem of nuclear waste management. The adoption of such a cautious approach to an asymptotic value of carbon-based liquid fuels would probably make it permissible to exceed the interim carbon dioxide emission rate for perhaps a few decades, while the asymptotic structure is being built up.

As already alluded to, the amount of energy stored in carbon atoms is a related environmental question. The most energy stored per carbon atom is obtained when the maximum number of hydrogens are bound to the carbon. Among liquids, the only possibilities are saturated aliphatic hydrocarbons of medium weight (roughly octanes to dodecanes) and methanol. These substances are well known. Gasoline is a mixture of hydrocarbons composed principally of octanes; kerosene is composed largely of dodecanes; and methanol is so-called "wood alcohol." The properties of methanol and gasoline are given in Table 3-2.

Environmentally, there is little real choice among the three substances. Kerosene and methanol are less flammable than gasoline, but kerosene cannot be readily used in automobiles. Conversely, kerosene is the preferred fuel for jet aircraft. Since gasoline evaporates more easily than methanol, it

Table 3-2. Properties of methanol and gasoline.

Properties	*Methanol*	*Gasoline*
Chemical formula	CH_3OH	C_8H_{18} (isooctane)
Molecular weight	32	114 (isooctane)
Specific gravity (kg/l)	0.79	0.72-0.76
Boiling point (°C)	64.7	38-204
Freezing point (°C)	-97.8	-40
Specific heat of combustion (kcal/kg)	4800	10,400
(kcal/l)	3800	7300
Vapor pressure 33°C (kg, cm^2)	0.32	0.6-0.84
Ignition temperature (°C)	470	427-510
Solubility in water	infinite	nil
Viscosity, 25°C (cps)	0.5	0.5
Exposure limits in air (parts per million)	200	1800 (isooctane) 60 (benzene)

is therefore more flammable; but the ignition temperatures of both substances are similar, making them essentially substitutable for each other in internal combustion engines. Maximum allowable ambient air concentrations are lower for methanol than for octanes; but in view of the greater volatility of octanes, the handling methods that are acceptable for one are generally acceptable for the other. The principal difference is that methanol is soluble in water, which permits safer and easier flushing of spills and also probably enhances its rate of biological destruction.

From these points of view, methanol has somewhat better environmental features than the other two competitive substances. Conversely, methanol is approximately twice as heavy and twice as bulky as gasoline for a given energy content, a fact that has environmental and economic significance for problems of fuel transportation.

COAL OVER THE NEXT TWENTY YEARS

The transition to the strategic role of coal outlined above will not happen overnight, and coal must therefore survive in the energy market over the next twenty years. The prices of available natural gas and conventional oil are, and for many years will be, relatively attractive. Therefore, over the next twenty years, two criteria have to be applied to coal use—the use of coal must be economically justifiable; its use must permit an orderly buildup of the coal industry, and in particular of the coal supply industry, to the levels required when coal becomes a major source of liquid fuels. Or in other words, How do we get from here to there?

First, an immediate but limited role for coal as a primary fuel is desirable. Second, priority should be given to exploitation processes, such as coal liquefaction, that are compatible with the long-term production of "liquid coal."

Currently, there are wide differences in the situation of coal industries in different countries. In a few countries, coal production has expanded considerably in the past and is likely to do so in the future; Poland and the Soviet Union are examples. Other countries, among them the United States, have experienced stagnation in coal consumption; and others—for example, the United Kingdom or more so the FRG—have recently seen a decline in coal consumption.

In order to identify the best means for using coal prudently, we examined the short-term possibilities for coal in the United Kingdom and the FRG. For various reasons, the coal industries in these countries must adapt to strong competitive pressures from other primary energy sources. We therefore concluded that strategies to improve the position of coal in these countries would most probably work elsewhere.

The in-depth studies were supported by and performed in collaboration with institutions of the coal industries in the United Kingdom and the FRG and reported on by a joint task force (Sassin, Hoffmann, and Sadnicki 1977). A rather consistent, yet somewhat unexpected, potential for an extension of the coal markets for the two countries was identified. Starting from a projection of the demand for final energy forms, the task force concentrated on those coal conversion technologies that would soon be technologically mature, that would offer a competitive secondary energy form in those submarkets where present sources could be substituted, and that would focus on sufficiently broad existing submarkets.

According to the task force, the internal trends of the energy market would not allow for a resubstitution at the final consumer end of liquid or gaseous hydrocarbons by the solid fuel, coal. Consequently, the prudent use of coal in the coming decades was not considered a simple return to the patterns of the primary energy markets of the past. Instead, "new coal," comprising both mining and conversion into competitive secondary energy forms, was defined as a new energy source that must penetrate the future energy market. It would compete against not only crude oil, nuclear energy, and other energy sources but even against traditional ways of using coal, which would gradually be phased out.

The main channels that would be opened for coal within the next twenty years by promising new conversion technologies are shown in Figure 3-6 for the specific situation of the FRG. In the figure we specify the various applications in which four coal-derived secondary energy forms—electricity, district heat, industrial steam, and pipeline gas—are expected to compete successfully. It also gives the assumed time periods in which penetration could begin, as well as the number of years needed for new coal to dominate the various applications. In determining these penetration times, we considered the estimates of the economic competitiveness of each of the technologies as well as the difficulties of competing with other supply channels and of adapting consumers to a somewhat different supply mode.

Figure 3-7 gives the estimated maximum supply of coal in the FRG up to the year 2000, assuming the projected implementation of new conversion technologies. It can be seen that the traditional technologies for the uses of

Figure 3-6. New coal technologies, their penetration characteristics, and applications in the FRG as projected for the year 2000.

New coal technologies coming in Instead of:	Penetration of New Technologies			Characteristics of New Technologies	Final Energy Forms in the year 2000 to be served by New Technologies
	Year	Level of coal use (1% of market)	Time to penetrate from 1% to 50% of market (yr)		
Nuclear?	1985	850 MW(e)	23	Power plant 4,000 h/yr pressurized coal gasification, fluid bed	Electricity
Oil (heavy and light) Natural gas	1990	1 GW(e)	50	Power plant 2,500 h/yr Pressurized fluid bed	Liquid Fuels
Heavy fuel oil	1985	200 MW(e)	18	Industrial boilers fluid bed 7,080 h/yr	
Natural gas	1990	4 GW(e)	18	Synthetic natural gas plant,.Lurgi 7,500 h/yr	Gas Solid District Heat

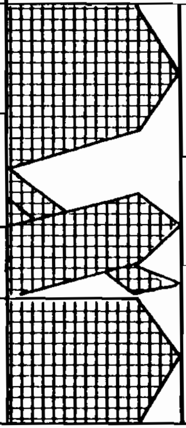
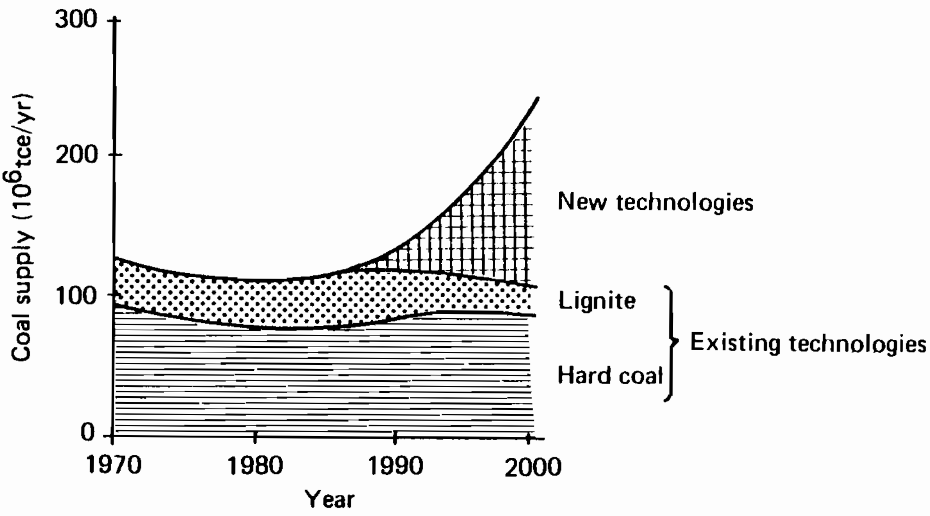


Figure 3-7. Uses of coal by existing and new technologies, FRG, 1970-2000.



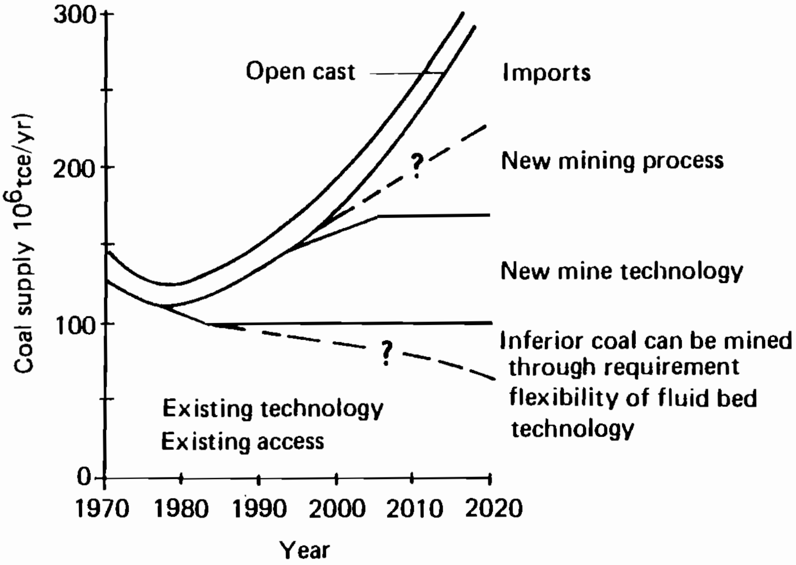
coal (e.g., for steel production and as a feed for existing coal power stations) are likely to maintain their position, at least up to the year 2000. While Figure 3-7 does not quantify the most likely development of the coal market in the FRG, it does show a conceivable upper limit for development, provided that events do not override the identified potential.

A similar pattern, but with a time shift of ten to fifteen years, has evolved for the United Kingdom. The likely delay for the larger scale use of coal in this instance reflects the discovery and exploitation of the oil and gas fields in the British sector of the North Sea. Figure 3-8 therefore extends to the year 2020. The results of the calculations are illustrated in the diagram in a disaggregated form with respect to projected supply possibilities. A conceivable increase in coal supply is shown for the United Kingdom.

For both studies, it was assumed that coal would begin to be favored—that is, coal use would be expanded—under one of two conditions: either the coal-derived secondary energy carrier would command a lower customer price than its competitors; or the incremental cost of coal would not require any price increase over existing prices at the consumer level. The second, less restrictive, condition was usually found to apply: maximum coal potential is unlikely to be explored under competitive market conditions.

As the data for the FRG indicate, the vigorous stimulation of coal utilization would nevertheless require ten years before new uses of coal would take on significance. Both case studies have shown that the introduction of new coal conversion technologies would not have an immediate effect on energy consumption rates. In Chapter 8 we give other, more conventional examples of market substitution, which prove that consumer's decisions of the past predetermine the market behavior for quite some time.

Figure 3-8. Coal supply allocation, United Kingdom, 1970-2020.



Furthermore, the rapid increase in the consumption rates of coal, once "new coal" has been introduced, would necessitate major investments in indigenous coal production at a time when the coal industries are likely to be suffering from stagnating sales. The alternative–to resort to massive immediate near-term coal imports (Figure 3-8)–is not consistent with the underlying assumption of a vigorous national coal policy from which the analyses started.

CONCLUSIONS

What general conclusions can be drawn from the analysis of these various aspects of a potential coal revival? Clearly, there must be a near-term revitalization of the world coal industries.[c] Otherwise, coal would not be able to fulfill its dual strategic role as a near-term primary energy source and as a long-term source of liquid fuels that may be needed over the next century or more. However, these two goals are not automatically harmonious. Given what we see as the historic and "natural" evolution of energy industries, along with all their supporting infrastructures, these dual roles are somewhat

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[c] In our analysis we have not dealt explicitly with the complex, albeit important, subject of the global coal trade in the revival of coal. However, we note with interest the ongoing World Coal Study (WOCA) organized by Carroll Wilson of the Massachusetts Institute of Technology in the United States.

in conflict and could give rise to ambiguous signals for those who would work to activate the current coal industry from its state of relative stagnation. A coal revival therefore needs to be carefully and consciously managed in ways that would counteract the natural decline tendencies and that would allow the industry to fulfill what might be regarded as, historically, the extremely vital transition to the long-term energy future.

In effect, we must revive an industry—actually create a new industry—at the same time that we do not expect it to exceed certain limits. To do that will require all the systems-analytic skills at our disposal, as well as keeping a continual eye on the growth and evolution of the alternative energy technologies and industries that must be nursed into being to support the lives of generations of people living long into the future.

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4 THE NUCLEAR OPTION

INTRODUCTION

Nuclear energy[a] could supply very large amounts of energy for periods of time far beyond the experience of individuals and society. Even within the period of this study—up to the year 2030—nuclear could supply large amounts of energy without requiring novel technology. We examined nuclear's potential contribution by constructing a reference case in which nuclear power is called upon to supply of the order of 17 TWyr/yr of primary energy by 2030. This would be a major, but not an overwhelming, contribution at that time to meeting the demands of a high energy demand world. However, this is more than supply allocations based on purely economic considerations.

Nuclear power is peculiar: most nonscientists see it as mysterious and complicated, but much more is known about it, by and large, than about other sources of energy. The scientific basis of nuclear fission is well understood: nuclear engineering is established by practical experience, and there is large expertise in many countries. Even the impacts of nuclear energy (e.g.,

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[a] Nuclear energy refers to both nuclear fission and nuclear fusion. Most of the attention throughout this chapter is on nuclear *fission*; nuclear *fusion* is considered, with its particular capabilities and characteristics, only in relation to the functions of fusion reactors as sources of nuclear fuel for fission reactors.

the biological effects of ionizing radiation) are better known than those of most of its competitive sources of energy.

As to its application, nuclear power seems to have been pressed into the format of merely replacing or complementing an older and long-existing technology—steam generation in electrical power stations. Today's nuclear reactors are designed to raise steam at temperatures of 250 to 300°C, sized and sited to conform to the requirements of electrical power grids, designed for maintenance at schedules convenient for electrical demand schedules, and required to be compatible chemically with the steam to be raised.

Therefore, the question is whether the real potential of nuclear power has been really understood. One gram of fissionable material yields roughly 3×10^6 times more energy than one gram of carbon. Nuclear power is not just a replacement for the old coal-fired station, but practically an infinite energy source. What happens when a source becomes infinite?

First, because of the very high concentration of energy in fissile material, nuclear fuel can be transported anywhere on the globe, with an infinitesimal cost in money or energy. Therefore, nuclear power might be better understood when it is put in the context where it belongs—the large-scale, long-range, and global supply of energy. The attribute "global" is not an *epitheton ornans* and thereby incidental; it is essential. It could be the key to the proper understanding of nuclear power: its potential can be fully appreciated only when nuclear energy is viewed in global dimensions as a contributor to the balance of energy supply and demand in the world's regions.

The global dimension is a spatial category. There is also the dimension of time. Nuclear power is peculiar in that respect as well. It can be argued both that nuclear power is too late and that it is too early. It might be considered too late because it contributed little to overcoming the oil crisis of the 1970s. From our point of view, this testifies to the parochial development of nuclear power; for, being tied to the electrical sector, which has only 10 percent of all secondary energy, it could do proportionally only that fraction of the job. Nuclear power might also be considered too early, even with regard to the theme of this book; the impact of the transition—from today's infrastructure using principally cheap oil and gas to an infrastructure using coal, nuclear, and solar power—has not been really felt. Any urgent need for nuclear power would lie only in the decades ahead.

This is the broad background against which the potential of nuclear power should be assessed. By necessity, then, we consider different types of nuclear systems—and different applications—from the ones that are known today.

The global dimensions and the temporal extensions of nuclear power also have their negative sides, which have made the technology controversial. The global dimension was introduced *ab initio* by the military uses of nuclear energy. It is widely recognized that the nuclear stalemate between East and West is the basis for the political order of this planet. Peculiar freedoms for smaller nations, even including possibilities for local wars, have indeed evolved over the last decades. This evolution has taken place under the umbrella of nuclear second strike capability in East and West—the expression of the nuclear stalemate.

Also, the implications of handling large amounts of fission products and plutonium are often, consciously or unconsciously, considered globally. A number of global political treaties can be seen in this context: the Antarctic Treaty prohibits both nuclear explosions and disposal of radioactive waste on that continent; the Limited Test Ban Treaty contains provisions not only for arms control but also for protecting the world environment; the Outer Space Treaty provides that even the moon will be kept free of "harmful contamination." By contrast, the vexing problem of carbon dioxide contamination of the atmosphere (see Chapter 10), which is aggravated by large-scale fossil fuel combustion, has received no political attention whatsoever. The perception of arms control and environmental concerns as global concerns is obvious when one considers the existing arms control and disarmament agreements as a whole. The fact that the hotly debated problem of the nonproliferation of nuclear weapons is considered a problem of peaceful nuclear energy underscores the global nature of nuclear energy even further; the explicitly intended Nonproliferation Treaty (NPT) and the International Fuel Cycle Evaluation (INFCE) are explicitly global undertakings.

For the temporal dimension of nuclear, one can only point to the long-term duration of the potential impacts on the biosphere from the release of fission products and actinides, especially from plutonium activity. While it can be reasonably argued that this aspect of risk applies a fortiori to toxic inorganic compounds (e.g., heavy metals) that persist forever, nevertheless the nuclear risk has received the most attention. Here, we can merely introduce the nuclear controversy. A checklist of issues would include the following:

Reactor safety. What is a credible accident? Farmer's (1976) probabilistic approach and the so-called Rasmussen report (USNRC 1975), as well as the Lewis committee critique (USNRC 1978), seem to indicate that serious accidents are very unlikely to occur. What low frequency of accidents can be considered acceptable? Starr (1969) has asked: How safe is safe enough? What procedure can be used to answer this question? The use of probabilistic procedures leads to the question: How sure is sure enough? Häfele (1975) has asked whether new categories of risk must be considered in view of the global consequences of modern technology. We may also ask whether basing risk acceptance on public perceptions is morally defensible (Schaefer 1978).

Radiation effects. What population is affected, and how badly, by radiation? What are the consequences? Although exaggerated claims of radiation effects by Gofman and Tamplin (1971) and others have been authoritatively refuted, new claims (e.g., Mancuso, Stewart, and Kneale 1978) continue to draw attention and require refutation (Sanders 1978; Marks, Gilbert and Breitenstein 1978). What standards of radiation are acceptable for the general population: the 170 mrem per year set by the International Commission on Radiation Protection (ICRP); the 25 mrem per year of the U.S. Environment Protection Agency (USEPA); the 5 to 15 mrem per year of the U.S. Nuclear Regulatory Commission (USNRC); or less?

On what basis should consequences be evaluated: by comparison with background, with existing mortality and morbidity rates, or in other ways? Should workers at nuclear facilities be permitted exposure levels above those for the general population? If so, how much?

Nuclear waste disposal. What is the nature of the problem? Do we have the basic information to make probabilistic assessments (Breckhaeft et al. 1978)? Is waste disposal in fact a trivial problem (B.L. Cohen 1977)? How does the long-term view affect the assessment of the problem: should we consider morbidity over human generations, centuries, millennia, or what? Does geological disposal of plutonium aggravate the problem? What are the risks of handling nuclear waste, including those of the components of decommissioned facilities?

Nuclear weapons. Issues thought to have been settled by the safeguards of the International Atomic Energy Agency (IAEA) and the NPT are being discussed anew. Do fuel reprocessing and national ownership of breeder reactors increase incentives to avoid or to violate international agreements? Would agreements on nuclear disarmament resolve this problem or aggravate it? What about terrorism and theft? Is security adequate? Because of modern experience of international terrorism, of the explosion of an Indian nuclear device, and of the North-South confrontation, many observers believe that the nonproliferation problem has not been tackled yet.

Public attitudes. How much of public opposition to nuclear power is the result of the transference of fears or hostilities from other problems—for example, nuclear power as a symbol of nuclear war, nuclear power as a target of opportunity for opponents of centralized technology? Conversely, how much support results from the symbolic transfer of positive attitudes, such as faith in science or in progress?

The ordering of the issues presented above leads from identified, and to that extent tangible, problems to problems that open into the broadest areas of human controversy. Sometimes, it seems as though the nuclear controversy is only the tip of an iceberg—the iceberg being a general and deep-seated cultural dissatisfaction in Western countries. These concerns and developments could well lead to a situation where a country (such as Austria, as of now), or a group of countries, would not explore the potential of nuclear power. The many extensive studies of policy projection have not resolved this question. Meanwhile, the nuclear controversy continues and evolves even further.

Probably the issues cannot be resolved by further head-on studies. If they really are at the tip of an iceberg, it is the iceberg underneath the water that is moving the tip and not the forces acting on the tip.

In that situation, it is essential to examine nuclear power within the broader context of which it is a part. We argued above that to do this one should have a global and long-range perspective. The following questions are therefore pertinent: What is the balance of energy demand and supply over the next fifteen to fifty years in the various world regions, and what role will nuclear power play in that balance? What is the alternative to nuclear power in that context, and what is its price, monetary and otherwise?

Nuclear power should also be looked at from the viewpoint of technical opportunity. It has been argued that nuclear power was developed for the sake of technological innovation as an end in itself rather than for the amelioration of a perceived energy problem. Yet as a practical matter, not much is known about the application of nuclear power beyond its use for generating electricity.

Perhaps the opposition to the further commercial deployment of nuclear electrical-generating capacity indicates that the most important uses of nuclear power have not yet been developed. We hope this is the case. We therefore emphasize later in this chapter those applications and settings for nuclear power that go far beyond existing practice and, indeed, that cannot be factored into our supply analysis for 2030 except in the most general (and therefore necessarily vague) way.

STATUS AND SYSTEMS

The Status of Nuclear Fission Power

Nuclear fission power is not in its infancy. Any new technological development must pass the three thresholds of scientific feasibility, technological feasibility, and commercial feasibility. The workhorse of nuclear fission power, the light water reactor (LWR)—a class of reactors that includes both the pressurized water reactor (PWR) and the boiling water reactor (BWR)—as well as the Canadian CANDU heavy water reactor (HWR), the British advanced gas-cooled reactor (AGR), and the Soviet Voronezh reactor (VR), have all passed these thresholds. Besides these reactors, there are new types under advanced development, such as the liquid metal fast breeder reactor (LMFBR) and the high temperature reactor (HTR). Table 4-1 lists the status of fission reactors worldwide. As of the end of 1978, the total capacity of operating reactors worldwide was roughly 110 GW(e). Through 1993, when the reactors presently under construction or on order would also be in operation, this total capacity is expected to be about 390 GW(e).

Operating reactors need a nuclear fuel cycle to serve them. There is a distinction made between the front end and the back end of the fuel cycle. The front end comprises uranium mining; uranium processing (milling) into yellowcake; conversion of yellowcake into the gas uranium hexafluoride; and in most cases, the enrichment and conversion of this gas into uranium dioxide and fuel fabrication. The status of the front end of the fuel cycle is shown in Table 4-2. The back end of the fuel cycle comprises intermediate fuel element storage, chemical reprocessing, intermediate waste disposal, waste solidification, and final waste disposal.

Later in this chapter we shall examine the availability of uranium. For existing and firmly planned reactors, known resources are adequate. The

Table 4-1. Nuclear power plants worldwide.[a]

Year[b]	Number Installed Plants	Total Installed Capacity per Year (GW(e))	Installed Capacity			
			Average Size MW(e)	Cumulative		Annual Growth Rate (Percent)
				Number	GW(e)	
			132.93	41	5.443	
1966	6	1.719	286.50	47	7.162	31.6
1967	5	1.217	243.40	52	8.379	17.0
1968	7	2.165	309.29	59	10.544	25.8
1969	11	3.384	307.64	70	13.928	32.1
1970	6	3.099	516.50	76	17.027	22.3
1971	10	5.755	575.50	86	22.782	33.8
1972	22	11.412	518.73	108	34.194	50.1
1973	15	8.541	569.40	123	42.735	25.0
1974	20	14.544	727.20	143	57.279	34.0
1975	19	14.464	761.26	162	71.743	25.3
1976	14	9.913	708.07	176	81.656	13.8
1977	19	15.160	797.89	195	96.816	18.6
1978	17	14.647	861.59	212	111.463	15.1
1979	44	35.580	808.64	256	147.043	31.9
1980	40	33.013	825.33	296	180.056	22.5
1981	39	34.938	895.85	335	214.994	19.4
1982	36	32.701	908.36	371	247.695	15.2
1983	32	31.974	999.19	403	279.669	12.9
1984	31	30.823	994.29	434	310.492	11.0
1985	23	24.902	1082.70	457	335.394	8.0
1986	14	15.409	1100.64	471	350.803	4.6
1987	9	9.536	1059.56	480	360.339	2.7
1988	11	11.997	1090.64	491	372.336	3.3
1989	6	7.190	1198.33	497	379.526	1.9
1990	4	4.226	1056.50	501	383.752	1.1
1991	4	4.880	1220.00	505	388.632	1.3
1992	0	0	0	505	388.632	0
1993	2	2.530	1265.00	507	391.162	0.7

[a] Plants either operable, under construction, or on order (30 MW(e) and over) as of 31 December 1978. Additional twelve power plants with a total of 10,487 MW(e) are not included here since the expected date of commercial operation is not known.

[b] Actual or expected date of operation.

Source: Based on data in *Nuclear News* (1979).

other front end steps are also in hand (Table 4-2). Enrichment, once the most heavily guarded of all the "secrets" of nuclear energy, has been developed independently in several countries. Indeed, several technologies have been developed, and more are in the laboratory. Enrichment plants are complex and expensive, so they are not likely to be built on speculation. But as has been demonstrated repeatedly, they can be built. An enrichment plant capable of servicing about forty LWRs can be built in about the same time as it takes to plan and build a LWR in the United States, and its construction cost is four or five times that of a LWR. Thus, we can assume that enrichment capacity will be built as needed.

Table 4-2. Front end of the nuclear fuel cycle.[a]

Uranium Mining and Milling			*Conversion*[b]			
Year[c]	*10^3 tons/yr*[d]		*Year*[c]	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 tons/yr*[d]
1979	47		1979	12	1	48
1985	92		1985	13	1	62
1990	110		1990			

Enrichment

	Nozzle			*Centrifuge*			*Diffusion*			*Aerodynamic*			*Total*		
Year[c]	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 swu/yr*	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 swu/yr*	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 swu/yr*	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 swu/yr*	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 swu/yr*
1979	–	1	0.5	3	7	0.4	6	1	22.8	–	1	0.006	9	10	23.7
1985	–	1	0.5	6	7	2.8	10	1	34.8	–	1	0.006	16	10	43.1
1990	1	1	5.5	6	7	16.5	10	1	38.8	1	1	7	18	10	75.6

Fuel Fabrication

	Uranium Metal			*Uranium Oxide*			*Mixed Oxide, Plutonium Oxide, and Carbide*			*Total*		
Year[c]	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 tons/yr*[d]	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 tons/yr*[d]	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 tons/yr*[d]	*Commercial Plant*	*Pilot or Laboratory Facility*	*10^3 tons/yr*[d]
1979	6	1	4.7	75	3	15.3	9	5	6.6	40	9	20.6
1985	6	1	4.7	76	3	16.1	10	5	6.7	42	9	21.5

[a] Number of facilities and capacities either operable, under construction, or on order as of 31 December 1978; worldwide excluding the centrally planned economies. USSR natural uranium output in 1976 was about 7 X 10^3 tons/yr; also around 3 X 10^6 swu/yr have been made commercially available by the USSR for the period 1975–1990 to countries with market economies. All capacity figures are underestimates because the data are not available for many plants.

[b] Different conversion steps (UO_2, UF_4, UF_6) are added together in terms of uranium content.

[c] Actual or expected date of operation.

[d] All units are in 10^3 tons heavy metal (uranium except in plutonium and carbide fabrication).

Sources: Based on data from OECD-NEA/IAEA (1977); Häusserman et al. (1977); and Fuji (1978).

Fuel fabrication also seems to be in hand. Most reactor manufacturers have either built up their own capabilities for fabricating fuels or made arrangements for cooperation with independent fuel fabricators. These firms are numerous, and the ability to erect new fuel factories has been demonstrated many times. These plants are, after all, essentially special purpose machine shops. In time, and in particular as radioactive recycled fuels are used extensively, there will be a need for new processes, remotely operated and preferably automated. Also envisaged are larger plants, co-located with fuel-reprocessing plants, built ultimately in nuclear fuel cycle centers. This arrangement would simplify procedures, decrease costs, and increase the security of moving fuel materials from one fuel cycle facility to another.

The processes at the back end of the nuclear fuel cycle are the chemical reprocessing of spent reactor fuel and the ultimate disposal of high level radioactive waste from this reprocessing. Neither reprocessing nor waste disposal is an urgent problem at present. However, time is needed to develop the related facilities and institutions that will certainly be needed before the year 2000 and probably by 1990.

Reprocessing is required to recover the valuable fuel materials (isotopes of uranium and of plutonium) that are present in spent reactor fuel and to simplify and make more reliable the disposal of high level waste. Waste disposal is needed as a matter of simple prudence, to avoid accidents that could occur during protracted storage of wastes.

As to reprocessing, the problems are not technical. The situation is similar to that of enrichment. Processes have been developed in many countries, and more are available from the laboratory. Several plants are operating with the solvent extraction process, the preferred commercial method. Yet the number of plants in operation and of those scheduled for operation in the next decade is insufficient for the volume of activity that is to be handled. One can therefore anticipate a growing world stockpile of unreprocessed, spent nuclear fuel.

More reprocessing plants could be built. That is not the problem. Again, as with enrichment, the required time and costs of constructing a reprocessing plant capable of handling the output of fifty to seventy-five LWRs are about the same as those for constructing a LWR. Thus, there are no overriding financial problems. The real question is whether reprocessing plants will be built. At present, the civilian industry can only call on the services of the French plant at La Hague, and scheduled additions to world reprocessing capacity are limited to the expansion of the La Hague plant and to the completion of a large, rebuilt facility at Windscale in the United Kingdom. Other countries have chosen to, or have been persuaded to, defer their plans, pending the resolution of questions raised about reprocessing and problems of safeguarding. The problem appears to be partly political, too; opponents of nuclear power are frank about their use of tactics to delay resolution of these questions with the hope of "choking off nuclear power in its own effluents." So here again, it seems that we must look at the part of the iceberg that is under water.

Nuclear waste disposal is in a state similar to that of reprocessing. There seem to be no technical problems of solidifying wastes into forms that are chemically stable and of emplacing them deep underground, either in mined cavities or in deep boreholes. Furthermore, the chances of significant leakage of the wastes back into the biosphere within the time that it takes for most of their radioactivity to die away are effectively nil, and the concentrations that might be released after that could only be, at worst, low enough to add very small amounts to natural radioactivity. These factors are poorly understood by the public.

As with reprocessing, the political impact of opposition to waste disposal plants has delayed the execution of specific projects in many countries. Indeed, France and Japan are currently the only countries with definite waste management projects. The United States, with about one-half of the nuclear power in the world today, has only one small pilot project, intended principally for wastes from its military programs, and even that is being delayed pending political negotiations.

In sum, the front end of the nuclear fuel cycle seems to be in hand and on schedule. The back end is in hand only in the technical sense and is well behind the schedule necessary for nuclear power to play an increasing role in the decades ahead. The resolution of the questions of the back end and the bringing into being of the necessary reprocessing plants and waste disposal facilities are the unfinished business of today's nuclear power.

Burners, High Converter Reactors, and Breeders

The LWR is a representative of a class of reactors that is designed to use one neutron out of the two to three fission neutrons. The one neutron is needed to maintain the chain reaction in which one fissionable nucleus after another is fissioned, thus permitting a steady power production by burning the fissile atoms. This class of reactors is referred to as burners.[b]

Apart from burner reactors, there is a second class of reactors, called breeders, designed to use more than two neutrons out of the two to three fission neutrons; not surprisingly, this technology is more difficult. Again, one neutron is used to maintain the chain of fissions. The other neutrons are used to convert fertile nuclei such as uranium-238 (^{238}U) and thorium (^{232}Th) into fissile nuclei.[c] A converted fertile nucleus thus replaces the fissile nucleus whose fission led to the liberation of energy. This is a fundamental difference: in effect, the fissile atom is no longer burned. Instead, it is the fertile nucleus that is being burned. The fissile atoms no longer function as fuel, but as catalysts for converting fertile nuclei into fuel and for burning them.

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[b] These reactors produce some new fissile atoms that can be fissioned. However, this *conversion* does not qualitatively alter the fact that burners use, basically, only the fissile atoms that exist in nature.

[c] A *fissile nucleus* is one that can be used to fuel a reactor: uranium-233 (^{233}U), uranium-235 (^{235}U), and plutonium-239 (^{239}Pu) are the most important nuclei.

While the difference between these two classes is pronounced, there are burner reactor designs that approach (but do not achieve) the situation of breeding. These are referred to as either advanced converters or near breeders. Examples are special versions of the HWR and of the HTR. But the LWR can also be made a near breeder (U.S. Congress 1969; Edlund 1975). Approximating the situation of breeding means increasing the share of fertile nuclei that ultimately are fissioned while maintaining the character of the fissile nuclei as fuel to be burned. Currently, with uranium still relatively inexpensive, advanced converters or near breeders are estimated to produce more expensive power than an economically optimized burner, say the LWR or the CANDU type of HWR. However, as the real price of uranium increases, their competitiveness with the burners improves. To some extent, the future of advanced converters and particularly of near breeders depends on how economical the breeders turn out to be. If the near breeders are cheaper to build and operate than breeders, one could envisage a rather long transition period in which near breeders first capture the nuclear market and then asymptotically share it with breeders. If the breeders are cheaper, or as cheap as near breeders, then the market share of near breeders does not ever become large (for a cheap breeder can easily be converted into an even cheaper near breeder). We will discuss the optimum use of reactors and breeders later in our discussion of possible strategies for meeting the requirements of a high nuclear world.

Breeding and Uranium. Natural uranium has a ratio of fertile to fissile atoms of about 140:1, and thorium consists of only fertile nuclei. Therefore, orders of magnitude are won by breeding, in terms of ore consumption. And this acts doubly: by reducing the ore consumption drastically, it is not necessary in the foreseeable future to go to low grade ores. Practically speaking, one could start by using the depleted uranium that would be left over from all the isotope separation performed thus far. This uranium has an energy content of some 600 TWyr, comparable to the economically recoverable global coal reserves (see Table 2-4). Moreover, we shall see that the planned evolution of the nuclear power industry would increase this stockpile of depleted uranium by more than an order of magnitude. Thus, in the near term and even for several millennia, resource constraints are largely eliminated by breeders.

Stated in another way: Nuclear power thereby becomes nuclear power. This is so when the resource of fissile nuclei, which nature has given, is considered a stockpile rather than a mine—that is, when an appropriate part of nature's fissile nuclei has been converted, by appropriate nuclear reactions, to a store of nuclei whose further importance is as catalyst and not as fuel. Such catalytic uses of resources we would like to call "investive" uses as opposed to "consumptive" uses. In our definition, an investive use implies that something is put to profitable use, but retains its value; a consumptive use implies loss of value—using something up. (By arbitrarily adopting these terms, we depart from accepted usage and trust that inferential meanings give us concise expressions with which to make an important distinction.)

The strategic importance of breeding makes it necessary to present this technology in more detail. The most advanced and proven version of the breeders is the liquid metal fast breeder reactor (LMFBR). Table 4–3 lists the major LMFBRs currently in operation or under construction worldwide. Earlier experimental reactors, which are numerous, were deleted from this listing. It is fair to say that for LMFBRs both scientific and technological feasibility have been reached. The target now is commercial feasibility. The safety of fast breeders is not considered a basic problem; as with the LWR and with other reactors, they can be designed to meet predetermined safety criteria. The development and operation of the LMFBRs is a broad and interesting area in itself, with a vast literature (e.g., Häfele et al. 1977).

Besides the fast breeder, there is another class of fission breeders, the thermal breeder (TBR), in which the neutrons are "moderate" to thermal (low) energies. Two versions of the TBR are the molten salt reactor (MSR), for which experimental units have been successfully operated (Robertson 1971), and the light water breeder reactor (LWBR) (U.S. Congress 1969), for which an experimental reactor core is now being irradiated. Both of these reactors breed new fuel at a much slower rate than do the fast breeders, even when one compares the production rate of surplus fuel with the system inventories. It is often considered that if the MSR and the LWBR have interesting prospects, they would be in the role of near breeders; they would be much more economical if not forced literally to produce more fuel than they consume.

Nonfission Breeders. If sufficiently broadly interpreted, there are even more breeders than the two classes of fission breeders mentioned above. There is also the fusion D–T (deuterium-tritium) reactor. The neutrons released in fusion are used to make more of the tritium, which is needed as a

Table 4–3. Power plants of liquid metal fast breeder reactors, worldwide.[a]

Year[b]	*Country*	*Name*	*Construction Stage (Percent)*	*Installed Capacity*	
				Net MW(e)	*Cumulative Net MW(e)*
1973	USSR	BN-350 (Shevchenko)	100	350	350
1973	France[c]	Phenix (Marcoule)	100	233	583
1976	United Kingdom	Dounreay PFR (Highland)	100	250	833
1980	USSR	BN-600 (Sverdlovsk)	–	600	1433
1983	France[c]	Super Phenix (Isère)	15	1200	2633
1984	FRG[c]	SNR-300 (Kalkar)	46	295	2928
1985	Japan	Monju (Tsuruga)	0	300	3228
Indefinite	United States	Clinch River (Oak Ridge)	0	350	3578

[a] Operable, under construction, or planned as of 30 June 1978.

[b] Actual or expected date of operation.

[c] The construction work in France and the FRG has continued, especially for the Super Phenix reactor. Therefore the construction stage, as expressed in this table, is more advanced today.

Source: Based on data in *Nuclear News* (1979).

fusion fuel. They do this by reacting with tritium. With the neutron energies available from fusion reactors, one can get somewhat more than one tritium atom back from lithium reactions. Therefore, the process can be arranged to breed tritium, since some of the neutrons can be used for other purposes, as yet unspecified. Deuterium and tritium are made to fuse in a sophisticated plasma configuration or in a rapidly heated (e.g., by laser or charged particle beam) pellet. Upon fusion of these nuclei, energy is released. Since tritium does not occur in sufficient quantities in nature, it must be converted from lithium, which then acts, together with deuterium, as a fuel. Lithium is thus comparable to natural uranium (or more precisely to ^{238}U), and tritium to the fissile material. Deuterium is not a limiting material.

The similarities go further. The fission breeder and the fusion breeder have an inventory of fissile and fusionable material, respectively, that must be preserved. Both breeders have a radioactive inventory that must be confined, and in both cases the radioactive waste must be disposed of. The two breeders have therefore qualitatively very much in common. Nevertheless, when properly designed, the fusion breeder can have smaller amounts of radioactivity associated with it. This does not happen automatically just because fusion is fusion; only the potential exists currently for such proper fusion designs (Edlund 1975).

More needs to be said here about fusion. So far its development has been aimed at achieving scientific feasibility—that is, producing more energy by fusion than is consumed by the fusion devices. This is now expected fairly soon (CONAES 1978) and obviously is a strong encouragement for the further development of the fusion breeder. But one should also consider industrial and then commercial feasibility, both of which are goals that will not be easily reached. If attainable, the time required is speculative and controversial. We hold the view that commercial feasibility with an electricity market share of, say 10 percent, is at best unlikely before 2030. Thus for the purpose of tis book, we do not take the fusion breeder into account explicitly. Should fusion be well established before 2030, it would then share the functions that are assigned to the fast breeder: their operational features in the broader context of energy strategies are practically the same. We note also that the resource situations of the two breeders are comparable. In both cases, the easily available resources are equivalent to a few hundred thousand terawatt years, so that for all practical purposes, each of the breeders permits an unlimited supply of energy.

In the more distant future, the fusion reactor could possibly go a step further, to allow fusion of deuterium with deuterium. Under these circumstances, the energy resources would be further enhanced by a factor of 1000; energy supply would then be even "more unlimited."

Besides "pure" fission breeders and "pure" fusion breeders, there are two ways that fission and fusion may be combined to achieve net production of fissile material. Both of these consider the use of a fusion reactor as the central part of the system.

The ratio of energy production to neutron production in the D-T fusion reaction (17 MeV/neutron) is much lower than it is in the fisson reaction

(80 MeV/neutron); also, the energy per nuclear reaction is more than an order of magnitude smaller for fusion than for fission. In this sense, fission is "energy rich," and fusion is "neutron rich." One therefore conceives of the possibility of "adding" the energy of fission to that of fusion by using a fusion reaction to drive a subcritical assembly that is used as a fission blanket of a fusion device. At low multiplication, it is easy to construct such a blanket, which both breeds its fissile material and provides the required regeneration of tritium for the fusion reactor.

The resulting combination, often referred to as the hybrid reactor, could conceivably be superior to either a pure fusion system or a pure fission system. It is, however, also conceivable that the hybrid reactor combines the disadvantages of both systems.

Bethe (1979) prefers a (nominally) nonmultiplying thorium blanket for the fusion reactor. The 14 MeV/neutrons from the D-T fusion reaction are energetic enough so that they can be relied on to produce fission and other neutron production reactions in the thorium. Again, these neutrons, over and above those needed to regenerate tritium, can be captured in the thorium to make ^{233}U. Bethe considers the fusion device to be principally a nuclear fuel factory, with only such power conversion as can be attached to the system at minimum cost. Variations of such system concepts have recently been proposed.

Related to these fission-fusion concepts is the concept of making fissile material from neutrons generated in accelerators. The chief advantage that is claimed stems from the absence of any initial fissile material requirements. However, this process has been criticized as doing little more than could be done with a well-designed critical reactor, with the accelerator behaving functionally as an extremely expensive control rod.

In contrast to the fusion concepts, accelerator breeders are technically feasible today. The key items are the accelerators themselves. Proton linear accelerators, feeding about 0.3 microamperes of protons at about 1 GeV energy, could be built with only little extension of present technology. Cost estimates of fissile material produced from them range from optimistic values of \$40 to \$60 per gram of ^{239}Pu (which is higher by a factor of two to three than plutonium for normal nuclear reactors) to upwards of \$140 per gram (Van Atta 1977).

EXPLORING THE POTENTIAL

Up to now, we have been concerned with the systems capabilities of the nuclear option. We have seen that there are no constraints because of technical problems. And by using breeder reactors, resource constraints essentially do not exist.

Yet nuclear power has had a wave of plant orders and commissioning, followed by a trough of low demand. This market performance is generally explained by the uncertainties generated by the nuclear controversy.

A curious feature of this controversy is the discrepancy between the most careful scientific evaluations of the problems and the popular perceptions of these risks. Chapter 11 discusses this situation with regard to risk assessment. Here, we characterize the controversy as appearing to be the visible part of a larger, submerged entity—the tip of an iceberg. The forces that move the iceberg are still unknown.

Having said all this, the fact remains that we see no technological, systems, environmental, or health rationale for not deploying nuclear power. The controversial issues that are not resolvable are mainly those relating nuclear power to nuclear weapons. Indeed, we can speculate that the human association of nuclear power with Hiroshima and Nagasaki represents a large piece of the iceberg. The solution to the nuclear weapons controversy must be political, diplomatic, and institutional. It has not been the purpose of the IIASA Energy Systems Program to analyze such problems. The fact that solutions have been proposed is encouraging.

Nuclear power is different, not only from fossil power, but even from the solar option. Fossil fuels are, sooner or later, depletable; solar and nuclear are not. Unlike solar, nuclear already has an infrastructure that could permit it to be deployed on a massive scale during the next fifty years.

Nuclear power is an option. The world may choose to exercise it strongly, weakly, or not at all. If the world makes one of the two latter choices, the remainder of this chapter is of academic interest. But if the world chooses to exercise nuclear power strongly, we must look at the needs and consequences of doing so. In any case, a decision must consider not merely the risks—which have received attention in numerous publications—but also the potential of nuclear power. The remainder of this chapter explores this potential.

Introduction Rates of Nuclear Power

The status of nuclear power is the starting point for considering feasible rates of the further introduction of nuclear power. Given the complexities of the energy problem in the decades ahead, time becomes a limiting resource. Cohen (1979) noted:

> What is feasible depends on the frame of reference. In a wartime mobilization, many things are possible which cannot be accomplished by business as usual. The purpose of planning, however, is to avoid, as much as possible, the necessity for crash programs that try to make up for the lack of foresight. We may not be able to attain our goals by business as usual, but it should be our ambition to depart from it as little as possible: to make plans which work with and not against normal economic forces and normal economic rhythms.

In determining what is potentially feasible, we assume that political and social constraints are to be resolved. The question of whether such resolution can or will occur is only pertinent to the question of whether this potential will actually be explored. The problem of determining the introduction rates of nuclear power achievable in the near term can be approached in one or two ways—by looking at the history of reactor commercialization or by estimating a priori the time required for new developments to be completed and for a supply industry to be created.

History of the Introduction of LWRs. The development of water-cooled nuclear reactors for commercial use in the United States had its roots in technologies and large-scale installations established previously for military purposes. Plants for the production and purification of uranium, as well as gaseous diffusion plants for uranium enrichment, were available on a scale that would not be required by the civilian power industry for roughly twenty years. To that extent, the early introduction rates of LWRs in the United States did not follow the usual pattern.

The first commercial commitments of the LWR in non-nuclear-weapon states was in 1966, most notably in the FRG and Japan, where enrichment plants did not exist; but the fuel for the reactors had to be imported from nuclear weapon states, at least at first. We therefore use this year as the starting point for our discussion (see Table 4–1). The maximum number of plants worldwide that can be completed by 1990 is nearly impossible to change in the upward direction in most market economy countries, and in many of them little can be added to the total before 1993. To the extent that new projects will balance delayed ones, the period up to about 1990 is already part of the history of the introduction of LWRs.

In the period 1975–1985, there is a wave of installations corresponding to a wave of orders ten years earlier. In the peak period, 1979–1984, over 175 GW(e) are expected to be commissioned. The decrease in the installation rate after 1985 stems from a decrease in orders after 1975. A variety of institutional problems are responsible for this decrease, including political opposition to nuclear power during this period and slower than expected growth of electrical supply industries in those countries with the technological infrastructure to operate many nuclear power plants.

A Priori Estimates of LWR Introduction Rates. The nuclear industry in the member countries of the Organisation for Economic Cooperation and Development (OECD) is operating below its capacity. Almost all manufacturing firms have experienced a higher level of activity than they now have. In these countries there are more than a dozen manufacturing organizations, each of which is capable of supplying at least 8 GW(e) per year, so that the total manufacturing capability is now of the order of 100 GW(e) per year. In the United States, 40 GW(e) per year could be handled. The imbalance between supply capabilities and current rates of ordering is such that unless orders are resumed, some firms are likely either to reduce their operations or to leave the nuclear supply business completely. Thus, in 1973 in the United States, the planned trajectory for LWR installation between 1990 and 2000 was 17 ± 3 GW(e) per year (Atomic Industrial Forum 1973); currently it is even lower, and it may not be realistic to expand this to more than 30

GW(e) per year, even if all the special institutional constraints on nuclear power were removed.[d]

World supply capability would be increased somewhat by including countries outside the OECD. These countries do not have specific social constraints on nuclear power growth; thus they are markets that are more predictable, at least statistically, than are the nuclear markets of the OECD member countries. But for now and for the near future, they are not large markets.

Considering all these factors, we judge that the nuclear industry worldwide, if called upon to do so, could supply of the order of 150 GW(e) per year by the period 1995-2000. This requires a 50 percent expansion of supply capability during the next fifteen years—an expansion that could be accommodated either by increased capability of firms already in the business or by the entry of a few new firms who are already in the nonnuclear electrical supply business. On the other hand, we judge that even a strongly accelerated, worldwide program of nuclear power installation could not increase the global growth rate of nuclear power stations for the period 1995–2000 to more than 150 GW(e) per year. In order to put this number in perspective, bear in mind that the global annual increment of power plants in general (nuclear or fossil) is presently only about 100 GW(e) per year. At a total world industry growth rate of 4 percent per year, such increments would become 240 GW(e) per year by the year 2000—that is, after twenty-two years. A figure of 150 GW(e) per year by the year 2000 for nuclear alone is therefore consistent. Nuclear's contribution would amount to about 62.5 percent of the new capacity. This is a large fraction, meaning that nuclear would represent most of the new capacity installed as thermal plants for baseload operations. Naturally, these numbers represent upper limits. Projections of growth are significantly lower, as shown in Table 4–4.

Estimates of Introduction Rates of Nuclear Power Using the Market Penetration Technique

A possible approach to estimating introduction rates of nuclear power is through price and cost estimates. For the period from now until 2030, costs must be considered uncertain; so, as with other technologies, we refrain from too rigorous econometric approaches. Nevertheless, nuclear power is the cheapest new source of central station electric power in many parts of the world today, and in that sense, it is already a reference technology.

Here we use the approach of market penetration, as will be explained in Chapter 8. The salient features of this approach are its broad, long-range time interval, applied backward or forward in time, and its strength in phenomeno-

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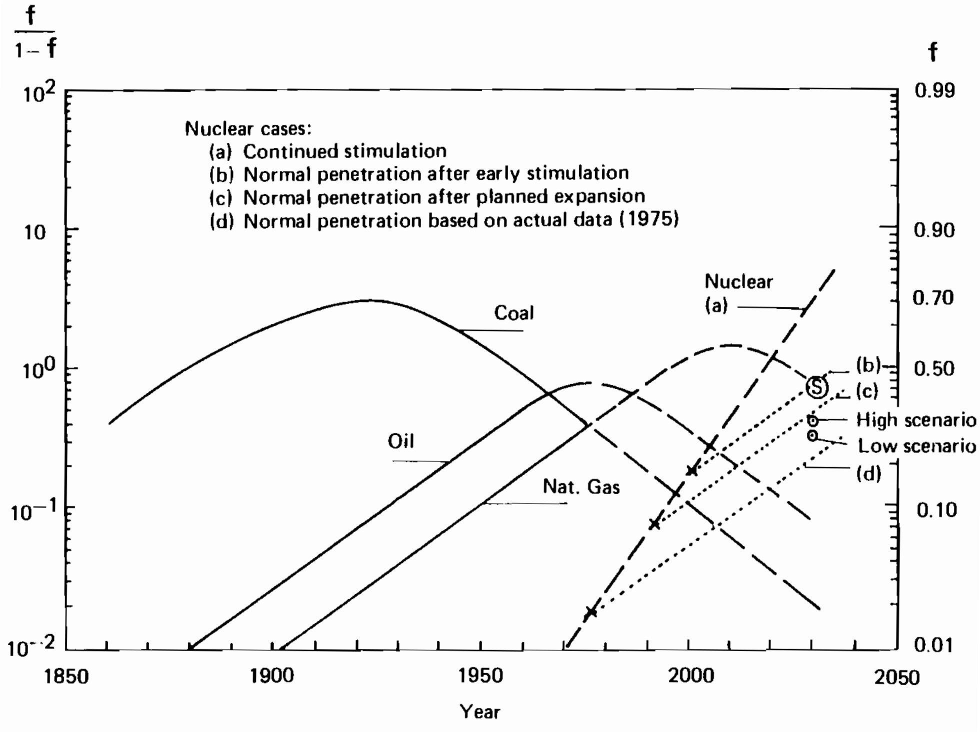
[d] The number is inferred from the "national commitment" scenario of the Supply/Delivery Panel, Committee on Nuclear and Alternative Energy Systems (CONAES), U.S. National Research Council. The information is from Chapter 5 of the panel's report, which at the time of this writing was in draft; thus the number is cited as private information, subject to revision.

logical terms. Of the more than 300 cases investigated at IIASA, all followed a logistic curve of market penetration with high precision. It seems that these logistic curves, continuous over long time periods, describe a system's feature of market penetration, which is more robust than cost-price optimization at any given time might suggest.

We now apply this technique to nuclear power. The objective here is threefold: first, to see whether the growth rates of nuclear power displayed in the previous sections are internally consistent; second, to establish a frame of reference for trajectories in which nuclear power plays a principal role (e.g., explorations of what we have characterized as its "real" potential); and third, to determine whether suggested strategies for supplying nuclear energy are optimistic or conservative.

Figure 4-1 plots the global market penetrations for coal, oil, and natural gas. As distinguished from other displays of these data in this book, here only the fitted curves are shown, rather than the actual data. The "system" properties of the substitution phenomenon are emphasized. In particular, the curves for natural gas and oil show the same penetration rate—about a 4.9 percent increase of $f/(1-f)$ per year, f being the market share of the

Figure 4-1. Global market penetration rate of energy sources and considered penetration rates for nuclear power.



particular technology. Even the curve for coal indicates a similar penetration rate (parallel slope) in the ascending part of the curve.

Three points, marked *x*, for nuclear power are shown on the dashed straight line marked (a) of Figure 4-1. These are successive benchmarks. The point for 1975 is taken from actual data. In that year, nuclear supplied 0.119 TWyr/yr (1.5 percent) of the 8.2 TWyr/yr global commercial primary energy. The point for 1990 is the fraction expected for nuclear in 1990. As already noted, the projection (Table 4-1) of almost 390 GW(e) of global capacity in 1990 would be difficult to change in either an upward or a downward direction. Assuming that the nuclear capacity factor is two-thirds and that the efficiency of conversion of heat to electricity is one-third, this amounts to 0.78 TWyr/yr of thermal energy. For 1990, we estimate a global total energy demand of 12.7 TWyr/yr. Thus, $f/(1-f)$ for nuclear in that year is 0.0654 (6.54 percent). Finally, we have projected an average world buildup rate of 100 GW(e) per year in the 1990-2000 period, as a result of setting a 150 GW(e) per year target for the year 2000. This would lead to 1.4 TW(e) installed by the year 2000 and an average production of thermal energy from nuclear sources at a rate of 2.8 TWyr/yr; based on a high figure of 19.1 TWyr/yr of primary thermal energy, we arrive at $f/(1-f) = 0.172$ (17.2 percent) for nuclear power in the year 2000.

The dashed line drawn through these points (Figure 4-1) is a rather good fit, indicating that the year 2000 "target" does not violate any continuity principles of the system. The early curve of market penetration often has a slope that deviates from the long-term one, up to the point at which a 10 percent market share is achieved, and the year 2000 point in particular shows the influence of stimulation of the nuclear option. If this curve were continued out to the year 2030, it would project a nuclear contribution of 60 to 70 percent of the world's total energy by that year. We consider this barely possible technologically and very unlikely.

Thus, the dotted lines (Figure 4-1) are market penetrations of nuclear power at the system rate already exhibited by oil and natural gas—4.9 percent per year in $f/(1-f)$. These are drawn from the three benchmark points marked *x*. By starting with the year 2000 point, nuclear power would have about 43 percent of the total energy market in 2030; by starting with the year 1990 point, nuclear power would have about 32 percent of the market in 2030. The 1975 benchmark projects to an 18 percent market share for nuclear power in 2030. The points labeled High scenario and Low scenario are the nuclear shares of the respective IIASA scenarios described in Part IV of this book; the point marked *S* is the market share of the here considered upper limit of 17 TWyr/yr that nuclear power would have in a high energy demand world of 36 TWyr/yr in 2030. As we shall describe subsequently, 17 TWyr/yr (corresponding to 10 TW(e) of installed capacity) is the number we selected to explore the potential of nuclear energy.

A projection is not a prediction, and we cannot draw unassailable conclusions from this exercise. Nevertheless, an inspection of Figure 4-1 shows clearly that if the system behaves similarly for nuclear power as it did for natural gas and oil, then 17 TWyr/yr of nuclear energy is not an unreasonably high number to use for exploring the nuclear potential. It is below what the historical market penetration curve would project after a somewhat stimulated acceleration of nuclear installation in 1990–2000. Moreover, the IIASA supply scenario allocations for nuclear power in 2030 (see Figure 4-1) are slightly conservative, if the market penetration of nuclear power beyond 1990 follows historical trends.

Reference Figure for Exploring the Potential of Nuclear Power

We noted that an accelerated program of nuclear power supply at the end of this century could bring this energy source into a position where, given continued normal market penetration, it could contribute 47 percent of all primary energy by the year 2030. We now explicitly define this projection as the basis of a high nuclear strategy for exploring the potential of nuclear power.

Specifically, we have chosen a number—17 TWyr/yr of thermal power—on the basis of combining a market penetration factor, $f/(1-f)$, of two-thirds, and a high primary energy demand estimate of 36 TWyr/yr in 2030. Our logic is simply that the buildup rate required for a high nuclear strategy is compatible with a world that emphasizes energy supply.

What does 17 TWyr/yr imply for the nuclear system? First, it requires a buildup of generating capacity to about 1.6 TW(e) by 2000, followed by a buildup to 10 TW(e) by 2030. This implies a rate of addition in this latter period averaging about 285 GW(e) per year, a number that is less than twice that postulated for the year 2000. This seems feasible.

The discrepancy between 10 TW(e) and 17 TWyr/yr is the distinction between installed electrical capacity and thermal energy generation per year—that is, thermal power. We have assumed that, by 2030, most reactors would show advanced thermal performance, so that the efficiency of conversion of heat to electricity would be 40 percent. High temperature gas-cooled reactors and liquid-metal-cooled fast breeders already approach this efficiency. Finally, we assume a capacity factor of two-thirds for the nuclear system in 2030. That is, mathematically,

$$\text{average thermal power} = \frac{\text{electrical power}}{\text{conversion efficiency}} \times \text{capacity factor or } 17 \doteq \frac{10}{0.4} \times \frac{2}{3}$$

We emphasize that the designation of 10 TW(e) as the nuclear system capacity is only nominal. Not all of this capacity would be used to generate electricity. High temperature and low temperature process heat would be available as well, to be used in industrial processes. Specifically, nuclear energy could then be used for generating forms of secondary energy other than electricity. But by designating 10 TW(e), we indicate the number of plants in the nuclear system by 2030—that is, 3000 to 10,000 units of 1 to 3.3 GW(e) capacity.

A Reference Trajectory for a High Nuclear Demand World and the Related Demand for Uranium

In subsequent sections of this chapter we deal, among other things, with requirements for uranium resources to meet the demands of a high nuclear world. For this, we used a reference trajectory for the schedule of nuclear power installations (Table 4-4). The numbers given for equivalent electrical capacity do not necessarily refer to generation for distribution in an electrical grid. Also, gross additions include replacements under the ad hoc assumption of a thirty-year service life. Growth rates, however, are net; they refer to growth after deductions for retirements. For comparison, recent trajectories published by the IAEA and by the World Energy Conference (1978) are also given.

A comparison of Tables 4-4 and 4-1—the latter having projected some 390 GW(e) of nuclear power by 1990—illustrates why we call this a high nuclear world. It would take a prompt upsurge in nuclear orders and the early completion of the new projects to bring the nuclear capacity in 1990 to the range of 500 to 600 GW(e) illustrated by most of the rows in Table 4-4, and the IAEA "high" of 909 GW(e) seems quite unachievable. Comparisons of the IIASA trajectory with the IAEA "low" and with the WEC figures (Table 4-4) shows that up to the year 2000 our thinking is consistent with other sources that are optimistic about nuclear power. Nevertheless, we emphasize that our trajectory is a pure construct, whose purpose is

Table 4-4. Trajectories for potential nuclear power installations worldwide (in GW(e)).

	Year					
	1980	*1990*	*2000*	*2010*	*2020*	*2030*
IIASA high nuclear reference trajectory[a]	160	580	1630	3640	7030	10,000
Annual addition[b]	24	64	154	305	359	252
Annual growth rate (percent)[c]	15	11	9	8	4	1
Nuclear capacity, INFCE high	188	698	1654			
Nuclear capacity, INFCE low	167	531	1082			
Nuclear capacity, IAEA high	207	909	2227			
Nuclear capacity, IAEA low	162	558	1403			
Nuclear capacity, WEC	152[d]	521[d]	1543		5033	

[a] Equivalent electrical capacity, not necessarily for distribution on electrical grids.
[b] Includes replacement after thirty years of service.
[c] Net growth rate, after deduction of replacements.
[d] Interpolated by IIASA.
Sources: Data for the IAEA figures are from Lane et al. (1977); WEC (1978); and INFCE (1979).

simply to provide a uniform framework for comparing reactor strategies under conditions of high requirements for nuclear power.

With the reference trajectory, it is possible to evaluate the corresponding uranium demand. An upper limit is easily obtained for the so-called "once-through" fuel cycle—that is, the irradiated fuel elements from LWRs go into intermediate or final storage, and no recycling of uranium or plutonium takes place. A figure of orientation for the specific consumption of such a once-through fuel cycle is 131 tons of natural uranium per GW(e) per year. This figure is based on LWR fuel at 3 percent enrichment, irradiated to a burnup of 32,000 MWd/tU (megawatt days, thermal, per ton uranium) in a reactor system of 0.31 efficiency of thermal-to-electrical energy conversion operating at a 0.7 capacity factor. The enrichment process was assumed to have a tails assay of 0.15 percent ^{235}U, corresponding to economic circumstances in which the relative cost of uranium to separative work is much higher than it is today. Table 4-5 gives the cumulated uranium demand of the reference trajectory, involving the once-through fuel cycle.

Beyond the year 2030, the cumulative consumption of uranium for the once-through fuel cycle would continue to grow. The generating capacity of 10 TW(e) would mean a consumption of some 1.3 million tons of natural uranium each year.

Uranium Resources

There is an ongoing debate about existing high grade natural resources inside and outside the United States. This quantity is important, because, as we shall see, it can be used to determine both the worldwide potential of a nuclear fission supply system in the absence of breeder reactors and, as a corollary, the rate at which breeder reactors can or should be built to achieve a truly long-range system. In essence, uranium resources both define and constrain the transition period for the fission energy system to move from burners to breeders.

Uranium resources include deposits that are not economical or are only surmised rather than confirmed, while uranium reserves are considered as known, economically recoverable, deposits. At any given time, some of the resources are considered well known, even though they have not been delineated and assayed as carefully as reserves. These are called reasonably assured resources. In addition, some resources can be surmised to exist as

Table 4-5. Cumulative uranium demand of the reference trajectory.

	Year				
	1990	*2000*	*2010*	*2020*	*2030*
Uranium demand, including initial inventory (10^6 tons)	0.7	2.5	6.7	15.0	27.5

Table 4-6. Estimated global[a] uranium resources (10^6 tons).

Forward Cost[b]	*Reasonably Assured Resources*	*Estimated Additional Resources*	*Sum*
< \$80/kg	1.65	1.51	3.16
	(1.75)	(1.54)	(3.29)
\$80–\$130/kg	0.54	0.59	1.13
	(0.73)	(0.80)	(1.53)
Sum (< \$130/kg)	2.19	2.10	4.29
	(2.48)	(2.34)	(4.82)

[a] Excluding Eastern Europe, the Soviet Union, and China.

[b] Includes production costs only; specifically excludes cost of exploration, land acquisition, and other sunk costs. Prices tend to be 1.5 to 2 times forward cost.

Source: Based on data from OECD-NEA/IAEA (1978). Numbers in parentheses are revised estimates by the International Nuclear Fuel Cycle Evaluation, given in the draft final report of INFCE (1979).

undiscovered deposits in existing mining districts or in unexplored but geologically favorable districts. These are called estimated additional resources. The sum of reasonably assured resources and additional resources form a total of global uranium resources, which must be used for planning individual projects or the immediate future of the nuclear industry. The findings of the joint OECD-NEA/IAEA study (1978) on this matter are summarized in Table 4-6.

For the purposes of this book, Table 4-6 represents a beginning, rather than a conclusion, for a number of reasons. First, we are interested in those resources that may be available over a considerable period of time, rather than those that have been discovered. Second, we are interested in the global availability of these resources. Finally, there is potential interest in uranium whose economic recovery price might be well in excess of \$130/kg of uranium. In sum, then, we extrapolate from Table 4-6 to an estimate of the amount of natural uranium that might be available globally after half a century of careful exploration and at whatever price might be economic.

The only completely honest answer to the question of what these ultimate resources might be is: we do not know. Such hints as we have from present knowledge of the nature of uranium deposits are, at best, qualitative. These hints are as follows:

- Uranium deposits were formed, for the most part, more than one billion (10^9) years ago. This means that the continental distribution of uranium today can to some extent be extrapolated back to its distribution before the latest episode of continental drift. In these terms, some parts of the world that might be good places to look have not been very well explored.
- Most of the U.S. reserves consist of uranium in sandstone deposits. They are characterized by sharp mineralization boundaries, so that the usual

rule of resource economics—that resources increase rapidly as mining proceeds beyond the deposits of highest concentration (and lowest price) —is confounded. Other types of uranium deposits are hydrothermal veins, for which a similar situation might be expected, and pebble conglomerates, for which the normal rules of resource economics should hold. We simply do not know how much uranium will be found in deposits that are currently below commercial grade.

- A vast amount of uranium exists in shales at quite low concentration (30 to 300 parts per million [ppm] uranium). The technological cost of extracting it is very high now, but there is always the possibility that new technologies (for example, in situ leaching) would make it economically accessible. More problematic is whether the environmental costs of extraction would be acceptable.

An earlier OECD-NEA/IAEA report (1977) gives information both on the amount of drilling for uranium and—when taken together with the figures for reasonably assured resources of uranium (specifically, resources producible at a forward cost of less than \$130/kg)—on the finding rates. These data are shown in Table 4-7.

The United States, with the largest uranium reserves, has one of the smaller finding rates (Table 4-7). Perry (1979), among others, draws the reasonable conclusion that this combination of events does not mean that the United States is unusually well endowed, but only that it has been relatively well explored. In the absence of any better assumption, and because

Table 4-7. Uranium findings and finding rates.

	Drill Holes (10^3 m)	*Findings[a] (10^3 tons)*	*Finding Rates (kg/m)*
Australia	≐1100	345	314
Central African Empire	55	16	290
Argentina	200	42	212
India	306	54	178
Finland	25	3.2	128
Philippines	8	0.3	38
Italy	74	2.2	30
Turkey	196	4.1	28
Germany, Federal Republic of	205	5.6	28
Spain	638	16	25
France	5151	123	24
United States	82,500	1918	23
Japan	393	7.7	23
Portugal	435	9.2	21
Mexico	723	7.1	9.8

[a] Findings include all resources producible at a forward cost of less than \$130/kg, plus cumulative production.

Source: Based on data from OECD-NEA/IAEA (1977).

the United States has a large enough area and a large enough diversity of geological provinces, it seems reasonable to take it as a representative sample of the world.

According to the 1977 OECD-NEA/IAEA report, the United States has some 1.7 million tons of uranium resources at a forward cost of less than \$130/kg and has already produced some 0.22 million tons of uranium, adding to a total resource base of some 1.92 million tons. It has a land area of 9.4×10^6 km^2, which translates to some 0.20 tons of available uranium per km^2 of earth surface. Using Perry's method, we then estimated global uranium resoures by taking a figure of 0.18 tons per km^2 and multiplying this by the area of each of the seven IIASA world regions considered in this book[e], to arrive at a global figure of 24.5 million tons. These results are also compared with the values in OECD-NEA/IAEA (1977) (Table 4-8). For regions IV (LA), V (Af/SEA), and VI(ME/NAf), which include most of the developing countries, the IIASA projection shows very considerable supplies of uranium. This is in agreement with the results of a procedure proposed by Alexandrow and Ponomarev-Stepnoy (1974). Using their approach, Belostotsky (1977) estimated global uranium resources at some 17.5 million tons, based on older OECD-NEA/IAEA (1975) data. Updated inputs would lead Belostotsky to estimate world uranium resources at some 21.5 million tons, which is essentially in agreement with IIASA's figures, considering the crudeness of both methods of estimation.

Let us not lose perspective. One can argue that it is impossible to get 24.5 million tons or that it is possible to get more than 24.5 million tons of relatively economical uranium. The point is simply that we might expect to find of the order of 15 to 30 million tons of uranium when most of the world's regions have been explored as completely as the United States.

A comparison of Tables 4-5 and 4-8 leads to the observation that a nuclear capacity of 10 TW(e) in the year 2030 using the LWRs in a once-through fuel cycle would use up the uranium resources that we have postulated to be available globally. This statement refers to globally averaged considerations. In some regions, supplies would be used up much earlier than 2030.

Reactor Strategies and Uranium Consumption

If we continue to rely on today's LWRs, which are designed for a once-through fuel cycle, then by the year 2030 we would use up even Perry's expanded estimate of uranium resources. Something must therefore be done before 2030 if our nuclear reference case is to be more than a boom and bust episode of resource consumption and depletion. Otherwise, the real potential of nuclear energy will not be brought out. Properly used, nuclear energy not only can play a major role in energy supply within the next fifty years but

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[e] See Figure 1-3 for the description of these regions and Appendix 1A for the list of countries in each of the regions.

Table 4-8. Adjusted uranium resource estimates.

IIASA World Regions	*Area (10^6 km²)*	*OECD-NEA/IAEA Estimate (10^6 tons)*[a]	*IIASA Estimate (10^6 tons)*
I (North America)	21.5	2.53	3.87
II (Soviet Union and Eastern Europe)	23.5		4.23
III (Western Europe, Japan, Australia, New Zealand, South Africa, Israel)	15.5	1.26	2.79
IV (Latin America)	20.6	0.08	3.71
V (Africa except Northern Africa and South Africa, South and Southeast Asia)	33.6	0.33	6.05
VI (Middle East and Northern Africa)	9.8	0.08	1.76
VII (China and centrally planned Asian economies)	11.5		2.07
I-VII	136.0	4.29	24.48
Polar regions (including uninhabited islands)	12.5		2.25
World	148.5	4.29 (14.2-26.4)[b]	26.73

[a] Excluding regions II and VII.

[b] Including the speculative resources given in OECD-NEA/IAEA (1977).

could play such a role for a long time thereafter. This durability must be assured by proper reactor strategies.

There are three ways of continuing the nuclear option beyond 2030: (1) to exploit more dilute sources of uranium than are currently used; (2) to rely on improved reactors and fuel cycles; or (3) to head for an asymptotic solution directly, which involves the use of breeder reactors. We discuss each of these approaches in the following sections.

Yellow Coal: Exploiting Dilute Sources of Uranium. Our analysis of global uranium resources was an extrapolation of the quantity of relatively rich uranium ores that might ultimately be found—that is, 2000 ppm (0.2 percent) down to perhaps 500 ppm. These ores are economically recoverable up to a forward cost of $130/kg of uranium considered here. Except for the uranium produced in small quantities as the by-product of gold and phosphate mining, all of the nuclear facilities considered in Table 4-2 work with uranium ores of this ppm level.

There has been very little discovery of intermediate grades of uranium, assaying between 300 to 500 ppm of uranium. However, it is known that many types of shale contain 30 to 300 ppm of uranium, with the average being 70 ppm. The quantity of shale is vast.

The amount of uranium that exists in these extremely low grade ores is enough to satisfy the needs of a very large-scale nuclear industry for a very long time. However, the problems of recovery are at least as forbidding as the quantity is attractive.

The recovery of uranium at a 70 ppm concentration would take a large amount of money. The forward cost would increase from $130/kg of

Table 4-9. Requirements for the operation of a 1 GW(e) power plant.[a]

	Land 30-Year Total (km^2)	*Mining Personnel (man-yr/yr)*[b]	*Material Handling Involved 30-Year Total (10^6 tons)*
LWR (2000 ppm ore)	3	50	45[c]
Coal	10-20	500	321[d]
LWR (70 ppm ore)	33	300	360[d]

[a] Corresponds to an electricity chain producing 6.1 TWh with a thirty-year life span.
[b] 1 man-year = 2000 hours.
[c] Overburden factor: 15 m^3 per ton (averaged).
[d] Overburden factor: 3 m^3 per ton (averaged).

uranium to at least several hundred dollars per kg. But the change from 2000 to 70 ppm has more than just price implications: the requisite mining operation would be very large.

To illustrate this, we refer to the WELMM concept (which will be presented in Chapter 9), and indeed specifically to the situation illustrated in Table 4-9. These WELMM results are for two types of LWR operations: (1) the LWR using 2000 ppm uranium ore, and (2) the LWR operation using 70 ppm ore. A third type of operation, that of coal mining, was also considered. The results of a comparison of these three mining operations are shown in Table 4-9.

Obviously, in terms of land use, manpower, and materials handling, the 70 ppm LWR operation approaches that of coal mining. When envisioning the use of uranium after our assumed 24.5 million tons of high grade uranium ore have been consumed, we must also consider the impacts, which are similar to those of obtaining the same energy from coal. For both the 70 ppm LWR and the coal mining operation, there are societal, environmental, and land use implications. Putting aside the problem of carbon dioxide emissions from combustion (see Chapters 3 and 10), we see that the 70 ppm LWR operation is, in fact, more difficult. Almost all the uranium ore taken out of the ground becomes solid (but not very radioactive) waste, whereas at least half of the rock removed in coal mining is, in fact, coal. Using very dilute uranium therefore turns this operation of nuclear power into that of mining "yellow coal."

For purposes of orientation, we apply the data of Table 4-9 to our reference case of 10 TW(e) of installed nuclear capacity. The resulting data, which are given in Table 4-10, are on a grand scale. The area, 330,000 km^2, is approximately the size of Italy, and three million workers may be 0.1 percent of the total work force worldwide. The approximately 3.6×10^{12} tons of solid waste and/or overburden is a thirty-year total, corresponding to approximately 120×10^9 tons per year. To put this number in perspective, the largest bucket-wheel excavators currently used in open pit mining are capable of handling about 240,000 bank m^3/day. Roughly, 1100 of such dinosaurs, each with an operation weight of 13,000 tons, would have to work with a 70 percent load factor throughout the year—a large operation, but not physically impossible.

We can similarly analyze the situation of getting uranium from the sea. While the resource base of such uranium has been estimated at about 5×10^9 tons, the concentration of uranium in the sea is only about 1.5×10^{-3} g/m^3 (Weast 1974). The annual demand for 10 TW(e) of the once-through fuel cycle LWR would be approximately 1.3 million tons of natural uranium. In order to recover this, it would be necessary to process some 870,000 km^3 of sea water annually. For comparison, the worldwide runoff—that is, the flow of all rivers to the seas—is only about 37,000 km^3. One may conclude by observing that this is a large operation and only conceptually possible.

Earlier, we observed that there is the factor of about 3×10^6 between the energy yields of 1 gram of fissionable material and 1 gram of coal. What a 70 ppm LWR operation does in effect is to reduce this factor to one. Out of the approximately 131 tons of natural uranium that a single, 1 GW(e) LWR uses per year, only about one part in 200 (5×10^{-3}) becomes actually fissionable because of enrichment plant tails losses and incomplete burnup. Thus a 70 ppm LWR operation means a further dilution of about 7×10^{-5}. And indeed,

$$3 \times 10^6 \times 5 \times 10^{-3} \times 7 \times 10^{-5} \cong 1$$

In sum, assuming, consciously or unconsciously, a LWR once-through fuel cycle using 70 ppm grade uranium ore means a return to the well-known scale of operation: it is equivalent to mining coal or, more exactly, to mining "yellow coal." We are faced with the old problems of large-scale mining and the new problems of solid waste, including both residues of rock milling and radioactive wastes.

The "Stretch Out" Approach. As noted, the use of LWRs of current design on a once-through fuel cycle would commit essentially all of the world's high grade natural uranium during the buildup phase of our reference case. This is a wasteful use of uranium compared to what could be accomplished, even without breeders.

Table 4-10. Requirements for maintenance of a 10 TW(e) LWR operation using 70 ppm ores.[a]

	Land 30-Year Total (km^2)	*Mining Personnel (10^6 man-yr/yr)*[b]	*Material Handling Involved 30-Year Total (10^{12} tons)*
LWR (70 ppm ore)	330,000	3	3.6[c]

[a] Corresponds to an electricity chain producing 6.1 TWh with a thirty-year life span.

[b] 1 man-year = 2000 hours.

[c] Overburden factor: 3 m^3 per ton (averaged).

Let us recall that the once-through fuel cycle is just that: no recycling is allowed. Given the reprocessing of spent fuel and the recycling of uranium only, the demand for "virgin" uranium could be reduced by about 20 percent; additionally, the recycling of plutonium reduces this demand another 15 percent. This capacity exists in LWRs of today's design. Also, by using fueling designs that include thorium and its conversion product, ^{233}U, somewhat less natural uranium becomes necessary. By going to enrichment schemes that produce uranium tails more depleted than 0.15 percent ^{235}U, an additional 15 percent of the uranium requirement might be saved. All in all, it is conceptually possible to run a LWR system, with reprocessing, using ^{233}U and more separative work, which would require about half as much natural uranium as does the existing LWR system.

Table 4-5 indicates that up to the year 2000 some 2.5 million tons of natural uranium would be required and between 2000 and 2030, some 25 million tons. If we were to employ all the techniques just mentioned for achieving a more efficient use of natural uranium, then this 25 million tons would be reduced to roughly 12.5 million tons. Adding the amount estimated to be consumed up to the year 2000—about 2.5 million tons—we get a total of roughly 15 million tons of natural uranium that would be consumed by 2030. This is still not far below what might be ultimately available, but it perhaps gives some time.

How much time? We recall two numbers. First, 10 TW(e) installed capacity under reference case conditions would consume some 1.3 million tons of natural uranium per year. Using the efficient mode of LWR operations just described, the amount of natural uranium needed would be about half that—or some 0.65 million tons per year. Second, if we assume that the world now has about 23.5 million tons of high grade natural uranium,[f] by 2030 there would be only about 8 million tons left. In brief, we would have about ten years left before we are forced into mining "yellow coal."

By employing all possible means—uranium recycling, thorium and ^{233}U, lower enrichment tails—and using reactors that are intrinsically more efficient in uranium use than are today's LWRs, it is possible to do even better than that. Heavy water reactors (HWRs) or graphite moderated, gas-cooled reactors can be designed to use only half as much natural uranium as LWRs. These are not extreme cases but systems that are simply extensions of existing reactor designs. Suppose only 7.5 million tons of natural uranium ore were needed between 2000 and 2030, as a result of switching to these reactors. Recalling that there are assumed to be some 23.5 million tons of natural uranium and that some 2.5 million tons are needed up to the year 2000, then by 2030 there might be some 13 million tons left, with perhaps "only" 325,000 tons of natural uranium being used annually. Thus, perhaps thirty-five to forty years of nuclear power could still be fueled.

This is not very long on the scale of human history. But this does give us on the order of one human generation before a permanent commitment to nuclear power might have to be made.

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[f] This figure is based on the estimate of 24.5 million tons of natural uranium from Table 4-8, minus the estimated 1 million tons of natural uranium already extracted.

A Word About Thorium. Since an input of thorium is required for maintaining the fuel cycles described in the stretch out approach, comments on its availability are in order. The OECD-NEA/IAEA (1977) reports 490,000 tons of thorium[g] as reasonably assured resources and some 833,000 tons of thorium as estimated additional resources. These figures parallel the data given in Table 4-6. There is little doubt that much more thorium will be found when it is searched for as intensively as uranium has been. Thorium is three times as abundant as uranium in the lithosphere (Weast 1974), and yet current reserves are more than adequate for the nonnuclear uses that dominate today's demand for thorium. There is no thorium in the sea, but the expected land resources, which for estimating purposes may be taken as approximately equal to those of uranium, are superabundant even for a large and durable nuclear fission economy. Thus, we do not see thorium as imposing any limits on the "stretch out" approach outlined above.

Breeders: The Asymptotic Solution. Advanced converters and near breeders can stretch out the time over which nuclear power can rely on high grade natural uranium. But sometime in the twenty-first century, the supply will run out; if not in 2030, almost certainly by 2070. At that point, a nuclear option would have only two choices: (1) mining "yellow coal" or (2) using breeder reactors.

Let us recall a few points already made. Burners have about a 1 percent efficiency use of the uranium mined. Advanced converters and near breeders stretch uranium supply by a factor of four or five and use at best 5 percent of the uranium mined. Breeders, by relying on a stockpile of fissile atoms as catalysts for burning fertile atoms, use almost all of the energy potential of uranium and can also be designed to use all of the energy potential of thorium that can be made available. In other words, if our reference trajectory were based on the use of 23.5 million tons of natural uranium in today's LWRs, by 2030 there would still be 23.3 million tons of fertile atoms that could be burned in breeders, plus any thorium that might be available. This translates into 60 thousand terawatt years of energy—and this would be fuel already extracted and separated from host rocks.

And if more uranium is needed a few millennia hence, it would be available. The factor of about one hundred in efficiency of resource use between LWRs and breeders brings even the mining of "yellow coal" into manageable proportions. To quantify this, the results of a WELMM analysis for the 70 ppm LWR operation and for the breeder (LMFBR) operation are compared in Table 4-11. The land, mining personnel, and material-handling requirements are all reduced for the LMFBR by two orders of magnitude. We no longer have "yellow coal"; instead, we have mining operations on a familiar scale. The environmental improvements are obvious.

In sum, burner reactors are cheap, but lead to consumptive uses of the stockpile of fissile material that nature has given us. Their use alone leads quickly to one of two situations—to no nuclear power or to mining "yellow

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[g] Natural thorium consists of the isotope ^{232}Th. The symbol ^{232}Th is therefore used interchangeably with natural thorium.

Table 4-11. Requirements for operating a 1 GW(e) plant[a] (6.1 TWh(e) ≐ 1 yr operation at 70 percent capacity factor).

	Land 30-Year Total (km^2)	*Mining Personnel (man-yr/yr)*[b]	*Material Handling Involved 30-Year Total (10^6 tons)*
LWR (70 ppm uranium ore)	33	300	255[c]
LMFBR	0.2	2	1.3[c]

[a] To calculate the requirements for running a 10 TW(e) operation, multiply the listed numbers by 10^4.

[b] 1 man-year = 2000 hours.

[c] Overburden factor: 3 m^3 per ton (averaged).

coal." Near breeder reactors ameliorate the fuel supply problem without eliminating it. They are somewhat more expensive than burners and could buy time, if it is needed, for technological development, resource exploration, and perfecting the institutions that might be required to safeguard the nuclear fuel against being diverted to weapons use.

Building Up a Breeder System

Breeder reactors are essential if nuclear power is to achieve its "real" potential. They could possibly be expensive, even compared to near breeders. But the proper perspective in which to view this expense is to realize the savings that breeders bring in resource costs—that is, the cost could be reasonable and justifiable. We now examine three possible strategies for getting from the present situation (burners and only a few experimental or prototype breeders) to the situation such that by 2030 there could be 10 TW(e) installed capacity and no further demands on uranium resources because of enough breeder reactors. These are the classical reactor strategy, the converter breeder strategy, and the multipurpose strategy.

The Classical Reactor Strategy. Because LWRs dominate the nuclear installations of today, the standard or what we call the "classical" reactor strategy has been to consider combinations of LWRs and breeder reactors. The idea was to make use of fissile plutonium,[h] which is produced in LWRs, for the installation of breeders, thus having a gradual buildup of breeders that would eventually replace the original burners. For instance, 1 GW(e) LWR of today's design produces between 150 and 200 kg of fissile plu-

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[h] Not all the isotopes of uranium and plutonium can be fissioned easily. Those that can are called fissile: for plutonium, the fissile isotopes are ^{239}Pu and ^{241}Pu; for uranium, they are ^{233}U and ^{235}U. When we refer to either fissile plutonium or fissile uranium, we mean the total content of these fissile nuclei.

tonium per year of operation at a load factor of 0.7. This plutonium provides the first core—the inventory—of breeders.

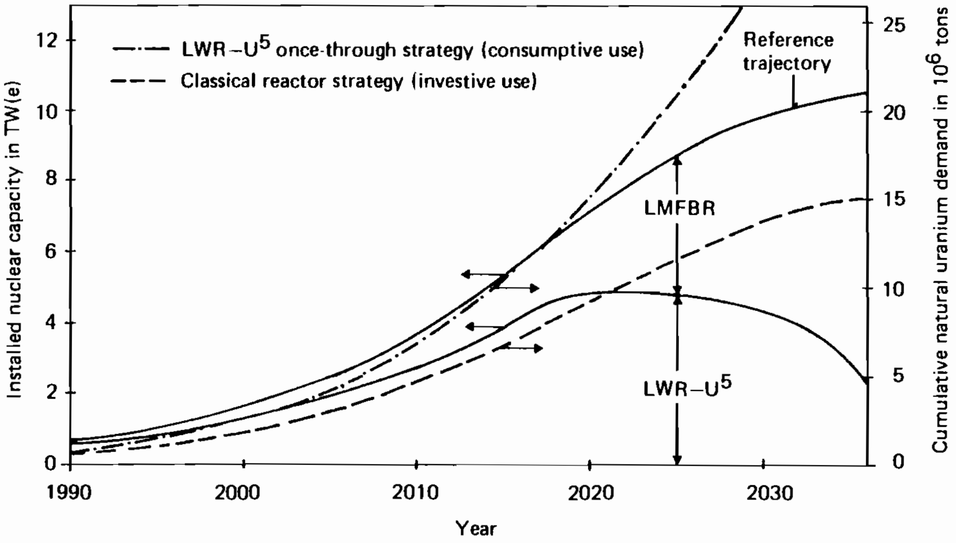
We use the LMFBR as a representative of breeders in general, because it is the most well known and the most advanced of the breeders. But the arguments below apply qualitatively to other breeders.

Roughly 5 tons of fissile plutonium are required as reactor and fuel cycle inventory per 1 GW(e) of LMFBR capacity. It is easy to determine the dynamics of such combinations. Using typical values for the breeding properties of LMFBRs, Nakicenovic and Perry (1979) computed the distribution of power between today's LWRs and LMFBRs and the cumulative natural uranium demand of the classical reactor strategy. The results are presented in Figure 4-2. The LMFBR builds up to an installed capacity of 5.7 TW(e) by the year 2030; it arrives at the 10 TW(e) installed capacity by the year 2040. Thus, by the year 2030 there is still 4.3 TW(e) of installed capacity supplied by LWRs, but this decreases rapidly.

For the classical reactor strategy, the cumulative natural uranium demand by the year 2030 is about 13.6 million tons. The asymptotic cumulative natural uranium demand—some 15 million tons—is reached around 2040, at which time virtually all the reactors would be fast breeders. The requirements for natural uranium were derived assuming uranium recycling. The very low, steady consumptive demand of the fast breeder reactor (FBR) is insignificant: the vast amounts of depleted uranium coming from the enrichment of the natural uranium used in LWRs are used up first.

In sum, the classical reactor strategy leads to a one-time consumption of natural uranium of the order of 15 million tons. This is comfortably below

Figure 4-2. A classical reactor strategy.



the approximately 23.5 million tons of high grade natural uranium resources envisaged (Table 4-8); in other words, the 23.5 million tons of natural uranium considered here are easily consistent with the uranium requirement of the classical reactor strategy. However, the 4.3 million tons of natural uranium (Table 4-6), which for planning purposes are reserves, are too small a quantity to be consistent with this strategy. Thus, unless the expectations that led to Table 4-8 are fulfilled, the classical reactor strategy is just not good enough.

Eliminating the Burners. The advantage of the LWR in today's nuclear market is its low capital cost. However, the LWR is a relatively inefficient converter of fissile uranium to fissile plutonium—the most efficient converter being a breeder. And in fact, if the goal were to minimize natural uranium consumption, only the LMFBR would be installed from the beginning (Spinrad 1979c). Then, the fuel used initially would be enriched uranium (of the order of 20 percent enrichment); gradually the LMFBR would shift to the use of plutonium fuel that is self-generated. The Soviet Union seems to be envisaging, at least to some extent, the use of breeders in this way.

We can put an upper bound to the resource demands of this approach. This upper bound is the result of assuming that all breeders are fueled initially with enriched uranium. This approach does not take advantage of the ability to fuel later breeders with the surplus fissile plutonium from earlier breeders. How much uranium is involved in this upper bound?

We assume that 10 TW(e) are required. If this amount were plutonium fueled, each GW(e) reactor would require about 5 tons of fissile plutonium for its critical core and associated fuel cycle inventory. Thus, with 50,000 tons of fissile plutonium, one could endow a 10 TW(e) industry that would need no further inputs of fissile material.

Although ^{235}U is not as efficient a fuel as fissile plutonium, in a breeder it is not a bad fuel. About 1.2 atoms of ^{235}U are needed to replace 1 atom of fissile plutonium. This replacement need only be done initially: the plutonium formed from the initial enriched uranium would be recycled and would therefore be enough to keep the reactor, first, in operation and, later, in operation as a plutonium breeder. Thus 60,000 tons of ^{235}U, in the form of 20 percent enriched uranium, is the approximate endowment for 10 TW(e) of breeders. If this amount of ^{235}U is obtained in an enrichment plant putting out tails at 0.15 percent ^{235}U assay, then the natural uranium requirement would be 10.5 million tons.

We made an approximate calculation of the effects of introducing 10 TW(e) of breeders by building 333 GW(e) of breeders each year for thirty years, of recycling all the fissile plutonium and ^{235}U, and of introducing as much virgin ^{235}U as is needed to keep the system operating: the requirement for natural uranium is about 8 million tons. Further, the breeder system would become independent of natural uranium requirements before 2030. Even smaller quantities of natural uranium, 5 to 6 million tons, would be needed if the demand schedule were relaxed by five years. To this amount must be added the natural uranium consumption of burner reactors during the buildup period, which could be 2 to 5 million tons, depending on whether advanced converters or today's LWRs are used.

Up to now, we have considered strategies whose only constraints on the introduction of breeders were those of providing the fissile fuel to get the breeders going. But breeders cannot be provided overnight. As with any new type of technology, one must examine the constraints of market penetration—that is, we must study the dynamics of penetration of breeder reactors into the market for nuclear power.

Economics and Market Penetration. Reference to Figure 4-2 shows that the classical reactor strategy is principally a LWR strategy until about 2015, after which LMFBRs begin to dominate new construction. Resource-efficient methods of LMFBR buildup can save a great deal of natural uranium as compared to that needed in the classical strategy, but the early substitution of LMFBRs for LWRs is necessary if the breeders are to have maximum impact. It therefore becomes important to ask how quickly LMFBRs might be able to penetrate the nuclear market.

Cohen (1979) analyzed this question using the method of Peterka (1977), which postulates that, besides considering the actual cost differential of power from different sources, high capital requirements must also be considered, since they, too, inhibit market penetration. Their results, exhibited in Table 4-12, indicate that LMFBR penetration would be very weak unless, simultaneously, LMFBRs achieved capital cost parity with LWRs and the cost of yellowcake became very high. (Yellowcake at $100 (1978)/lb is the cost equivalent of $260/kg of contained metal.)

Peterka's method was analyzed by Spinrad (1980a), who showed that the inhibiting effect of high capital cost in Peterka's model results from the assumption that utility system expansion must be self-financed. Removing this assumption, Spinrad's model remains mathematically similar to Peterka's, but depends more strongly on comparative power cost. But even

Table 4-12. Economic penetration of LMFBRs, by the Peterka model (1978 $).

Capital Cost of LWR *Capital Cost of LMFBR* *($/kW)*	*Cost of Yellowcake* $220/*kg* (*GW(e)*)	 $441/*kg* (*GW(e)*)	 $661/*kg* (*GW(e)*)	 $882/*kg* (*GW(e)*)
700/700	410	1490	4210	7500
700/850	100	330	1000	2500
1000/1000	280	710	1720	3600
1000/1200	75	180	400	940
1000/1500			80	160

Assumptions: Total nuclear installation follows the reference trajectory. Penetration period is 1995–2030. Separative work cost is $100/kg-U. Capacity of LWRs in 1995 is 970 GW(e). Capacity of LMFBRs in 1995 is 10 GW(e).

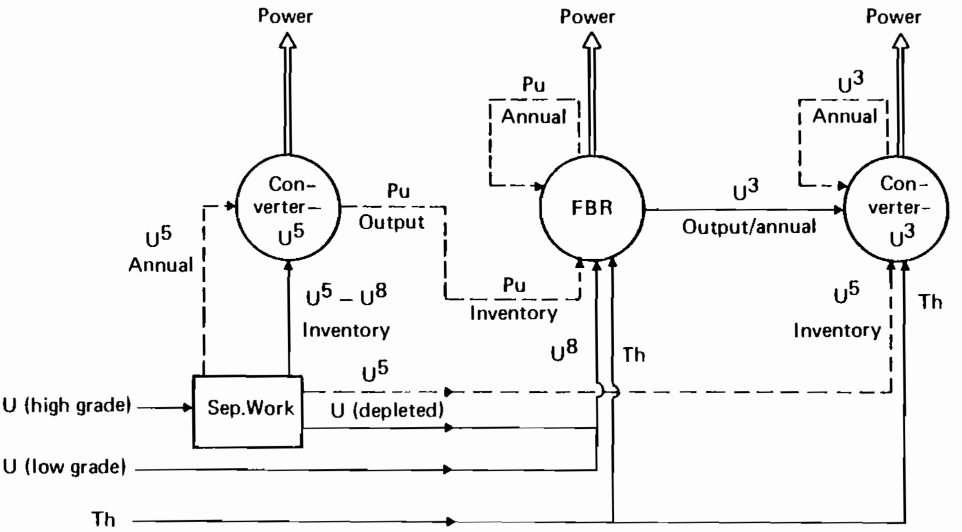
Note: For details on the Peterka model, see Peterka (1977).

with this change, and with inflation-free costing (Spinrad 1980b), market penetration of LMFBRs begins to occur rapidly only when the price differential of power strongly favors LMFBRs. This situation occurs only when prices of natural uranium go beyond \$200/kg of uranium. Such a situation is only likely to be realized well after the year 2000.

A Converter-Breeder Strategy. We are confronted with two observations. First, the rate at which LMFBRs can be introduced would probably be slower than that envisaged for FBRs in the classical reactor strategy. Second, it seems to be prudent and responsible to envisage eventually only investive uses of natural uranium—that is, to count on the use of only a finite amount of high grade natural uranium on the order of 20 million tons. Ideally, we would like to use less than this amount. This makes the eventual installation of breeders a prerequisite for large-scale uses of nuclear power. We consider now a strategy for meeting the 10 TW(e) installed nuclear capacity by the year 2030 by means of converters and breeders. This is illustrated in Figure 4-3 and explained below.

The slower rate of introduction of breeders can be compensated by the enhancement of the neutron balance of burners, which means an enhancement of their conversion ratio. They must become more nearly near breeders. One possible way of achieving this is to use ^{233}U in advanced converter reactors (as well as in advanced LWRs); it is then possible to bring the conversion ratio up to 0.9, whereas present LWRs based on the uranium-plutonium cycle have values close to 0.55. It is also necessary to consider recycling uranium (including ^{233}U and ^{235}U in spent fuel) in advanced converter reac-

Figure 4-3. A converter-breeder system.



tors. This means spent fuel reprocessing, which is required for breeders as well as for the efficient use of converters. Because the back end of the nuclear fuel cycle is already delayed relative to the front end, spent fuel reprocessing is even more important for the future than for the present.

In order to present a consistent picture of resource efficiency we contemplate a change in the tails assay of uranium enrichment plants. Instead of 0.15 percent ^{235}U tails assay assumed previously, we now consider 0.1 percent ^{235}U. This has its price: the enrichment capacity required thereby becomes larger by a factor of about 1.2.

In the converter-breeder system envisaged here (Figure 4-3), the radial blanket of LMFBRs is the source of ^{233}U. Schikorr (1979) has shown that the core characteristics of a LMFBR remain essentially untouched irrespective of whether the radial blanket is filled with ^{238}U or with ^{232}Th. Schikorr's work supports earlier proposals of a similar nature (e.g., Bragli and Schultz 1974; Lang 1968; Wenzel 1971). We assume slightly improved breeding ratios by going to values of 1.3 through proper design measures in breeders, such as increased fuel volume shares in the core. The 240 kg of ^{233}U produced per GW(e) and per year of LMFBR operation, at an available load factor of 0.7, are then put into converter reactors that operated previously on an uranium basis. The plutonium from these reactors is not recycled in them, but is fed to the LMFBRs.

The schedule for the installation of LMFBRs was determined exogenously in such a way that around the year 2030 the plutonium balance is closed: all converters then operate on a ^{233}U basis. A small LMFBR growth in capacity of the order of, say, 1 percent per year is still possible by devoting a small share of its breeding capabilities of its own growth after 2030 (Nakicenovic and Perry 1979). The asymptotic requirement of 1 percent growth per year fixes the asymptotic ratio of converters to breeders. Data explaining the schedule of LMFBR introduction are given in Table 4-13. The yearly additions to LMFBR capacity reach a maximum around 2020. After that, the fissile plutonium for new breeders, which comes from the ^{235}U converters, begins to decrease. Of course, one could flatten out the curve by using more highly enriched (20 percent) uranium to supply LMFBRs, rather than investing the same amount of ^{235}U in new converters, but this does not change the results significantly.

Considering the target ratio of converters and breeders and requiring that total capacity follow the reference trajectory, we arrive at Figure 4-4. Compared with the classical reactor strategy, the converter-breeder strategy uses almost the same amount or uranium, but does so at a more deliberate rate of market penetration for breeders. The converter-breeder strategy is only about 60 percent breeders by 2030, whereas the classical strategy required about 80 percent of all reactors to be breeders at that time. It, too, is just not good enough.

A Multipurpose Strategy. The use of improved converters, particularly those employing the ^{233}U–^{232}Th cycle, permits attainment of an asymptotic condition in which no important uranium resources are needed and yet only

Table 4-13. LMFBR introduction schedule of the converter-breeder strategy (GW(e)).

	Year				
	2000	*2010*	*2020*	*2030*	*2035*
LMFBR capacity[a]	114	480	1470	3678	4288
LMFBR annual additions[b]	18	61	153	133	76
Annual growth rate (percent)[c]	16	13	10	3	1

[a] Equivalent electrical capacity, not necessarily for distribution on electrical grids.

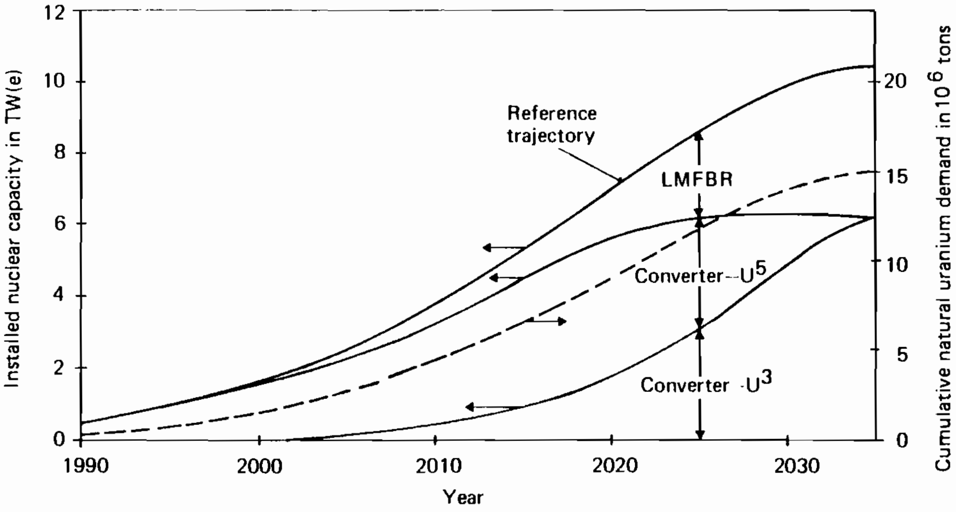
[b] Includes replacement after thirty years of service.

[c] Net growth rate after deduction of retirements.

a fraction of the reactors are breeders. As we go from improved converters to advanced converters, the fraction of required breeders drops further. We are therefore led to explore a multipurpose strategy in which advanced converters are deployed as rapidly as possible. The type we use for illustration is the high temperature gas-cooled reactor (HTGR), in view of the potential of this system for applications other than electricity.

But some applications of nuclear power—research reactors are a current example—might be better performed using reactors that are "pure" burners, with no conversion at all. There are doubtless applications for low and medium temperature steam for which LWRs are optimal. Thus, we are led to consider an asymptotic system made up of breeders, LWRs, HTGRs, and pure burners. Assuming good breeding (i.e., a breeding ratio of 1.25) and good conversion in the HTGRs (i.e., 0.9), we set up a trajectory (Spinrad 1979c)

Figure 4-4. A converter-breeder strategy.



that emplaces, by 2030, 10 TW(e) of nuclear power in the form of 5000 GW(e) of HTGRs; 3500 GW(e) of FBRs; 1000 GW(e) of LWRs; and 500 GW(e) (equivalent) of special purpose burners.

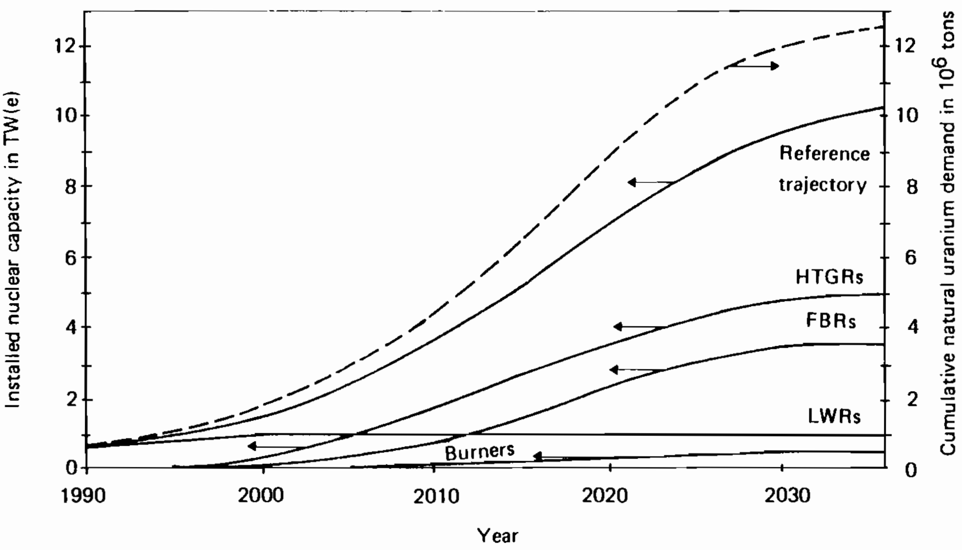
The trajectories constructed for the multipurpose strategy shown in Figure 4-5 add up to our reference trajectory (see Table 4-4). The critical problem would be the buildup of the HTGR system as a replacement for LWR additions after LWRs have reached the 1000 GW(e) level.

The system is fueled in the following way: LWRs and the special purpose burners are fueled from enriched natural uranium until a surplus of ^{235}U or ^{233}U develops in the other reactors. In the study summarized here, this occurs in the year 2021. LWR and breeder fuels are recycled for their fissile uranium content. Any plutonium that is produced is used in the FBRs. Also, FBRs are fueled from self-generated plutonium. Any additional FBR capacity beyond what can be fueled by available plutonium is made up by enriched uranium. By 2021, there is enough plutonium so that ^{235}U remaining in FBRs can begin to be removed from them; this ^{235}U is then redirected to LWRs and burners. By 2028, the input of fissile plutonium from LWRs and of self-generated FBR plutonium makes it possible to produce net ^{233}U in FBR blankets.

HTGRs are fueled with enriched ^{235}U and thorium. All fissile uranium is recycled. By 2030, no further input of ^{235}U is needed, since ^{233}U from the FBR blankets is ample to support the HTGR system.

The system as a whole becomes a net fuel producer (about 1 percent per year increase in fissile isotopes) by 2035. Ultimately, it is fueled by ^{233}U produced in FBR blankets. This production supports the requirements of LWRs,

Figure 4-5. A multipurpose strategy.



burners, and HTGRs. The FBRs are slightly less than self-sufficient for their fissile plutonium, but LWR production of plutonium balances that account.

The schedule of uranium demand levels off at about 12.5 million tons of uranium cumulatively used (Figure 4-5). Because of the cross-feeding of fissile isotopes, it is not possible to detail which reactors are most responsible for this demand.

We arrived at a figure of 10 to 15 million tons of natural uranium as a resource requirement to achieve an asymptotic supply of 10 TW(e) in these strategies. The figure of 15 million tons of natural uranium is still within the range that we consider feasible here. But a word of caution should be added. Any delay in introducing advanced reactors, and in particular breeders, increases rapidly the amount of uranium needed to achieve the investive mode.

A Nuclear Fuel Cycle for 10 TW(e)

What are the fuel cycle implications of a 10 TW(e) equivalent nuclear operation? What throughputs and losses are implied when 10 TW(e) are in operation on a continuing basis, beyond the year 2030? Avenhaus, Häfele, and McGrath (1975) studied the problem for a specific system of reactor types; the qualitative features are not changed for other combinations of reactors, which are at steady state after the investive phases of resource use are completed. The most important findings follow.

Under consideration is a reactor system in which LMFBRs and thorium high temperature reactors (THTRs) are operated on a steady state basis, as explained in Figure 4-6. Avenhaus, Häfele, and McGrath considered a system producing 3.6 TWyr/yr, with the FBR and the THTR contributing 50 per-

Figure 4-6. A reactor system for investive uses of uranium resources.

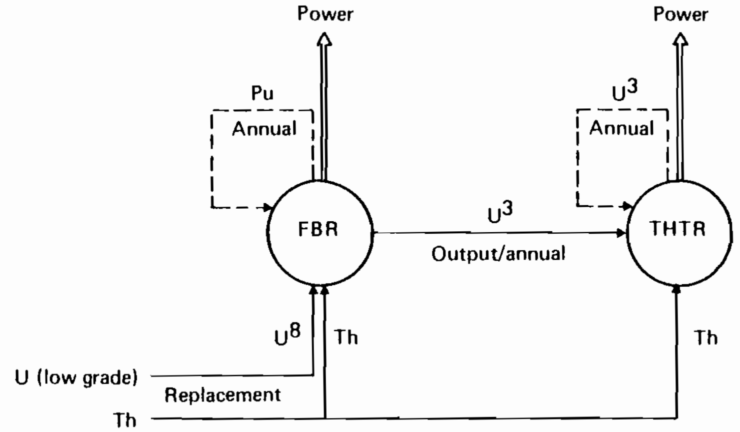
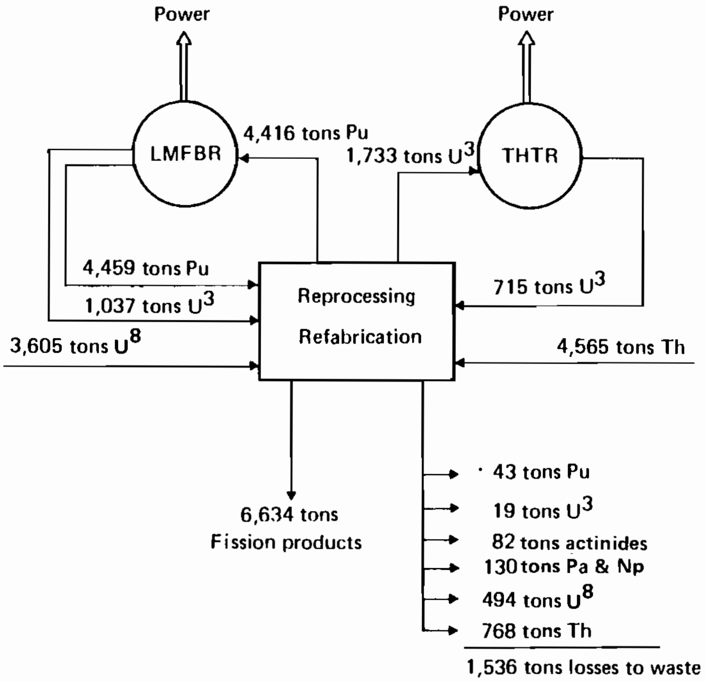


Figure 4-7. Annual throughputs and losses (in tons) for a 17 TWyr/yr, FBR/HTR operation. Only closed balances for Pu, U^3, and total (U^8 and thorium) are shown. The 6 ton mass defect associated with 17 TWyr/yr is not accounted for.



cent each. For exploring our 17 TWyr/yr—10 TW(e)—nuclear case, we retained this fifty-fifty partitioning and simply scaled up all the findings by a factor of 4.8.

Total Throughputs and Losses. Figure 4-7 gives in a simplified format the throughputs and losses that go along with an operation of 17 TWyr/yr of nuclear power. This mass balance is remarkable in a number of ways.

Less than 8500 tons per year of both natural uranium and thorium make up the generation of 17 TWyr/yr. If this energy were generated by coal, the annual mass flow of coal alone would be of the order of 18.3×10^9 tons—a factor of 2×10^6 more. Or in other words, we are now considering a unique feature of nuclear power. Of this 8500 tons per year, about 44 percent—or 3600 tons—is ^{238}U. If 15 million tons of natural uranium had been mined to establish the investment of reactors and of the fissile materials needed, then virtually all of the 15 million tons are available and stored. It is virtually all the ^{238}U. This would last at a rate of about 3605 tons per year for some 4500 years! This means the complete elimination of uranium mining after the year 2030. Global consumption of thorium would be about 4565 tons per year. This is again a negligible amount; it means practically no thorium mining.

The annual production of fission products is about 6634 tons. In solidified waste form, this would be a cube of roughly 20 X 20 X 20 m coming from the whole globe each year. In the case of coal, the analog would be the generation of some 60×10^9 tons of carbon dioxide per year on the order of 3.5 percent of the natural carbon dioxide content of the global atmosphere each year.

The heavy elements discarded in waste (losses) are about 1536 tons per year. Of this amount some 144 tons—or 1.7 percent of the total waste (fission products[i] and losses)—are ^{233}U, fissile plutonium, and higher actinides, all of which are of potential long-term concern.

The yearly handling of fissile uranium and plutonium material is about 6211 tons. In view of extremely low maximum permissible concentrations (MPCs) for these materials, this requires extremely tight confinements, as will be discussed later in this chapter.

Total Number of Nuclear Facilities. A fuel cycle operation of 17 TWyr/yr from an installed generating capacity of 10 TW(e) would require the following nuclear facilities:

- Ten thousand nuclear reactors, each of an equivalent of 1 GW(e) or 3000 of 3.3 GW(e) rating. The present number of electrical power stations, nuclear or nonnuclear, worldwide is of the order of 15,000.
- Ninety-four fuel fabrication plants capable of handling 1500 tons per year.
- Ninety-four chemical reprocessing plants capable of handling 1500 tons per year.
- Six hundred and fifty intermediate (five-year) waste storage facilities (tanks) of 1000 m^3. Seven such facilities would go with each reprocessing facility.
- Forty-seven final waste storage facilities—one for every two reprocessing plants, for example. The inventory of radioactivity practically saturates after twenty years of input. Each final waste storage facility therefore contains, under equilibrium conditions, the equivalent of twenty years multiplied by 6634 tons per year for the total of the forty-seven facilities —that is, 2823 tons per facility of stored fresh fission products equivalent.

Confinement of Radioactivity. The potential of nuclear power cannot be achieved without paying a price. Nuclear power by its very nature is connected with radioactivity, and handling this radioactivity on the scale assumed here requires meticulousness comparable to what has up to now

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[i] Fission products are the new nuclei that are produced by fission. Most of them are intensely radioactive, with half-lives of a few years or less.

been necessary only for handling very toxic chemicals or dangerous biological systems (e.g., bacterial cultures). This is the price.

For a rational approach to this problem, it is necessary to identify several levels of consideration. First, there is the total inventory of radioisotopes in nuclear reactors and other nuclear facilities. Conceptually, this just sits there. Under normal operating conditions, the inventory can physically leave the nuclear facility only at a certain rate.

This rate leads to a second level of consideration, described by the confinement factor (CF). (This is defined as the ratio between the annual flow of a radioactive isotope in question through a given nuclear facility and the related annual release of that radioactive isotope.) In most cases, the CF is a large number. The concept of the CF can also be applied to accidental conditions. In that case, it is the inverse fraction of the total inventory that is released in an accident.

On the third level of consideration are the pathways of the released radioactive isotopes in the environment. These result in ambient concentrations of radioactive isotopes at places where persons are exposed to them. Pathways usually result in dilution, as one can evaluate the volumes of air or water that dilute the released amounts of radioactivity between release and any points of biological impact. One must also consider pathways that could lead to increased concentrations of a particular radioactive isotope, in spite of potentially available large volumes of air and water for dilution. The famous pathway for iodine-grass-cowmilk-baby is a case in point: it enhances the danger by a factor of 700. It also works the other way around. For instance, fissile plutonium seems to sit on the ground once it has gotten there, withstanding further spreading by incorporation into living systems.

Fourth, the radiobiological level comes into consideration. It relates an ambient concentration to the doses and dose rate of persons exposed to it. The doses and dose rates are what cause biological effects.

By considering those levels of dose that have acceptably trivial impacts, one arrives at maximum permissible concentrations (MPCs), from which it is possible to work backward to infer how large the appropriate CFs have to be. Table 4-14 shows the factorization relating releases to radioactive dose rates of persons. It is convenient to compare the dose rate B with the already existing natural background B_o For quick orientation, it is sufficient to take B_o = 110 mrem per year.

Table 4-14. Factorization of radioactive impacts on persons.

Annual Flow		*Confinement*		*Dilution*		*Exposure*		*Dose Rate (Body Burden)*
Q	X	CF^{-1}	X	s	X	ρ	=	B
$\left(\frac{Ci}{sec}\right)$	X	$\left(\frac{release}{flow}\right)$	X	$\left(\frac{sec}{m^3}\right)$	X	$\left(\frac{m\ rem/yr}{\frac{Ci}{m^3}}\right)$	=	$\left(\frac{m\ rem}{yr}\right)$
First level		Second level		Third level		Fourth level		

Avenhaus, Häfele, and McGrath (1975) used this methodology to evaluate the design requirements for containment factors in a large-scale development of the nuclear fuel cycle. It was applied in determining the CFs needed for the nuclear facilities of the preceding section. The most critical isotope releases involve ^{85}Kr, ^{3}H, ^{129}I, Pu, and actinides.

A distinction is made according to whether dilution takes place through air or through water. Further, a distinction is made between localized impacts and impacts that eventually spread out all over the globe. In the case of localized impacts, only the neighborhood of a particular nuclear facility is affected; thus it can be considered a point source. In that case, no integration of all the other facilities takes place; only the actual inventory of the one facility matters. In the case of impacts that are widespread, partial or total integration of the impacts of all the other facilities takes place. In Table 4-15, we give the CF for each isotope and facility required to make each contribution to the relative dose rate B/B_0 well below 1 percent.

A few comments on the information in Table 4-15 are in order. In the case of ^{85}Kr, total integration of all outputs to the global atmosphere takes place. Present reactor designs lead to contributions that are at the $B/B_0 = 0.01$ border line when 17 TWyr/yr are produced; accordingly, a slight improvement of the confinement of ^{85}Kr, by a factor of three to ten over the next decades, is probably necessary. This should not be too difficult. By contrast, present designs of reprocessing plants with no ^{85}Kr retention would lead to contributions $B/B_0 \geqslant 2$, and this would be unacceptable. Confinement factors of one hundred must therefore be postulated. This is technically within reach, but requires development.

Tritium releases into the air are essentially local, and no global integration needs to be considered. This is because at the global level, the natural production of tritium is far greater than that from the nuclear industry. Present design of reactors seems to be satisfactory. In the case of reprocessing plants, confinement factors of up to one hundred may be considered necessary, depending on evaluations of the actual biological hazards. More information on pathways of tritium, varying from case to case, it also required. Confinement factors of the order of one hundred are within reach, but are not exactly straightforward. Special sites for the reprocessing plants could lead to a relaxation of such confinement requirements.

Table 4-15. Required confinement factors for making each relative dose rate contribution well below 1 percent.

	Reactors	*Reprocessing*	*Fabrication*
^{85}Kr	Present designs, slightly improved	100	–
^{3}H into air	Present designs	100	–
^{3}H into water	Present designs	100	–
Pu into air		10^{9}	10^{10}
Pu into water		10^{9}	10^{10}
Actinides		10^{9}	10^{10}
^{129}I		$\sim 10^{3}$	–

Tritium releases into water may lead to a partial integration of related impacts in a given river basin—thus, the confinement requirements. Again, with the same remarks as for air releases, this may lead to postulating a CF of one hundred, which is possible, but not easy. Both krypton and tritium are believed to have relatively small consequences, biologically, for a given dose rate. If this belief is confirmed and accepted, some relaxation of CFs, perhaps by a factor of ten, might be reasonable.

Plutonium releases into the air constitute a local impact, but such releases must be very limited. A CF of 10^9 in the case of reprocessing facilities and a CF of 10^{10} for fabrication facilities are tough conditions. For instance, plutonium-contaminated scrap must be handled with extreme care. Nevertheless, CFs of 4×10^{10} have already been confirmed experimentally in operating pilot plants. Since it is reasonable to expect further progress in the decades to come, such confinement must be considered possible, even at an industrial scale.

Plutonium releases into water, as in the case of tritium, may become regionally integrated. On the other hand, the MPC of plutonium in water is significantly higher than that of plutonium in air. The same CFs for plutonium in water as in the case of air—10^9 and 10^{10}, for reprocessing and fabrication, respectively—seem to be appropriate and can be obtained when the technical effort is large enough. The actinides (α emitters including ^{239}Pu and other α emitting transuranium isotopes) appear to be similar to plutonium itself as far as the CFs are concerned.

^{129}I is a special case. It appears only in small amounts, but decays with a half life of 17×10^6 years: this is large enough for the problem to last a very long time, but small enough to make an impact. If one assumes the release of iodine into the air, only a region within, say, 10 km must be considered because of the low chemical release rate of iodine. In the long run, such released ^{129}I would reach equilibrium with all of the stable iodine in the biomass. The biomass density on land is about 0.23 tons/m^2. As the average iodine content in the biomass, including water, is about 0.3 ppm, the release of ^{129}I from reprocessing plants with a CF equal to 10^3 would lead to a relative buildup of 1.6×10^{-4} per year without saturation. Within a few decades, this could therefore reach the $B/B_o = 10^{-2}$ limit under consideration here. Thus, one thinks of higher CFs. In the case of dilution into large amounts of sea water, the ^{129}I should not be a problem. However, the ^{129}I situation requires further study.

In conclusion, the fuel cycle operation of a 17 TWyr/yr nuclear world appears feasible. It has its price meticulousness, and this is not a straightforward thing. Whether such a price is worth paying is a relative question, not an absolute one. What is the alternative? Does it have a better price?

Each situation must be evaluated on its own grounds, which becomes a complex matter. The considerations of this section provide only a general orientation and should be taken only as an indication of the orders of magnitude. Fortunately, there is a vast literature on more specific evaluations.

Nuclear Safety. The large-scale deployment of a 17 TWyr/yr nuclear power industry is not only a problem of considering normal operative conditions.

Equal attention must also be paid to the problem of accidents. At IIASA, very little research has been done on this subject, because the state of the art is sophisticated and specialized and the problems can be attacked only by examining systems and system types in engineering detail. Small groups, such as the IIASA Energy System Program, cannot contribute substantially. The breakthrough by Rasmussen and his group (USNRC 1975) have provided a methodology. It was a detailed procedure, requiring dozens of man years, and yet of necessity the results have large uncertainties (USNRC 1978). It has proven impossible to do better with general and flat considerations.

One remark seems pertinent here. In evaluating design targets for confinement effects exhibited in the previous section, we considered not only normal operating conditions but also accidental conditions. The principal approach was to consider expectation values. Essentially this means that the radioactive inventory release in Table 4-15, $Q \times CF^{-1}$, which has the dimension *Ci/sec,* is replaced by the product of three factors: (1) a frequency (or probability) of accidental release per second (P); (2) the radioactive inventory I (curies) subject to dispersal in an accident; and (3) the conceivable fractional exposure time d (*sec* per year) of persons affected by such an accident.

As a formula, the substitution is (Farmer 1976):

$$Q \times CF^{-1} \rightarrow P\ [sec^{-1}] \times I\ [Ci] \times \frac{d}{3.15 \times 10^{7}} \left[\frac{sec}{sec}\right] = \frac{Ci}{sec}$$

This permits the use of the same formal procedures as in the situation of normal operating conditions. However, whereas for normal operations one evaluates the CF needed to meet target values for the relative increase of the dose rate B/B_o, now the probability density P is the required parameter for meeting such target values. In the evaluation by Avenhaus, Häfele, and McGrath (1975), the reactor did not turn out to be the most critical facility: the intermediate and final waste storage had the smallest target values of P. Both with regard to the ranking and to the absolute values of these target values, the results of these studies are contradictory to common perceptions. However, the target values are probably easier to achieve in static facilities, such as waste storage systems, as opposed to active ones, such as reactors and reprocessing plants.

Because the method deals with expectation values, a large number of small accidents is conceptually equal to a small number of large accidents. That is just not the way the public perceives the problem of nuclear safety. There is a large discrepancy between mathematical approaches that seem to offer a rigorous treatment of nuclear safety and the risk situation as it is perceived. This discrepancy is discussed in Chapter 11.

Using Nuclear Power

Up to now, nuclear power has been considered principally as a source of large-scale, centralized electricity. This role will undoubtedly continue, yet it relies on only one unique characteristic of nuclear energy—the size of the resource base of fertile materials available as fuel. Once breeding has been established, the availability of this resource base will be confirmed. What then?

Other uses have been tried and are indicative. One example is the widespread use of nuclear power to propel naval vessels, particularly submarines, and the much more tentative experimental uses for propulsion of various types of civilian vessels—for example, the Lenin, the Mutsu, the Savannah, and the Otto Hahn. A more tenuous example is the provision of remote base power in Greenland and Antarctica. Still other uses have been suggested: for the most remote bases (we currently contemplate in space or deep undersea); for factory ships and floating cities; for district heat and chemical heat.

Does nuclear power have, in fact, special characteristics that suggest these futuristic applications or only tentatively explored applications? The answer is clearly yes. Three properties are significant:

Nuclear fuel is extraordinarily compact. The factor of more than 10^6 in energy availability per unit weight, compared to oil, means that it can be transported almost anywhere inexpensively and a very long-lasting stockpile of fuel can be stored conveniently at the site of use.

The nuclear chain reaction requires no air to burn the fuel and consumes nothing that must be supplied by the environment. This fact makes nuclear power attractive for submarine propulsion and potentially useful for exploring or operating bases undersea or in space.

Fission produces energy of such high quality that the potential exists for generating very high temperature heat. Nuclear heat can be generated at high temperatures and transferred, still at high temperatures, to an inert working fluid such as helium. This gives the possibility of using nuclear heat directly for chemical reactions that have special environmental requirements, such as absence of combustion gases.

The multipurpose strategy previously illustrated was, in fact, investigated with these advanced, sometimes futuristic, applications in mind.

Electrical Networks. Nuclear electricity is generally considered, both inside and outside the nuclear industry, as being associated with very large units—1 GW(e) and up. The initial economic breakthrough of nuclear power occurred when economies of scale were reached with units of 500 MW(e) or higher capacity, and the trend has continued. There is no doubt that large units will be the backbone of the industry for some time to come. Indeed, their aggregation into "energy parks" with associated nuclear fuel facilities is a topic of active research today. We conclude this section with an illustration of a nuclear energy park use that is likely to become extremely important.

This is not all there is to nuclear electricity. It may turn out that one of the most important aspects of nuclear power will be to improve the electrical network by locating smaller plants at appropriate nodes of the grid. It is well known that transmission losses can be reduced and system reliability improved by judicious location of a generating plant. Can we use the "portability" of nuclear power to advantage for this purpose?

It seems possible. Particularly for smaller nuclear plant sizes, there are intrinsic reasons why public safety can be improved over standards now set for large plants. For example, for smaller reactors, the ability to supply shutdown cooling becomes an almost trivial engineering problem, and locating the reactor underground becomes much easier. It is also generally the case that is is not so costly to "overengineer" a small system as a large one. Of course, economies of scale would necessarily be sacrified, but a considerable recovery of the sacrificed economies might be achieved from lower reserve requirements and from greater ability to rely on factory construction, to use components already standardized for other applications, to schedule construction labor forces more flexibly among several units under construction, and to shorten construction schedules. This might be sufficient to close the cost gap to the point that decreased transmission losses and improved grid reliability make the final difference.

The physical independence of a nuclear power plant from an umbilicus of railway fuel supply and the absence of the crucial air pollution hazard would make nuclear power the choice for such plants: the only environmental requirement would be waste heat removal capability. But the point is more than just using nuclear power in a different way. A fine-grained electrical generation network has so much resilience that it can virtually function as an energy storage system as well. Such a network can, for example, accommodate more easily the inclusion of intermittent sources, such as sun and wind power. And under these circumstances, it may be possible for the network to substitute more for liquid fuels than it could otherwise do. In short, nuclear power might really be the key to using electricity effectively.

Small Heat Sources. As soon as we open up nuclear power to the small as well as to the large sources, many new applications become possible. In the industrialized regions of the world now, and in the industrializing regions in the future, a very large fraction of the energy requirement is in the form of low to medium grade heat. Most of the energy for these industrial applications comes from oil- or gas-fired boilers. Individual units of less than 20 megawatts output are very common. There is such a large amount of energy used in such units that cogeneration of electricity can make an important contribution to the electrical system.

A similar product is steam or hot water for district heating systems. Where waste heat from an electric power plant is not available, a fossil-fueled boiler is again used.

Twenty years ago much effort was put into designing nuclear systems to do these jobs. In particular, small packaged reactors in the megawatt range, containing fuel to last a decade or longer, were investigated. Most of this effort was shelved in favor of putting the limited nuclear manpower to work on central station power systems. More recently, there has been a revival of interest, and such designs as SECURE (Nelsson and Hannus 1977) are beginning to appear. With modern advances in automatic operation, the chances are very much improved that such systems can be designed to be operable by a small crew, which is a major consideration for this application.

If such reactors are economical, they could account for almost as much nuclear power as might be generated for central station electricity. For this purpose, small LWRs seem very appropriate, and that is why these reactors were included in our multipurpose strategy.

Indeed, even one of the by-products of nuclear power might be useful for these low temperature heat applications. Suitably encapsulated, solidified fission products could spend their early years as package heat sources, until their decay has proceeded to the point that they are not powerful enough sources; at this point, their geological disposal is greatly simplified. Interestingly, small reactors and isotopic heat sources satisfy all of the performance requirements of soft energy systems, illustrating that the hard-soft dichotomy is ideological rather than social or physical. (See Chapter 24 for a discussion of the hard-soft controversy.)

Remote and Mobile Energy Sources. The uses of nuclear reactors for shipping have only begun to be explored. Most of the reasons for the tentative nature of this exploration are included under the heading "public acceptance problems"; yet there has been no outcry about the much more extensive use of reactors in naval vessels and in particular in submarines. Indeed, the excellent safety records of ships in nuclear navies is one of the bright stories of nuclear power. We thus consider it axiomatic that, given public acceptance, nuclear power will play a great role in shipping. Its immediate value in that context is in freeing up the space normally occupied by ship's fuel, making it convertible into payload.

It take only a little imagination to consider unconventional uses of nuclear vessels. The famous Northwest Passage from Europe to Alaska is accessible by submarines under the Arctic ice pack. Submarine cargo ships? Or, given such ships, would they be used also in transoceanic shipping, capable of submerging to avoid storms? What about transoceanic tugboats? The concentrated fuel of a reactor is entirely capable of hauling a string of barges—perhaps DRACONE type plastic cargo carriers—around the world.

One goes further and further into science fiction—floating cities, manned bases deep under the ocean, bases in space. Will a reactor be carried to the first permanently manned lunar base? To Mars? Any place far, any place without air, any place without strong and constant sun—these are the places for which there does not seem to be a rival to nuclear power.

This group of applications, from mundane cargo hauling to planetary exploration, requires special purpose reactors. For many uses, severe design requirements are eased if the power source can be run on enriched fuel—either highly enriched or enriched at least to the point of denaturing (20 percent ^{235}U in ^{238}U, about 10 to 12 percent ^{233}U in ^{238}U). These are the pure burner reactors of the multipurpose strategy.

Electricity and Hydrogen. Even given all the opportunities listed above, the generation of large amounts of electricity and the uses of nuclear heat for chemical synthesis will probably still be the principal applications of nuclear power. Of the 10 TW(e) of equivalent nuclear capacity by 2030 in the multipurpose strategy, 8.5 TW(e) were allocated to reactor types (FBRs and HTGRs) appropriate for these basic purposes. Recall that at 40 percent conversion efficiency and a capacity factor of two-thirds, this is a thermal output of about 14 TWyr/yr.

This is about as much electricity as is projected to be needed in the IIASA High scenario (see Chapter 17). The 8.5 TW(e) of capacity translates into 5.7 TWyr/yr of generated electricity, and the IIASA High scenario calls for 4.7 TWyr/yr in 2030. But we must recall that electricity would also be generated from other energy sources (solar, hydroelectric power, and other renewable sources) and would be cogenerated in some industrial applications using coal, oil, and LWRs. Thus we have considerable surplus capacity for both electricity and high temperature heat in the multipurpose strategy. What uses are contemplated?

Häfele and Sassin (1975) confronted this problem; the solution is examined in Chapter 3. The new major energy sources produce heat and electricity, whereas the looming shortages in the world are of gaseous and liquid fuels. The natural partner of electricity in the future turns out to be hydrogen, a gaseous fuel that can be used in the synthesis of liquid fuels from coal. Both electricity and hydrogen are energy carriers with no or negligible entropy content; both are environmentally clean. Ideally hydrogen upon energy delivery would react only with oxygen, leaving pure water as the burning product. (In most practical cases hydrogen would react with air, leaving water together with some nitric oxides in the ppm range).

Hydrogen would be a partner for electricity because it can be stored and transported. At present, electricity can be stored only in small amounts or indirectly; today's technology of electrical batteries permits the storage of energy only on the order of megawatt hours. For larger amounts of energy, hydrostorage is used, but this is expensive and limited to a few terawatt hours in most cases. The very large hydroelectric power facilities of the Bratsk-Ilimsk area of East Siberia provide, in principle, a storage capacity of up to 30 TWh; in all practical cases the storage capacity is less than that. Yet the quantity it would be desirable to store adds up to hundreds of terawatt hours for a 10 TW(e) world.

Electricity can be transported by means of high voltage lines, but the costs are relatively high (Figure 4-8). Therefore, in practice no more than a few gigawatts are transported over, say, a few hundred kilometers, and the average electrical kilowatt hour travels less than 100 km before it is consumed. The transportability of electricity is limited, and the easy transportability of hydrogen is very welcome.

The uses of hydrogen as final energy require a significant adaptation of the existing infrastructure. Figure 4-9 shows the branching out of ever smaller scales of energy handling of more local features of existing infrastructures such as industrial facilities, houses, and transportation devices. Such adaptations require time. It is therefore appropriate to look for solutions that could accept the infrastructure as it is and that would play at least

Figure 4-8. Comparative costs for the transport of energy over a distance of 1000 km.

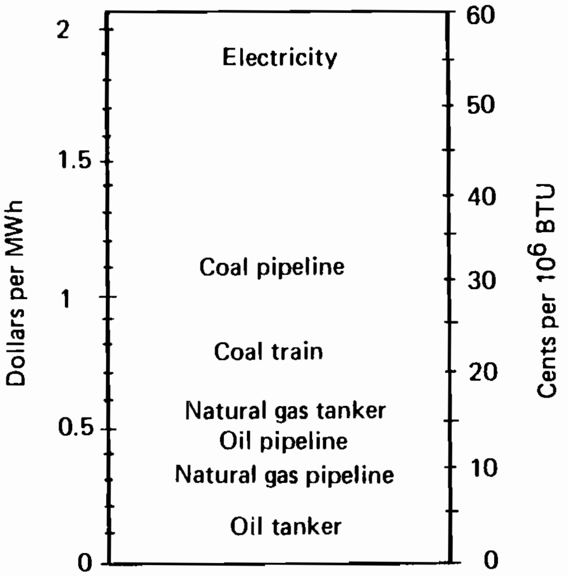
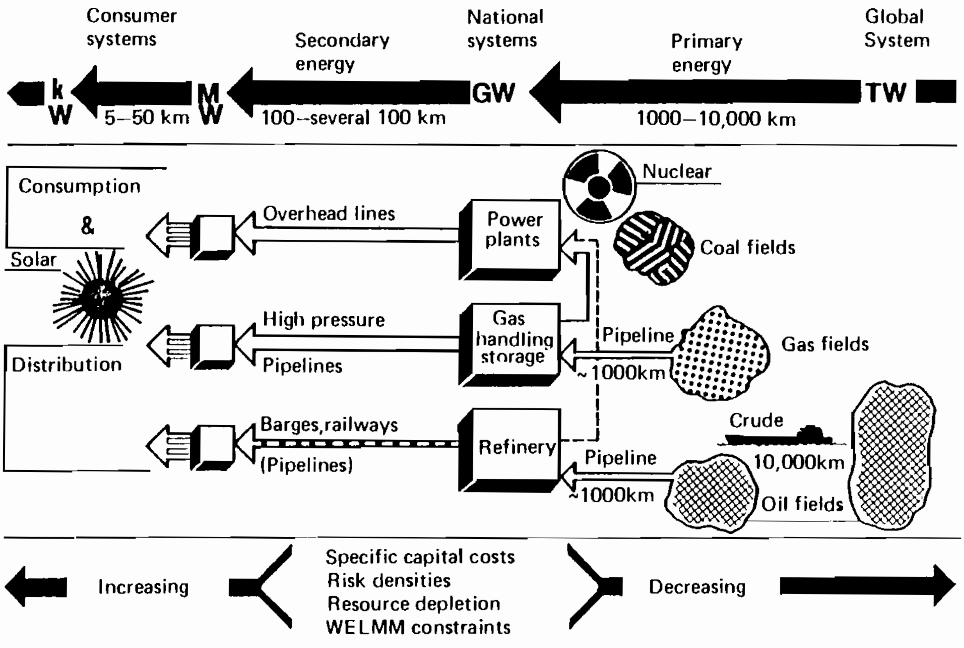


Figure 4-9. Present structure of the global energy system.



an intermediate role by buying time. A few decades could mean a lot. A most prominent candidate for such a function is methanol. Roughly 50 percent of its energy content is due to the carbon atom in it; the other 50 percent is due to two of its four hydrogen atoms. The salient point is: it is liquid.

The uses for methanol and its partner (or competitor) gasoline have also been discussed in Chapter 3. The synthesis steps require hydrogen and, in the most coal-conserving processes, heat from external sources. The most straightforward route to hydrogen (see Chapter 22) is electrolysis, while alternate routes make use, wholly or partially, of high temperature heat.

Electrolysis is often criticized as being inefficient. The reactors we have concentrated on have efficiencies up to 40 percent. Given an efficiency of the electrolyzer of 60 percent, this leads to an overall efficiency of 24 percent only. But let us recall our argument: Nuclear power becomes nuclear power, and not "yellow coal," by the eventual use of the breeder, with an investive (not consumptive) use of a finite amount of uranium. Such investive use then permits the practically unlimited production of energy because the residual requirements of fuel are indeed negligible. A low thermal efficiency is therefore no longer critical. Instead, the problem is waste heat handling, and the criterion is capital cost efficiency at the gigawatt scale. This is a new context, and although electrolysis is an established technology, it must be looked at anew. A similar fresh look must be taken at the approach of splitting water by staged chemical processes, which follows up the pioneering work of de Beni and Marchetti (1970).

Thus, the next major task of nuclear energy is to produce not merely several terawatts of electrical power, but to store free energy in hydrogen at a several terawatt rate as well. If nuclear energy is not allowed to do the job, something else must do it. The most likely "something else," solar power, is discussed in Chapter 5. The two forms of primary energy, nuclear and solar, can be thought of as competitive, but we prefer to think of them as complementary, since it is likely that both will be needed and both will be used on a large scale.

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5 THE SOLAR OPTION

INTRODUCTION

Is the sun the answer to the energy problem? Can it provide all the energy required for a growing world and, if so, when and under what circumstances?

In keeping with the general approach of this book, in this chapter we conceptualize a future based on energy from the sun, with the purpose of stretching our thinking to the limits and thereby learning about constraints, timing, and other pertinent features. This parallels what we have done in the preceding chapters on coal and on nuclear power, where we have also focused on supply options that are global in nature.

As we explained earlier, in addition to global options, there are energy sources that are locally significant. Solar power in particular has both a local and a global aspect. Often the locally significant applications of solar power are labeled "soft," and in Chapter 24 we shall elaborate on the notion of soft and hard energy systems. Furthermore, in Chapter 6 we shall discuss in detail renewable energy sources, all of which essentially come ultimately from solar power. Thus the discussion here of the global "hard" aspect of solar should be viewed as a complement, rather than as a contradiction, to the treatment of soft solar yet to come. Still, we find it important to distinguish between hard and soft solar power, because analyses of these different aspects of solar are often based on two very different sets of attitudes and perspectives. And such differences must be kept in mind when evaluating various arguments and analyses.

What would a hard solar option look like? Consider the following assertion. Sunlight—hard, centralized solar power—could eventually be the primary and, conceptually, even the exclusive source of heat, electricity, and synthetic fuels (liquid or gaseous) for the entire world—continuously and eternally on a scale generally regarded possible only with fusion or with fission via the fast breeder reactor. This could be achieved through a global network of solar conversion facilities, coupled with appropriate energy transport and storage systems. And this appears to be possible within acceptable constraints on energy payback time, capital investment, and available suitable land. Environmental and social consequences are not negligible, but they appear possibly less problematic than those associated with fission or fusion alternatives used on the same scale. The political consequences are likely to be the most far reaching; while the fast breeder reactor in principle permits countries to eventually achieve complete energy independence, running the world from sunlight would require extensive, perhaps unprecedented, international cooperation.

Is this long-term possibility realistic? What does it take to have a solar-energy-supplied world? Here we consider the possibilities, in light of the observations of this book about the limitations of fossil resources and the potential range of energy demand over the next five decades.

THE SOLAR RESOURCE

Each day the earth receives from the sun 100,000 times more energy than is produced in all the world's electricity—generating plants. The average power input from the sun is some 178,000 TW(th). The challenge is to find practical ways to tap even small portions of this incredible flow of natural energy.

The energy density of solar radiation is too low to be used directly; in comparison, that of fusion or fission can be considered too high. Therefore, these resources must be transformed into convenient energy carriers that match the set of energy end uses of future social systems. As we have already indicated, increased urbanization of human society can be expected in both the developing and the industrialized countries. Around the year 2030, the developing countries will likely reach a level of urbanization close to that in the developed countries today. Because human settlements are becoming more extensive, dense, and technological, their metabolic needs must increasingly be provided through the use of secondary energy carriers characterized by high thermodynamic quality as well as flexibility of conversion, storage, and transport. That can be done by electricity and chemical fuels, both liquid and gaseous. In Chapter 3 we have elaborated on this subject; therefore we shall not go into further detail here, but rather concentrate more directly on solar energy.

Table 5-1. Characteristics of solar radiation as an energy resource.

The solar constant	1353 W/m^2
Effective radiation temperature of the sun	5760 K
Maximum direct beam irradiation at sea level	~1000 W/m^2

Region, Irradiance		*kWh/m^2-Day*	*W/m^2 (average)*
Tropic, deserts	Annual average horizontal	5-6	210-250
Temperature zones		3-5	130-210
Less sunny regions (e.g., Northern Europe)		2-3	80-130
Average annual direct beam irradiance in sunny regions		7-8	290-330
Monthly average direct beam radiation in sunny, arid regions		5-10	210-420

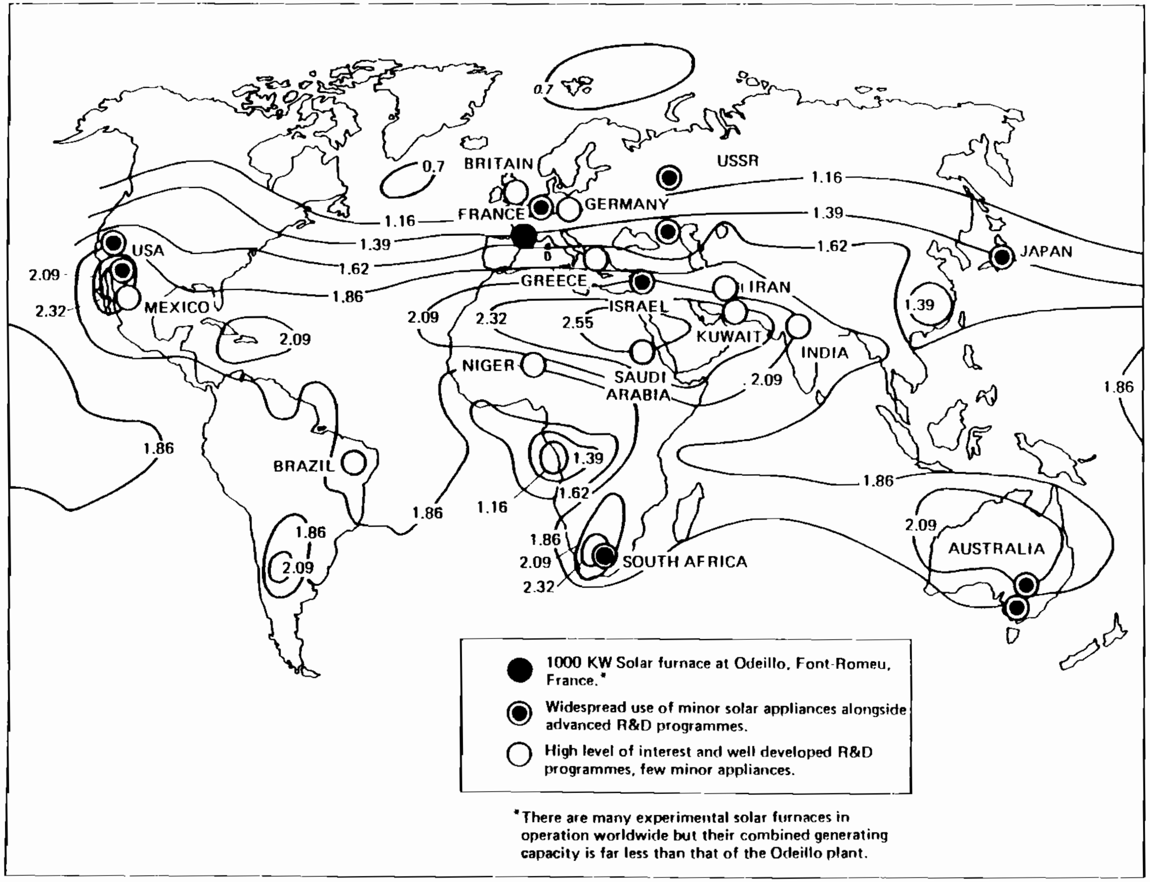
Source: Weingart (1978).

The average annual distribution of solar radiation and the locations of potential solar sites are shown in Figure 5-1. For quick orientation, Table 5-1 presents a summary of the information in the figure. Solar radiation varies by a factor of three from sunny arid regions to the less sunny regions of northern Europe. Monthly variations over the year can be almost negligible in equatorial regions but vary by a factor of ten from summer to winter in northern Europe. Extremes in the availability of direct beam radiation are even more severe. In areas such as the United Kingdom and central and northern Europe, where as much as 85 percent of total irradiation in the winter months is received as diffuse radiation, the use of tracking or tilted solar collectors cannot really compensate for the seasonal variations in sunlight. This translates into a central question: How can these areas obtain a substantial share of their energy needs from sunlight? With this question in mind, let us now examine the various solar technologies as they appear at present.

SOLAR TECHNOLOGIES

The development of most potentially important solar technologies is just beginning, and present activities are emphasizing hard, complex, and perhaps inelegant technologies because they are closest to our other industrial and engineering capabilities. The attempt to mimic precisely with solar energy facilities the behavior and function of traditional fossil fuel facilities for power and heat may be as inappropriate for solar technologies as it is (though for other reasons) for nuclear technologies. Basic research is opening up entirely new possibilities, particularly in solid state and photobiochemical conversion processes. It is quite possible that the large-scale use of

Figure 5-1. Average annual distribution of solar radiation and locations of potential solar sites. Radiations levels given in TWh/km^{2}yr. *Source:* Crabbe and McBride (1978).



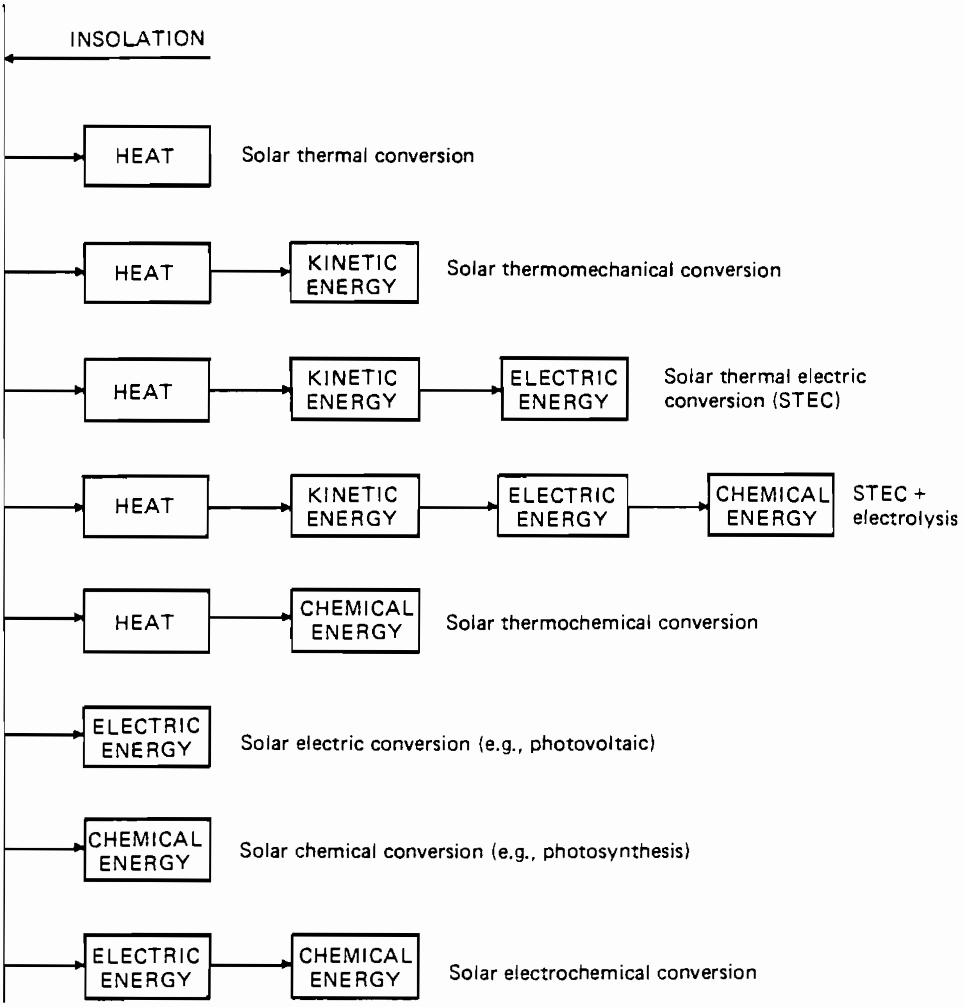
*There are many experimental solar furnaces in operation worldwide but their combined generating capacity is far less than that of the Odeillo plant.

sunlight in the future will be with technologies not yet available and perhaps even with technologies still unknown.

A large number of thermodynamic pathways are in principle available for the conversion of direct and diffuse radiation; eight specific configurations are shown in Figure 5-2. To make use of any energy resource requires combining, in an integrated system, energy conversion processes and energy transport along with power conditioning and control functions. For any specific pathway, the variety of possible engineering realizations is enormous.

Moreover, economic judgments are difficult to make since it may take nearly a century for some mix of solar technologies to make a substantial

Figure 5-2. Some thermodynamic classes of solar energy conversion.



fractional impact on energy use. To compare an expensive but emerging technology with a cheap and disappearing one (oil and gas) is inappropriate; the economics of solar technologies should be compared with those of the other energy sources that will also be available on a large scale during the same period—for example, fusion and the fast breeder reactor. Under optimistic circumstances, the cost of large-scale production of solar-derived synthetic fuels may be on the order of \$60 per barrel of oil equivalent. (Gasoline, before taxes, is \$20 to \$40 per barrel.) While the world could probably live reasonably well from high grade fuels at this price, an enormous amount of fuels derived from nontraditional fossil sources will almost certainly be available at substantially lower prices. Still, uncertainties in the technical and economic characteristics of all these options, plus societal reactions to many of them, make it impossible to identify primary reliance on any one option as the preferred path. A diversity of options remains our best insurance policy against future uncertainties.

Solar Thermal Electric Conversion

Heat at temperatures as high as 4000°C can be produced by concentrating direct solar beam radiation on an absorber. This heat can be used to operate an engine or turbine, which in turn can be connected to an electrical generator. This specific sequence of processes is commonly referred to as solar thermal electric conversion (STEC). In one specific configuration (Figure 5-3), the "central receiver" system, thousands of sun-tracking mirrors or heliostats focus solar energy on a receiver located atop a high (100 to 250 m) tower. The receiver in turn produces the superheated steam or hot gases required to drive either a conventional Rankine steam cycle or a high temperature Brayton cycle. To generate, for example, 100 MW(e) busbar output assuming 500 W/m^2 average insolation and a capacity factor of 0.5, a total land area of 0.2 km^2 would be required for the direct transformation of sunlight to electricity, in the case of 100 percent efficiency. But because of the overall conversion efficiencies for a STEC power plant—of between 15 and 25 percent from direct beam solar radiation incident on the heliostat surfaces to electricity—the mirror area required to generate 100 MW(e) is approximately 0.9 km^2, which corresponds to about 3.8 km^2 of total land area. Since many of the factors that enhance conversion efficiency also entail added costs, it is not yet clear what the relationship between energy cost and total power plant efficiency will be. Figure 5-4 describes the evolution of area requirements for a 100 MW(e) STEC plant in view of cumulating efficiency losses.

The solar engine has a century of history behind it, but only since 1973 has there been a substantial effort to develop a variety of STEC power plants to commercial reality. A large number of thermal cycles, spanning a range of a few kW(e) to a few hundred MW(e), are under engineering development. In Europe, Japan, and the United States, prototype (precommercial) STEC plants are in construction. Many of these (Winter 1978), which will be in

Figure 5-3. Central receiver solar thermal electric power plant. *Source:* Fujita et al. (1977). Provided courtesy of the Department of Energy through an agreement with NASA, California Institute of Technology, Jet Propulsion Laboratory.

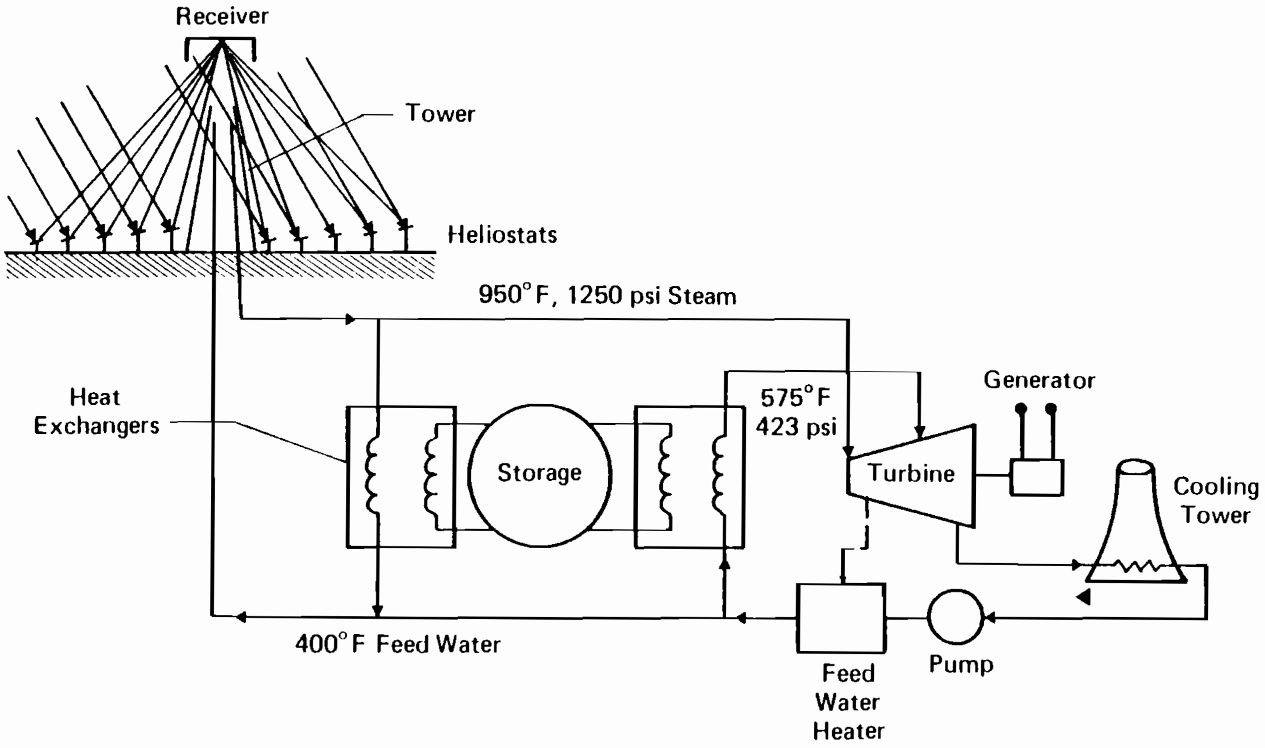
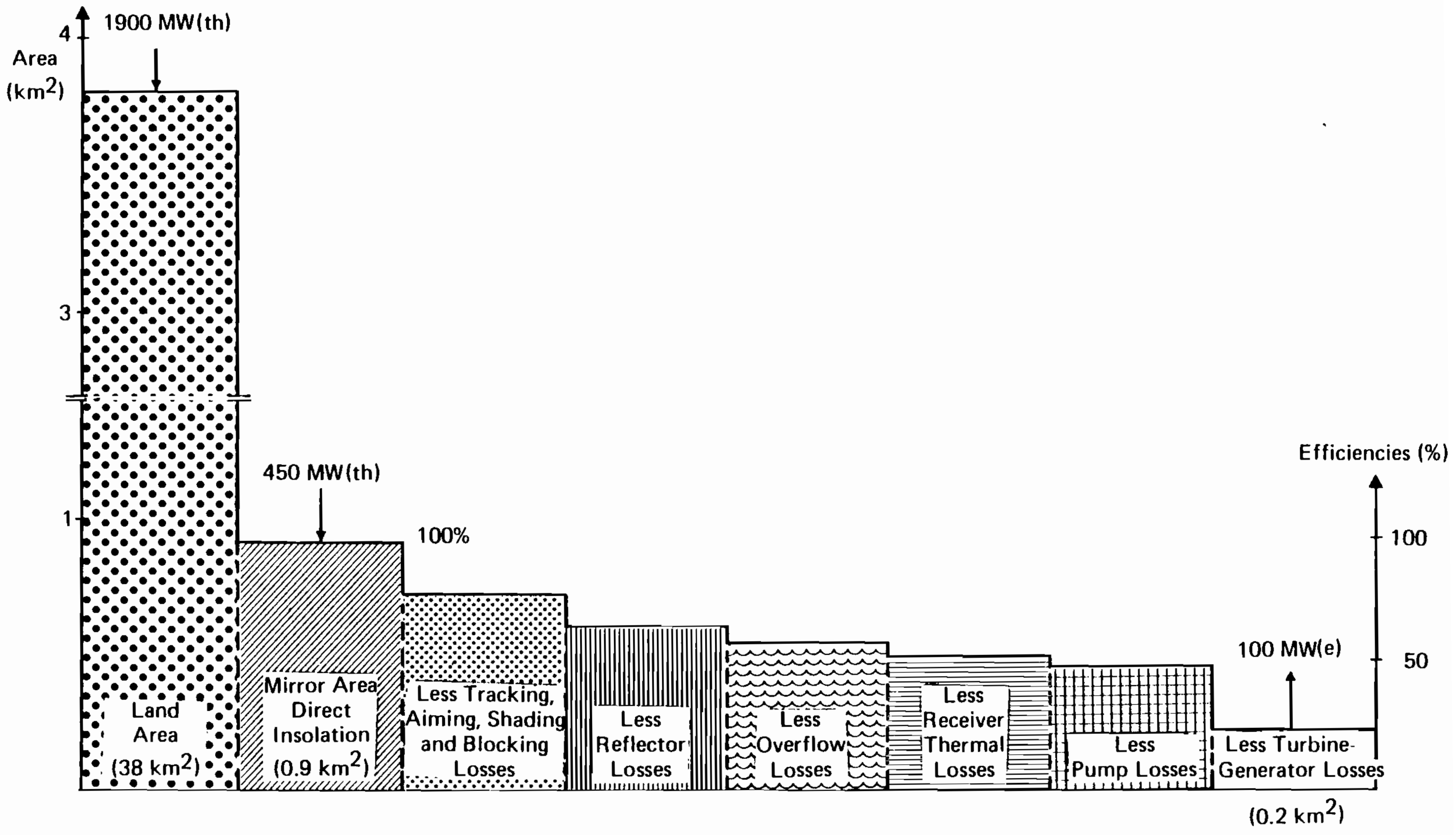


Figure 5-4. Evolution of area requirements for a 100 MW(e) STEC plant in view of cumulating efficiency losses. Average insolation 500 W/m² (highest levels in sunny, arid regions) and capacity factor 0.5.



the range of 0.5 to 10 MW(e), will be operational shortly after 1980 (Table 5-2). Fully commercial plants are expected in the 1990s. One reason that technical progress has been so rapid is that the engineering principles are all well understood. Major design problems have included development of inexpensive heliostats and solution of materials problems in the high temperature absorbers.

We studied a variety of published estimates (e.g., Weingart 1978) of the estimated costs for a central receiver STEC plant operating under optimum meteorological conditions. These are summarized in Table 5-3. Six different plant designs and estimates are arranged in identical categories, with indirect costs being computed as a straight 50 percent of direct costs and the total (direct plus indirect costs) escalated from the year of the estimate to 1977. As can be seen, the average of the five most favorable of these estimates is some $2300 per kW(e).

Present cost estimates for commercial STEC systems are high compared with more traditional fossil and nuclear fuel cycles. Yet even these costs will be difficult to achieve. Cost estimates for the prototype STEC systems

Table 5-2. Central receiver[a] and distributed[b] solar thermal electric facilities (constructed, planned, or contemplated).

Year	*Country*	*Installed Capacity (MW(e))*	*Cumulative Electric Installed Capacity (MW(e))*	*Cumulative Number of Facilities*
Mid-1960	Italy	0.1	0.1	1
1969	France[c]	1 MW(th)		
1977	USA (CR)[c]	0.4	0.5	2
1978	United States[c]	5 MW(th)		
1978	France (DR)	0.3	0.8	3
1978	FRG (DR)	0.01	0.8	4
1979	United States (DR)	0.15	1	5
1979	FRG (DR)	0.05	1	6
1980	France (CR)	2	3	7
1980	United States (DR)	10	13	8
1980	United States (DR)	10	23	9
1980	Spain (CR)	1	24	10
1980	IEA[d] (CR)	0.5	24.5	11
1980	IEA[d] (DR)	0.5	25	12
1980	Italy[e] (DR)	1	26	13
1981	Spain (CR)	1	27	14
1981	United States (CR)	2	29	15
1982	Japan (CR)	1	30	16
1985	United States (CR)	100	130	17
1985	United States (DR)	100	230	18

[a] Central receiver facility (CR).

[b] Distributed receiver facility (DR).

[c] Test facilities.

[d] International Energy Agency (IEA).

[e] European communities (private communication, Günter Schuster).

Table 5-3. Estimated costs for central receiver STEC power plant designs.

Cost Component *$/kW(e)*[a]	*JPL* *(1)*[b]	*McD* *(2)*[b]	*Martin* *(3)*[b]	*B&V/EPRI* *(4)*[b]	*B&V/EPRI* *(5)*[b]	*Smith* *(6)*[b]
Land and site preparation	10	32	150	27	10	11
Structures and facilities	–	32	–	110	–	–
Heliostats and collectors	935	678	760	1933	620	616
Absorber/receiver	230	143	180	658	348	99
Boiler plant	250	230	182	658	NA	200
Turbine plant	250	230	83	145	262	200
Electric plant	250	230	83	145	262	200
Miscellaneous plant equipment	250	5	–	98	52	10
Condensor and cooling	250	–	61	98	NA	–
Storage	122	122	169	127	7	60
Direct costs	1547	1210	1550	3196	1299	996
Total direct and indirect costs updated to 1977	2700	2100	2700	5560	2260	1610

Note: Average total cost estimates excluding (4): 2274 $kW(e).

NA—Not applicable.

[a] Capacity factor = 0.5; 1977 U.S. dollars.

[b] (1) JPL Jet Propulsion Laboratory (Selcuk 1975).
(2) McD McDonnell Douglas (1973, 1974).
(3) Martin Martin Marietta (F. Blake et al. 1975, 1976).
(4), (5) B&V/EPRI Black and Veatch (1976).
(6) Smith O. Smith (1976).

mentioned above are in the range of $8000 to $20,000 per kW(e). But prototype systems are always more expensive than their commercial progeny. A combination of engineering, industrial, and meteorological considerations suggest that achieving the commercial goals is possible, though difficult.

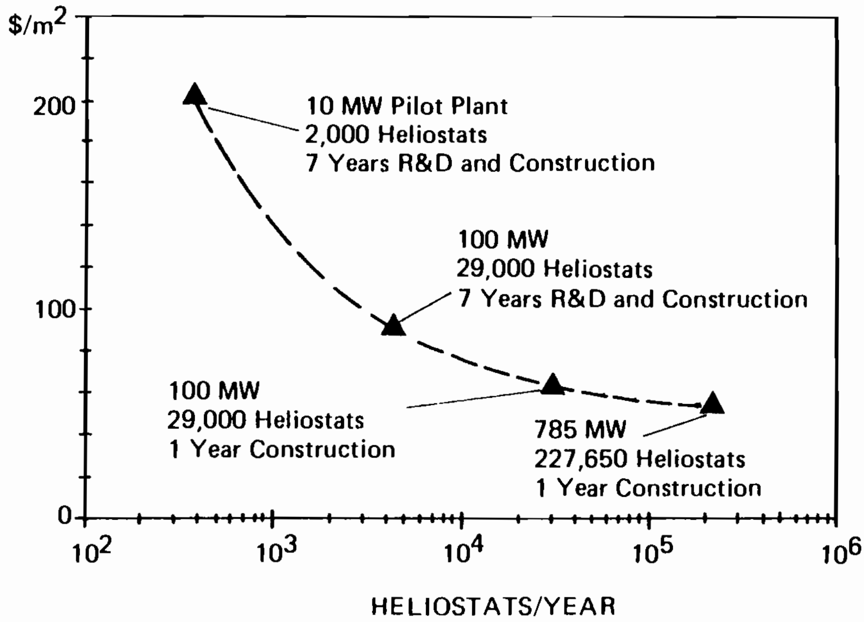
Though we discuss this subject later in this chapter in more detail, it is instructive at this point to do some rough cost calculations based on STEC material requirements. The steel required for current prototype heliostats weighs on the order of 50 kg/m^2 of reflecting area (in order to withstand stresses); given that optical and thermal subsystem efficiencies limit total STEC conversion efficiencies to between 15 and 25 percent, then at least 9 m^2 of heliostat area are needed per kW(e) busbar (500 W/m^2 average isolation, capacity factor of 0.5). Production costs for the cheapest products of the most rationalized and largest mass production activity in the world today—the automotive industry—are about $3.50 per kg. We know from extensive experience in a variety of industries that other mass-produced machines cost (excluding profit, distribution, installation, etc.) roughly $3.50 to $5.00 per kg. If heliostats produced on a comparable scale cost $3.5 per kg of steel, then the heliostats alone (excluding glass and concrete) will add $1575 per kW(e).

It is worth inspecting the estimates for heliostat costs a little more closely.

The results of a detailed study of the costs of mass-produced heliostats are shown in Figure 5-5. In this study, a number of production processes were considered, ranging from a seven-year research, development, and construction period for limited production of 2000 heliostats to the establishment of an automotive industry type of process producing 250,000 heliostats per year. The study (McDonnell Douglas 1976) suggests that an asymptotic cost of \$60/m^2 of reflecting area might be eventually achievable. This will be a remarkable accomplishment, even under optimal conditions, in view of the experience of the automotive and other industries, if these costs can really be achieved, even within a factor of two. The development of fully commercial STEC systems is expected to take several decades and to require research and development costs of about one billion (10^9) dollars (Caputo and Truscello 1976).

Taking the cost range of Table 5-3 we can estimate the cost of STEC-derived electricity under several climatic (insolation) conditions. At a 10 percent fixed charge rate (FCR), the levelized busbar cost of electricity would be on the order of 50 to 100 mills per kWh(e) in desert areas (where 1 mill = \$0.001); in less sunny regions (e.g., the United Kingdom and central and northern Europe), the range would be 200 to 300 mills per kWh(e). By contrast, long distance high voltage DC transmission from Spain to Oslo or from Phoenix to Boston is estimated to cost about 10 mills per kWh(e) (Caputo and Truscello 1976). The production of STEC electricity in sunny

Figure 5-5. McDonnell Douglas heliostat production rate and cost projections. *Source:* McDonnell Douglas (1976).



regions, such as large areas of Spain and Portugal, Turkey, southern Yugoslavia, and southeastern Bulgaria, as well as shipment to the less sunny areas of Europe, would be far cheaper than on site generation.

Thus if large-scale use of STEC-generated electricity is ever to be an option for the densely populated, cloudy regions of the world, it will be by coupling STEC plants in the south with load centers in the north. It might then be possible to provide electrically driven services in Oslo with STEC electricity from Spain at the same unit cost as with locally generated electricity costing 35 to 50 mills per kWh(e) today.

What does all this mean? STEC plants are really an attempt to imitate with concentrated sunlight what we do today with coal, oil, and gas (and nuclear reactor cores)–namely, the production of steam to run a turbine generator unit. There have been no real scientific challenges to the development of such systems, although the engineering accomplishments have been exceedingly impressive. Yet these cumbersome machines, requiring thousands of heliostats, huge concrete towers, sophisticated thermal absorbers, heat transport and storage units, turbines, generators, cooling towers, and so forth, may really turn out to be museum pieces by the end of the century. The combustion of fossil fuels, which have an enormous energy density and can be converted to shaft horsepower via combustion at very high efficiencies, is probably not the best model for the design of a solar power plant. Rather, the techniques that use the high inherent energy (on the order of 1 eV) of the visible light photons, as well as techniques that bypass the Carnot cycle and the complexity of thermal-mechanical systems, will probably be the really important approaches to solar energy conversion over the long run. Among such techniques, the most well known are those that involve photovoltaic cells.

Photovoltaic Electricity and Fuels

Two very important features of photovoltaic cells are that they are inherently modular and responsive to both diffuse and direct radiation. These features have far-reaching implications that can hardly be overestimated. First, in middle latitudes it is not impossible to devote even relatively large amounts of land (on the order of several thousands of km^2) to solar power uses, but not in large units. Instead, such land is usually available only in "bits and pieces," and exploiting its potential therefore requires a technology adapted to modular applications. In a later section of this chapter, specifically that on the architecture of a global solar system, we examine this point in more detail. Second, the possibility of using diffuse as well as direct solar radiation makes photovoltaic applications viable even in areas where the cloudiness is rather high. In actual cases, such as Austria, potentially this can make a great difference when photovoltaics are compared to STEC. Finally, photovoltaic systems have no moving parts, have potential lifetimes that substantially exceed those of existing commercial power plants, and exhibit efficiencies of up to 20 percent. Thus, these technologies are potentially very important for the industrialized world and could have revolutionary consequences for the developing world: the crucial problem is economic.

Of the possible approaches, the single crystal silicon cell, which is the most developed as a result of aerospace activities, is currently the frontrunner. It has made steady progress toward commercial terrestrial applications, but the U.S. program is still a factor of twenty from the 1986 cost goal of $\$0.50/w_p$ for a module (peak watt based on maximum insolation of 1 kW/m^2), and a silicon module efficiency of 12 to 15 percent is expected at the cost goal. In addition to the silicon single crystal program, gallium arsenide, with its higher efficiencies (about 20 percent), high concentration capability, and insensitivity to higher temperatures (up to 200°C), as well as amorphous silicon, thermophotovoltaic designs, vertical multijunction silicon, poly crystalline silicon, and cadmium sulfide-copper sulfide, are in the early development stage.

There is some expectation that $\$1.00/w_p$ can be reached using mass production techniques with current technical approaches based on single crystal silicon (Metz and Hammond 1978), and recent studies indicate that even $\$0.40/w_p$ is achievable (Aster 1978). However, cost reductions of this order may turn out to require the development of another approach. Since there is a large number of candidates in the early stage of development, some researchers are confident that at least one approach will reach the $\$0.50/w_p$ goal. However, because it is early in the research and development stage for these other approaches, this speculation has an unknown pedigree, and strong support can be found on both sides. The photovoltaic module would be the dominating part of a photovoltaic system. The rest of the system would be made up of the support structure (which, if cost goals are reached, is likely to be a fixed plate tilted at approximately the latitude angle), power conditioning (DC to AC), and power collection.

Estimates of photovoltaic plant performance and cost are shown in Figure 5-6, based on single crystal silicon on a tilted plate structure costing $17.50 per m^2 with a global radiation of 1900 kWh/m^2-yr on this tilted plate. With this set of assumptions, some concentration (2:1) is attractive economically. A simple concentration scheme can be used with a fixed angle but asymmetrical "V" trough, which is adjusted biannually (Caputo 1976). This reduces both the energy cost slightly (by less than 10 percent) and the area requirement by about 15 percent. A compound parabolic concentration (CPC) may be used with a three to five times concentration that is adjusted five to ten times a year. However, the cost estimates of Figure 5-6 simply use a flat plate scheme without concentration.

Through the use of very strong optical concentration, it is possible to reduce the area requirements for the active solar device by a factor of hundreds or even thousands. With adequate cooling, device efficiencies as high as 25 percent have been observed (Table 5-4). Thus, the main effect of concentration may be to stretch the otherwise limited materials (such as gallium), rather than to decrease the total cost of photovoltaic electricity.

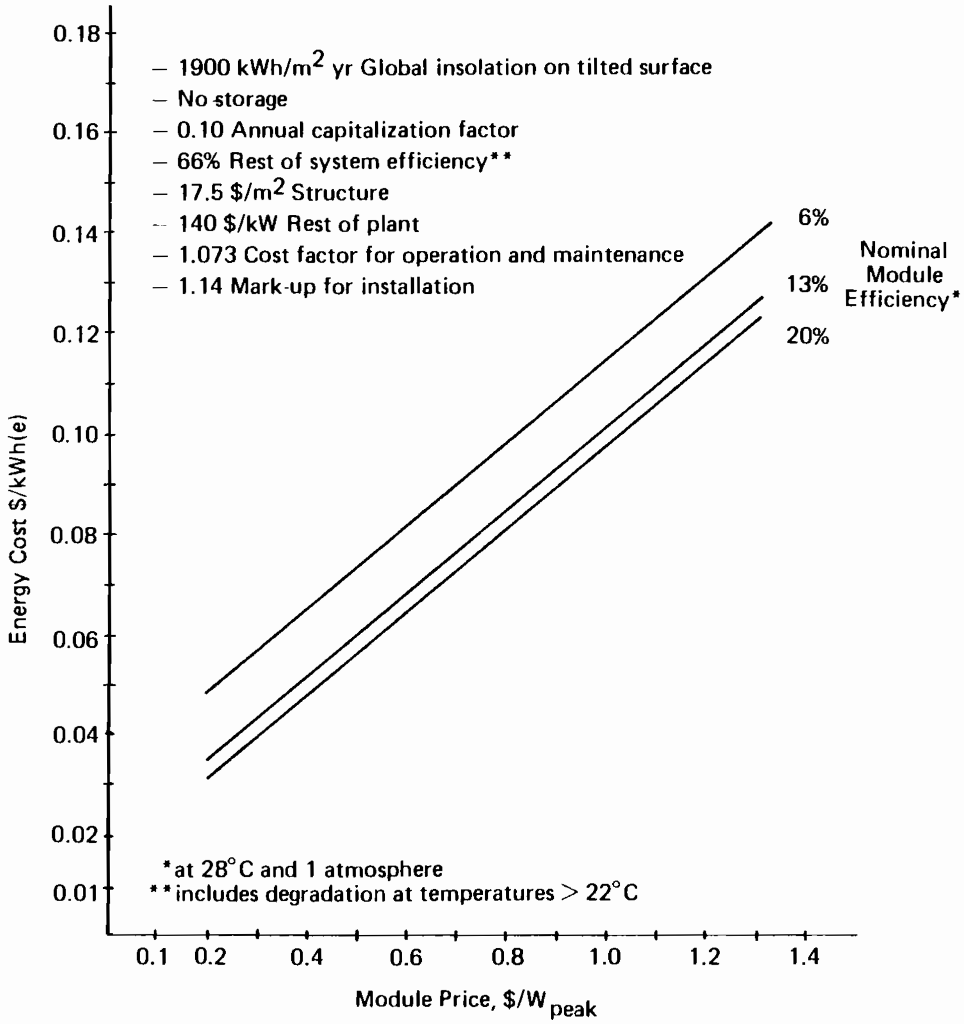
At the cost goal of $\$0.50/w_p$ and without storage, the estimated capital

Table 5-4. Characteristics of photovoltaic conversion units under intense concentrated illumination.

Material	*Concentration*	*Efficiency*	*Temperature (°C)*	*Cooling*	*Investigator*
GaAs/GaAlAs	500–1800	0.20	<50	Forced	Varian (1975)
Silicon	1500	0.25	15	Forced	Chappel and White (1977)
Silicon	50	0.10	100	Passive	Sandia (1976)
Silicon	300–500	0.10	<50	Passive	RCA (1976)
Silicon	300–1500	0.20	20	Forced	Schwartz (1976)

Source: Weingart (1978).

Figure 5-6. Photovoltaic electricity cost.



cost is about \$1500 per kW(e) at an annual capacity factor of 0.25 and at a global insolation level of 1900 kWh per m^2 per year, which is typical of sunny regions. The resulting electricity cost is \$0.073 per kWh, as shown in Figure 5-6. Of the two main parameters—dollars per w_p and module efficiency—it is the former that is the dominant cost driver. A factor of two reduction in dollars per w_p (1.0 to 0.5) at constant efficiency would reduce energy cost by 40 percent. However, a factor of two increase in module efficiency (6.5 to 13 percent) would reduce energy cost only by 18 percent.

Electricity, Hydrogen, and Solar Power

For both the case of STEC and that of photovoltaic solar power conversion there remains an inherent problem of matching supply characteristics with those of demand, both in space and time. To solve this problem, large-scale energy transportation and storage technologies are required. This is in contrast to the case for nuclear or coal sources, where the basic principle of the energy conversion process involves the liberation of binding energy, either chemical or nuclear.

The need for cheap storage and transportability leads to either liquids or a gas as a partner to the solar primary energy source. The most interesting candidate is probably hydrogen, and (as will be discussed more fully in Chapter 22) two principal direct routes to the generation of hydrogen are electrolysis and thermolysis.

Thermolysis, in particular, might be appropriate in combination with solar power, and estimated costs for a commercially mature system operating under ideal (desert) conditions suggest that this route might produce hydrogen for approximately \$50 per barrel of oil equivalent (Weingart 1978). These calculations are summarized in Table 5-5. Using available technology, a pipeline system could transport this hydrogen from Turkey to Oslo or

Table 5-5. A rough estimate of solar-hydrogen production costs.

Assumptions: High Insolation (~1000 W/m^2)	
Thermochemical Route to Hydrogen	
Capital Costs:	
Solar high temperature thermal[a]	1650 \$/kW(th) [σ(standard deviation) = 300 \$/kW(th)]
Hydrogen for thermolysis	600 \$/kW(th) [σ = 400 \$/kW(th)]
	2250 \$/kW(th) [$\sigma \geqslant$ 500 \$/kW(th)
At 100% effective load factor, a fixed charge rate of 10% thus corresponds to	44 \$/bbl oil equ. [$\sigma \geqslant$ 10 \$/bbl oil equ.]
Note: gasoline prices without taxes range from	20 to 40 \$/bbl oil equ.

[a] Cost estimates for production of high temperature heat (> 600°C) by solar central receiver systems of Jet Propulsion Laboratory (Selcuk 1975); McDonnell Douglas (1973, 1974); Martin Marietta (Blake, Walton, et al. 1975); Black and Veatch (1976); and Smith (1976).

from New Mexico to Maine for about \$2/MWh (Beghi et al. 1972; Weingart 1978); the hydrogen could be reliably stored for several years or more in aquifers, in depleted oil and gas fields, or in similar geological formations. At least as far as STEC-generated electricity is concerned, it will probably be far cheaper to produce solar fuels on the required scale in the sunny arid regions and to use transcontinental shipment by pipeline and global transport by tanker than to operate the plants in most of the regions now occupied by the industrially advanced countries.

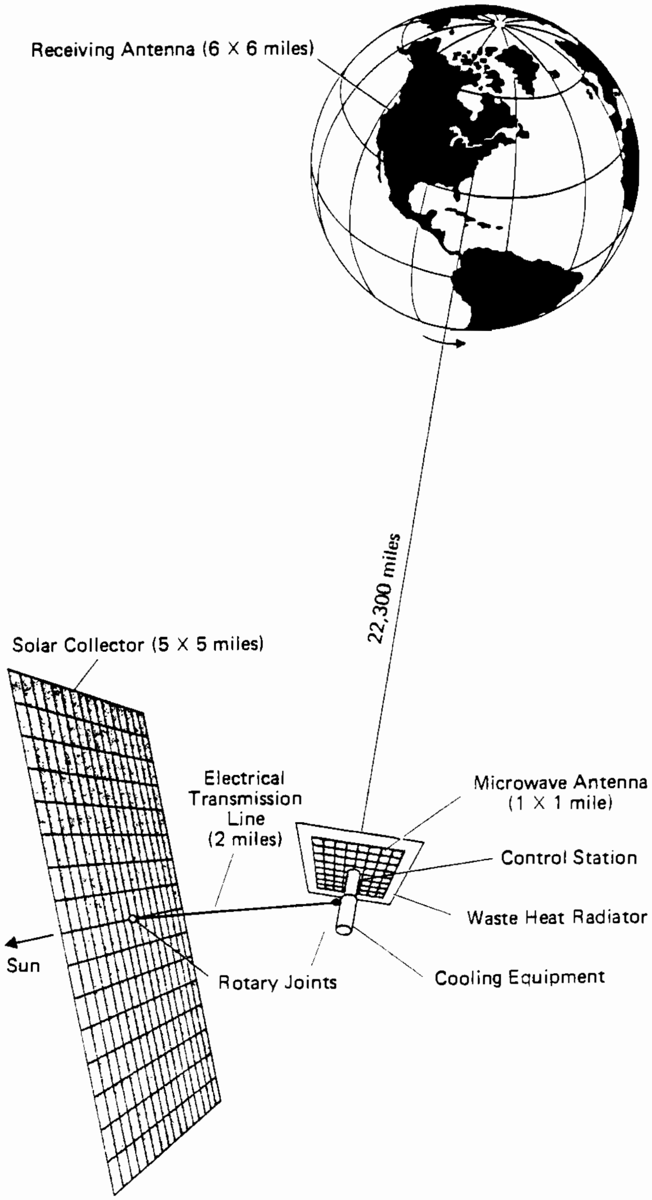
Biotechnology

Biotechnology refers to a very broad class of systems that have at their heart photosynthetic and biological energy conversion processes. For example, the development of high efficiency plants that are then cloned and raised for feedstock for fuels and chemicals would represent a new level of industrialization of biomass systems. Other biotechnologies, such as those under study by Calvin (1976a, 1976b) and Broda (1976), would combine biological processes into a mechanical matrix to convert sunlight and water into hydrogen and oxygen. Calvin points out that plants have long "known" how to use the energy of sunlight to split water, but do not evolve hydrogen explicitly since it is needed only for internal energetic processes within the plant itself for reduction of carbon dioxide. It may be possible to develop new biological structures that in fact do evolve hydrogen (Mitsui 1978; Yagi and Ochiai 1978), and at IIASA, Marchetti (1978) has considered the concept of hydrogen-producing trees. Again, as in the case of electricity production via STEC and photovoltaics, it may be that new, almost unexplored approaches to the production of fuels will be far more attractive, both economically and in terms of other impacts, than the cumbersome, purely mechanistic approaches such as the thermochemical hydrogen production route.

The Solar Satellite Power Station

Above we have argued that the features of solar power lend themselves to a natural linking with the features of hydrogen. Principally it was the necessity of energy storage and transportation that led to that linking. However, there seems to be one possible exception to this argument for combining solar power and hydrogen. This is the extraterrestrial solar power generation concept, provided primarily by Peter Glaser of Arthur D. Little, Inc. It considers a light weight solar satellite power station (SSPS) in a geostationary orbit in the neighborhood of the equator. The power station, at roughly 36,000 km above the earth, is nearly always exposed to direct and intense sunlight of 1353 W/m^2. The radiant energy would be collected by the solar cells and then transported to the earth by high frequency microwave beams that are able to reach receiving antennas on the earth even at great distances away from the equator. Figure 5-7 illustrates the SSPS scheme.

Figure 5-7. Solar satellite power station. Solar collector in stationary orbit has been proposed by Peter E. Glaser of Arthur D. Little Inc. Located 22,300 miles above the equator, the station would remain fixed with respect to a receiving station on the ground. A five by five mile panel would intercept about 8.5 X 10^7 kW of radiant solar power. Solar cells operating at an efficiency of about 18 percent would convert this into 1.5 X 10^7 kW of electric power, which would be converted into microwave radiation and beamed to the earth. There it would be reconverted into 10^7 net kW of electric power, or enough for New York City. The receiving antenna would cover about six times the area needed for a coal-burning power plant of the same capacity and about twenty times the area needed for a nuclear plant. *Source:* Summers (1971).



Sometimes one hears the argument that this scheme is too futuristic and, above all, inherently too capital intensive. While we appreciate the perspective of such an argument, we are not persuaded by it, for we are envisaging a time horizon of fifty years. And given the latest developments in space shuttle technology, it is no longer necessarily so that required advances in SSPS technology are more difficult to achieve than the widely expected breakthroughs in photovoltaics or biotechnology that we have alluded to above. One should also realize that the SSPS scheme has inherently a capital cost bonus. For terrestrial STEC there is a factor of approximately four between peak power plant rating and the baseload rating (where this factor incorporates assumed storage losses of 25 percent). Thus, the cost per baseload kW(e) is at least four times the cost per peak kW(e); including storage costs, as such, would increase the factor even further. For SSPS, the factor is one; the sun always shines in space.

Here we would like to discuss briefly three issues that are of a systems nature. We thus leave aside technical feasibility and costs associated with SSPS.

First, what are acceptable microwave radiation densities—that is, the lowest standards for continued exposure? There are wide differences in international standards—between 100 W/m^2 continuous exposure for the United States and 0.1 W/m^2 in the East European countries. Applying the lowest standards of 0.1 W/m^2 effectively includes situations where animals and human beings might pass through the SSPS-generated microwave beam. Once passage through the beam is prohibited, power densities of 800 W/m^2 at the center of the beam appear acceptable, while the lowest health standards of 0.1 W/m^2 would be met at the outer fringes of the antenna—about 10 km from the beam center. The antenna area requirements would then not be excessive. By contrast, the application of the 100 W/m^2 standard throughout the beam would imply a partial replication of industrialized areas (with energy consumption densities of 50 W/m^2) in terms of the related antenna area. In fact, 100 W/m^2 density would easily match the conditions of normal solar insolation in many areas.

The second issue is the possibility of hostile access to the high frequency beams or the accidental deviation of the beam from the center. Glaser maintains that the microwave beam directional system and the phase control achieved by means of a pilot signal from the center of the antenna preclude deviation and exposure beyond allowable standards. In the event of failure or of hostile manipulation of the microwave-pointing system, the coherence of the high frequency beams would be lost, and the beam would not be focused, resulting in beam spread and dissipation of energy. The power density would drop below 0.1 W/m^2, maintaining the inherent safety of the system.

The last issue has to do with possible discriminatory access to SSPS. This problem leads to the same institutional considerations as for nuclear energy. While it should not be underestimated, it should not be considered insurmountable over the long run.

Having reviewed the various hard solar technologies, we can move on to the question of what a global solar system might look like—that is, how the different technologies and different scales of application might all be interconnected. In addressing this question, we note that in view of the enormous areas required for solar conversion on the global scale and the high costs of such systems, we must deliberately, aggressively, and imaginatively search for solar systems that have low mass per unit area, high efficiencies, and very long lifetimes (centuries or millennia). For while sunlight may constitute an ultimate energy endowment, solar energy systems that must be replaced every three or four decades are no endowment at all. (The subject of endowments is discussed along with the concepts on negentropy and information in Chapter 21.)

ARCHITECTURE OF A GLOBAL SYSTEM

In order for sunlight to be a primary source of energy for civilization it will be necessary, through the use of energy storage and transport, to decouple this resource in space and in time from the patterns of energy demand. This will require integrated energy systems with a spectrum of sizes ranging from individual domestic solar water-heating systems to a global solar fuel network. A system or network of systems using sunlight to provide the necessary heat, electricity, and fuels for the world would ultimately be globally extensive and technologically complex and would display enormous regional variation in its character and evolution.

For example, Scandinavia might evolve an integrated system incorporating large quantities of biomass fuels from Sweden and Finland, wind-generated electricity and fuels from Denmark, and hydropower-generated electricity and fuels from Norway and Sweden. Energy requirements for water and space heating, which now constitute roughly half the total energy needs of the region, could be reduced through more effective energy conservation measures, passive solar design, and active solar heating (especially for hot water). Such a scheme would permit "small is beautiful" and "big is necessary" to merge harmoniously.

This global system would have the following features:

- Local use of solar-generated heat for space heating, water heating, and industrial process heat where economically and logistically suitable.
- Local and regional use of small-scale, solar-mechanical, electrical-, and fuel-generating units, especially in developing countries.
- Solar electric power plants of various sizes located throughout the world, primarily in sunny regions, interconnected through large integrated electric utility systems over distances of many thousands of kilometers.
- Solar fuel generation units primarily in sunny regions and interconnected globally via pipeline and, for a few locations (Japan), by tanker (cryogenic or liquid fuel).

Again we note that the more local uses of solar power are dealt with in Chapter 6, while in this chapter we deal rather with the hard aspect of solar power (which is what permits solar to potentially assume a significant share of the power supply). Merging these two aspects requires a sensitive fitting: small consumption shares of, say, low temperature heat should be provided by power sources designed principally for that purpose, while larger segments of demand—for instance, for an aluminum plant—must come from more centralized sources. Ultimately a careful systems-oriented integration has to be carried out, and this almost always requires that one examine specific cases—for example, Western Europe—in great detail.

While we have not developed such an analysis at IIASA, we anticipate that the degree to which a global solar system can be fine tuned (that is, the degree to which different supply sources can be ideally matched to appropriate kinds of demand) is limited. The problem is that the more perfectly matched sources and demands are, the less capability there is to substitute different sources in meeting a particular demand. It is just such a substitution capability that is the salient characteristic of existing interconnected grids. However, it remains to be seen from specific case studies how severe the limitation really is. Still, even without detailed case studies, it is possible to explore to some extent the characteristics and constraints associated with a global energy system, and that is our purpose in this section.

The scale of future energy use, even in the most modest strategy and using the most efficient of solar technologies, would require substantial land areas. However, despite pressures from increasing food demands, urbanization, the need for forests, and the maintenance of ecological diversity, the arid sunny wastelands of the globe will remain essentially unused and potentially available for large-scale use.[a] In the United States, Europe, and elsewhere, the land requirements per se may not be the crucial constraint. The case of Austria has been analyzed in detail at IIASA by Korzen (1979) as an indicative example of an industrialized, densely populated European country. Here we report a few findings of the Korzen study to demonstrate the kind of detail that must be considered when solar power is studied for practical application.

For large-scale introduction of solar energy use, wastelands and not the best agricultural areas should be used. In Austria, fallow land and marginal farm land present possibilities for solar utilization. Furthermore, fallow land can be found in the Austrian lowlands as well as in the Alpine regions. For example, industrialization, a changed social structure, and the loss of capital have led to the situation in the Austrian province of Burgenland where 70 km^2 can be counted as fallow land, not for agricultural reasons but for social ones. Small farmers, who owned only a couple of hectares and were not able to invest or buy additional land, have not been able to survive with the gains

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[a] The potentials and constraints in global land use and population densities are discussed in greater detail in Chapter 23.

from agriculture. Many have therefore emigrated to other countries or changed to industrial jobs.

In the Alpine regions of Austria, large meadows in altitudes between 1400 to 2000 m remain largely unaided by technology, and therefore many of them are unlikely to be used for agricultural purposes. The inclination of the slopes can be used as a parameter for estimating the present and future fallow land potential. The highest tilt of slopes on which agricultural activities can be expected is, for the Alpine areas, around 40 to 50 percent and for lowland agricultural areas around 25 percent. The Institute of Agricultural Economy in Austria estimated a fallow land potential of around 3000 km^2 in the Alpine region and 4000 km^2 in the lowlands. For solar energy use, only the south-oriented slopes in both cases are of interest. Calculations show that in the Alpine region, around 1700 km^2 of grassland (with a tilt of more than 40 percent), and in the lowlands around 2300 km^2 (with a tilt of more than 25 percent) are southwest- to southeast-oriented. These are the areas with potential for solar energy use.

The second largest wasteland potential lies in pieces of marginal farm land. For tax reasons, the quality of all agricultural areas in Austria is assessed in terms of the potential gain from each piece of land, given the local earth quality and climatic conditions. These data are listed on computer tape. If a limit for the low quality areas, the marginal farm land, is defined, the potential area for all of Austria, for each federal province, for each community, and so forth can be determined. The reference to each single piece of marginal farm land can also be obtained and verified on a map. In this way, more than 60 percent of the total agricultural area of Austria was evaluated, and from the results, the total marginal farm land potential of Austria was estimated to be 4700 km^2 However, the whole area cannot be used solely for solar energy applications. Many of these marginal farm land pieces are disperse and therefore may not be usable, particularly for a centralized solar conversion system such as STEC. Other marginal farm areas are either within the borders of wildlife areas or are on northern slopes. On the other hand, there are communities where the marginal farm land seems to be accumulated—for example, in areas where the average quality of the land is extremely low.

Both land potentials (fallow and marginal farm land) demonstrate that there is a considerable area that could potentially be made available in Austria for solar energy use. If all the anticipated constraints are included in the estimation, an overall usable land area of perhaps 2500 km^2 could be made available even in a densely populated country such as Austria. This corresponds to 3 percent of the total land area of Austria. This is not to say that it would be easy to utilize this whole area. Because of complex land ownership arrangements, this potential could be made available only with extensive social changes.

A comparable analysis done for the southwestern United States indicated that between 2 and 16 percent of the total land in an eight state area was available (Aerospace Corporation 1974). These states (California, New

Mexico, Arizona, western Texas, Nevada, Utah, Colorado, and Oklahoma) represent one-third of the total continental U.S. land area, and the range from 2 to 16 percent represents 0.05 to 0.40 × 10^6 km^2. The approach taken listed reasonable exclusion criteria, such as land with a tilt greater than 20 percent, land with any reasonable crop or grazing potential, and land owned by Indian tribes or used as a local, state, or federal park. Some more stringent criteria were also introduced that, for example, excluded all federal lands (which in one of these states amounted to half the land area).

On a global perspective, the waste, desert, and mountainous regions of the world exclusive of uninhabited islands and polar areas cover 62 × 10^6 km^2 (Doxiadis and Papaioannou 1974). Let us first assume that 20 × 10^6 km^2 of this land is worth considering as arid, sunny wasteland available for central solar systems. Then, in line with the percentages for Austria and the southwestern United States as arrived at above, let us take 5 percent of this number as an estimate of land with some potential for solar utilization. The result is 1 × 10^6 km^2. (Note that for an electricity generation density of 20 W/m^2, this corresponds to 20 TW.) A completely independent estimate (based on FAO 1969) of potential sunny wasteland excluding sandy regions and low use grazing land comes up with 4.3 × 10^6 km^2. If sunny and other nonwaste regions were included, the number could be ultimately as high as 10 × 10^6 km^2. The lesson to be learned from these sorts of calculations is that as long as only physical conditions and relations are reviewed, land availability is not likely to be an ultimately binding constraint on solar development. Let us then turn to storage and transportation.

The price of solar-derived energy would be (approximately) inversely proportional to the magnitude of the available insolation. For direct conversion technologies, this means that the least expensive secondary energy production would be in the sunniest regions. For centralized uses of those technologies (solar thermal electricity, solar thermochemical production of hydrogen), which respond only to direct beam sunlight, location in arid sunny regions would be essential.

It is expected that in the near future electricity can be transmitted several thousand kilometers with low losses via high voltage DC transmission, thus permitting the linking of geographically dispersed solar power plants within larger integrated electrical networks. This system integration of dispersed solar generating capacity can substantially increase the reliability of solar units relative to any one specific site. All of Europe is within such high voltage transmission distances of Portugal, Spain, and Turkey; also in the near future, undersea cables from North Africa could bring solar electricity to Europe. However, advances in central storage technologies, plus extensive load-leveling management practices (using dispersed storage), would be required before solar electricity could provide the bulk of base and intermediate load requirements. For now, only a few European countries (Austria, France, Italy, and Switzerland) have some seasonal hydrostorage, thus permitting the initial stages of a solar-electric partnership in the near future.

For our Austrian study, we have looked into this possibility in greater detail. Assuming a ground cover ratio of 0.5, a 30 percent efficiency, and the 2500 km^2 of available land as mentioned above results in 405 TWh/yr of potentially available secondary energy from solar power. For purposes of comparison, the secondary energy consumption in Austria in 1976 was 204 TWh/yr, out of which 33 TWh/yr were in the form of electricity. Figure 5-8 gives two-year insolation diagrams for two stations—namely, Sonnblick (in the Grossglockner area) and Salzburg. The average values are also indicated in the diagrams, and it turns out that for these cases, something like 15 percent of the solar power generated would have to be stored over roughly a six month period if electricity production is to be constant throughout the year. For Austria in general the value of 15 percent may be optimistic, and more realistically, we should consider a range from 15 to 30 percent. Applying such a range to 405 TWh/yr gives 61 to 122 TWh/yr, while applying it to 33 TWh/yr yields 5 to 10 TWh/yr. Comparing these numbers with the existing hydrostorage capacity of Austria and other countries as shown in Table 5-6, one sees that an undertaking on the order of the Bratsk-Ilimsk development project in Siberia is needed if we are to provide a storage capacity of only 30 TWh. Effectively this means that hydrostorage can be only an intermediate stage in the buildup of large-scale hard solar power. Eventually, it is chemical energy storage—specifically hydro-

Figure 5-8. Monthly direct solar insolation over a two-year period. *Source:* Based on Weyss (1977: Figure 12).

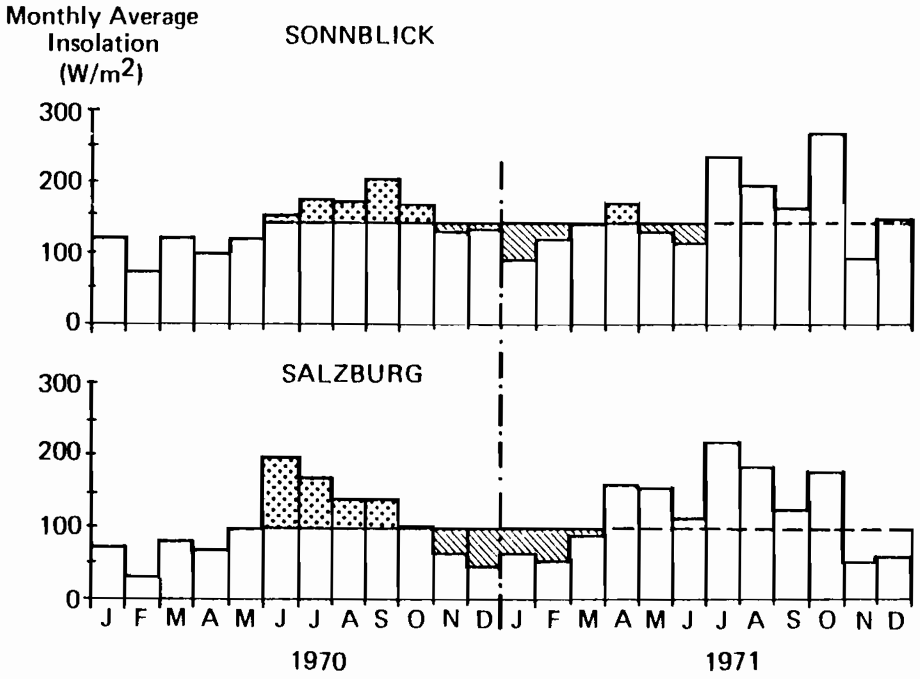


Table 5-6. A storage capacity in large electricity networks.

	Electricity Production	Storage Capacity (pumped hydro)	
Network	*(TWh)*	*(TWh)*	*(%)*
Electricité de France	180	12	6.7
Bratsk-Ilimsk, Siberia	135	30	22
Austria	34	2	6

gen—that must be introduced. Strategically that means that the development of the new technology of hard solar power is linked to the development of the new technology of hydrogen. In Chapter 22 we further elaborate on this line of argument; however, a few comments are in order here.

Large-scale generation of hydrogen and liquid fuels, long distance energy transport, and seasonal energy storage would permit the complete decoupling of the solar source and energy needs. Liquid fuels (e.g., methanol) could be produced by combining hydrogen with carbon from coal or directly from the atmosphere or ocean. Hydrogen could be transported over even continental distances of 5000 kilometers or more, with available or developable pipeline system technologies. With the exception of Japan, which must be served by liquid fuels via tanker, virtually the entire world is within practical hydrogen pipeline transport distances (5000 km) of large regions of arid, sunny land.

Thus, the ultimate potential contribution from the large-scale global use of hard solar power would seem to be substantial as far as land, storage, and transportation are concerned. We shall now go further and consider what other constraints there might be that would limit how far and how fast we can actually exploit that potential.

MARKET PENETRATION

The penetration rates of solar energy options will depend on the competitive situations of all energy sources, and uncertain cost estimates for most potentially significant solar options limit the procedures that can be used to determine the solar market penetration rates. In addition, there are strong reasons to believe that the present cost estimates will come down in the future—in some cases (e.g., photovoltaics), dramatically and fairly rapidly. Initially, during the developmental phases, external capital is used to support new technologies even if their direct costs are somewhat higher than the competition. However, after these achieve a market share of a few percent and commercial maturity, their penetration rates depend on their competitive situation: nonprofitable technologies are rarely supported for very long time periods. This will also be the case, we expect, with solar options once they achieve significant shares of the primary energy market.

Rather than attempting to estimate market penetration rates by developing cost projections, let us try another approach. In the past it has always required roughly one century for any of the various traditional primary energy forms to increase its share of the world primary energy supply from 1 to 50 percent. While an understanding of the time required for new energy systems to make major contributions to energy supply is crucial to any realistic assessment of the potential role of solar or nuclear energy, whether in a single country or worldwide, the present projections of future U.S. energy demand and the possible contributions from solar energy display enormous dispersion. This is illustrated in Figure 5-9.

Consider now the market penetration dynamics in the world as given in Figure 5-10. We see that historical penetration rates were rather slow and fairly regular for all primary energy sources and that, therefore, one should be wary of those who would argue that either the nuclear or the solar option can proceed much faster; there are no historical precedents on the world level to justify that. More historical examples of market penetration are

Figure 5-9. Scenarios and projections of total energy demand and the share potentially available from solar energy, United States. Curves marked by underlined numbers describe projections of total energy demand; those marked by numbers not underlined are projections of that share of total energy demand that is potentially available from solar energy. *Sources:* (1) The MITRE Corporation (1973); (2) Morrow (1973) "maximum solar"; (3) Morrow (1973) "minimum solar"; (4) Wolf (1974); (5) Lovins (1976); (6, 7, 8) Reuyl et al. (1976); (9) ERDA (1975); and NAS (1977); (10) Weingart and Nakicenovic (1980); (11) BNL (1975) "future ref. energy system."

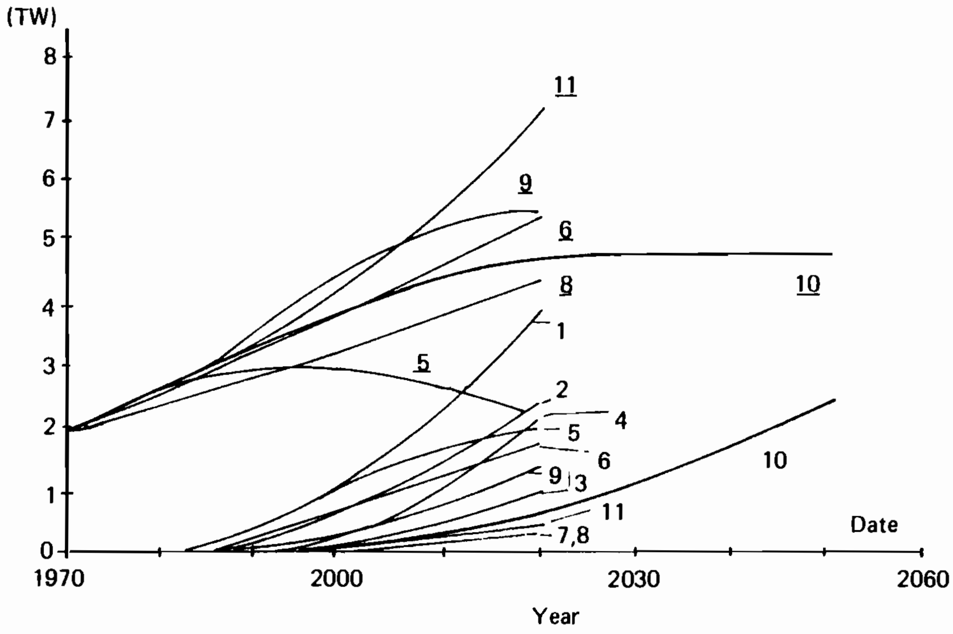
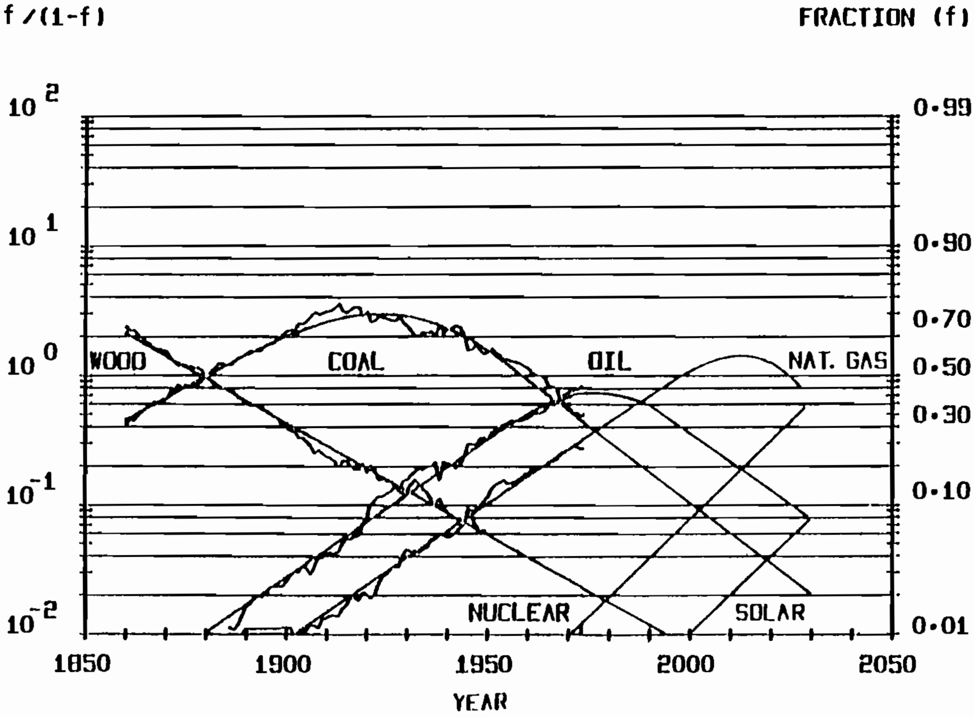


Figure 5-10. World primary energy substitution, 1860-2030. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show logistic model substitution paths.



given in Chapter 8, but the general conclusion is that only in smaller world regions and countries are more rapid penetration rates possible. The market penetration dynamics in Figure 5-10 are extended beyond the historical period, to the year 2030. For the purposes of Figure 5-10, while keeping in mind all the precautions explained in greater detail in Chapter 8, we have simply estimated a penetration rate for solar energy that is consistent with those of other energy sources in the past.

Thus, we can get an impression of what the potential rate of penetration might be in the situation in which solar thermal, electric, and fuel technologies are directly competitive with other secondary energy sources and acceptable in social, environmental, and political terms. For example, assuming a 1 percent market share for solar in 2000 leads to a market share of 6 percent by the year 2030. Exogenous to the market penetration technique is the absolute level of the total primary energy use. Taking a figure of 36 TWyr/yr in 2030 leads to 2.2 TWyr/yr of solar energy production. Alternatively, if we select 22 TWyr/yr in 2030, 1.3 TWyr/yr of solar energy results.

Many people have argued that with adequate government incentives, the rate of market penetration of solar technologies can be far greater than that suggested by the application of the historical penetration rates of other energy sources. But what is the role and effect of government incentives? First, proper incentives, including adequate support for research and development, can substantially compress the time required to bring a technology to commercial readiness. Second, the initial stages of commercialization can be shortened through such incentives. This is not in dissonance with the observation that the market penetration dynamics of various energy forms can exhibit rather steep slopes when the total fractional penetration is a few percent or less. However, once penetration has reached several percent, the dynamics of the system take over. Government support can no longer sustain extremely rapid growth; market and system effects become dominant; and the penetration behavior becomes smooth and regular. We might say that below a few percent, the government can speak. Above a few percent, the system speaks.

So the bad news from this analysis is that it could take the better part of a century to make the transition to abundant energy forms; the good news is that in less than a century we can make the transition. Thus, seen from a rather long-term perspective, solar power has a potentially promising future. The salient question, then, is whether existing energy sources can bridge the time gap, and it is this question that is at the center of the quantitative energy strategy analysis of Part IV of this book. Fortunately, the answer is, It could be done.

MATERIAL REQUIREMENTS

The construction, operation, and decommissioning of solar facilities used at the multiterawatt level will probably result in substantial material requirements as shown in Table 5-7. Some feeling for these requirements can be obtained from considering, first, that all solar energy systems must be extensive in order to convert the incident radiation to other forms of energy. And, second, because these systems must operate in a variety of natural environments, they must also have sufficient structural stability to insure operation and survival under occasional extreme conditions as well as under continuous "routine" environmental conditions. This requirement translates into a mass density per unit area. The minimum density of a system that can withstand the weather for decades is likely to be at least 10 kg/m^2. This might be a tough, thin film, photovoltaic system interconnected and supported by lightweight space frame techniques. If placed on a roof with minimum framing, the material density would be closer to 5 kg/m^2.

Present U.S. prototype (McDonnell Douglas, 1977; Martin Marietta 1977; Honeywell 1977) heliostats for STEC plants weigh about 50 kg/m^2, considering the steel but excluding glass and concrete. The concrete and sand are considered to add about 155 kg/m^2 to the heliostat weight. The rest of the plant adds about 165 kg/m^2 of concrete and 10 kg/m^2 of steel.

Table 5-7. Annual material requirements for 1 TWyr/yr.

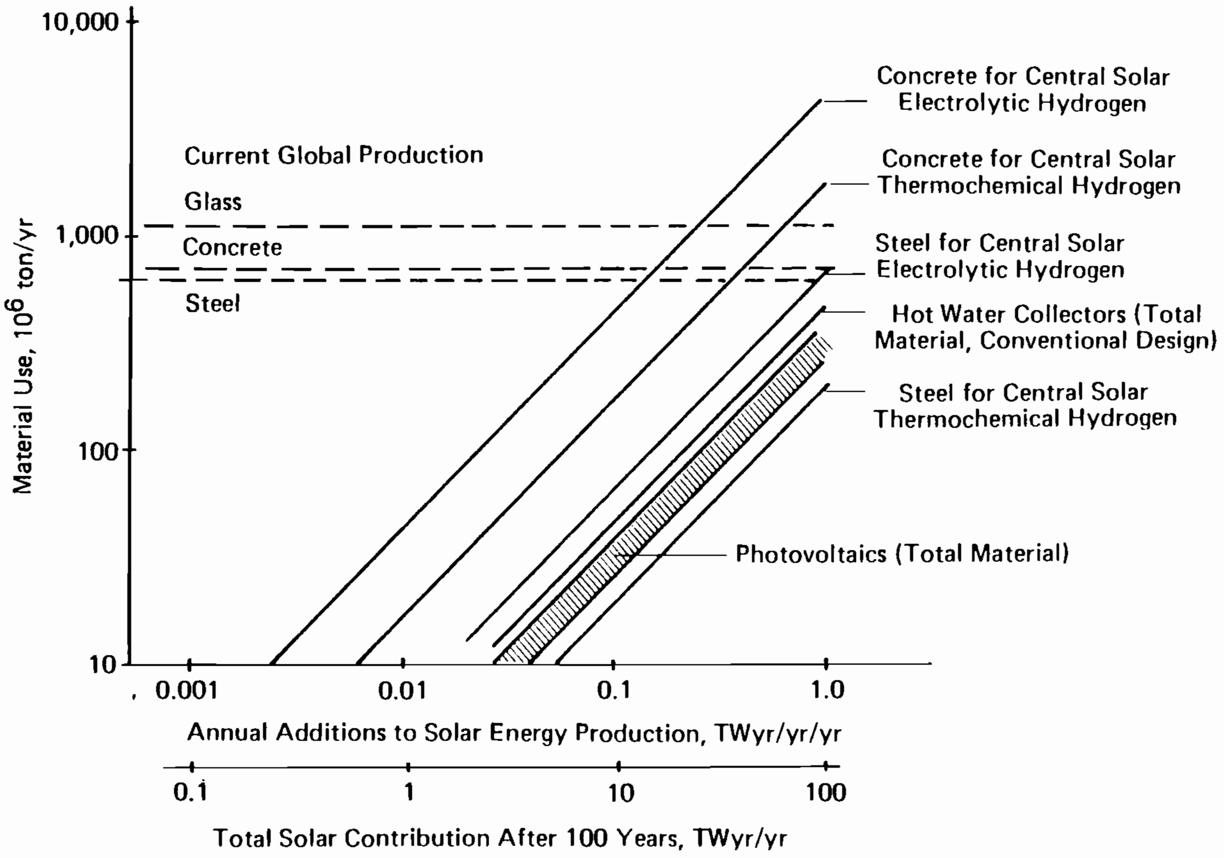
	Mirror Area $\frac{10^6\ km^2}{TWyr/yr}$[a]	Net Material Density kg/m^2	Material Required $\frac{10^6\ Ton/yr}{TWyr/yr/yr}$[b]
Central Solar Thermal[c]			
Steel material in heliostats			
electrolysis	0.0129	50[d]	645
thermochemical	0.0048	30[e]	144
Total material			
electrolysis	0.0129	390[f]	5030
thermochemical	0.0048	390[f]	1870
Photovoltaic			
central[g]	0.035	10	350
roof top[h]	0.0538	5	269

[a] Mirror area per TWyr/yr primary equivalent based on 25 percent end use electricity, 25 percent transportation liquids, and 50 percent heat.
[b] Material per TWyr/yr in metric tons.
[c] 2750 kWh/m^2yr direct beam insolation.
[d] Average of U.S. prototype heliostats using glass.
[e] Novel design using stretched aluminized mylar.
[f] Central receiver plant includes concrete (83 percent), steel (14 percent), glass (3 percent).
[g] 2000 kWh/m^2yr global insolation.
[h] 1200 kWh/m^2yr global insolation.

The steel and glass in some European prototype designs—for example, that of Soterm and Cethel (Saumon 1977), weigh about 80 kg/m^2. Some unique heliostat designs (Boeing 1977) have achieved 30 kg/m^2 for steel and glass even at the prototype stage, but with just as high a concrete requirement. A more recent design by General Electric (1978) keeps the low steel and glass requirement ($\sim 30\ kg/m^2$), but substantially substitutes rock for the concrete. Although the mass is similar, rock has a reduced environmental impact per ton.

Figure 5-11 shows these data as a function of, first, the annual increase in solar energy production and, second, the total solar contribution after one-hundred years. To reach a total solar contribution of 35 TWyr/yr after one-hundred years would then require increasing solar energy production at the rate of 0.35 TWyr/yr per year, and this requires almost 640×10^6 ton/yr for the solar thermochemical hydrogen system ($\sim 65 \times 10^6$ ton/yr of steel, $\sim 20 \times 10^6$ ton/yr of glass, and the rest concrete). As a rough measure of what this represents, 1975 annual global production of concrete was 700×10^6 ton/yr, steel was 630×10^6 ton/yr, and glass was 1070×10^6 ton/yr. The 1975 global production of concrete was therefore similar to what would be required to increase solar energy production by 0.35 TWyr/yr each year; 1975 steel production was approximately ten times more than what would be required, while 1975 glass production was more than fifty times more. As is clear from Table 5-7, the reduced material requirements

Figure 5-11. Material requirements for central solar systems.



for photovoltaics make them relatively more attractive, especially if rooftop (or south-facing wall) systems are used.

However, the material requirements presented here should more properly be compared to the global materials use projected in the future. In the High scenario described in Part IV of this book, the steel production in 2030 is projected to be four times today's, while concrete production is five and a half times today's. The projected use of concrete for solar construction is therefore about 14 percent of 2030 production.

Thus, only concrete requirements would exceed 5 percent of projected production by 2030 for the assumed case, and that would occur only if central solar systems are considered to provide 0.35 TWyr/yr of new energy production each year. This is a conservative estimate in that this type of central solar system is concrete intensive. If distributed collectors without central towers are used instead of central receiver solar systems, then half the concrete and about 10 percent of the steel is not required.

The relative amount of construction material required for solar thermal electricity is obviously many times that required for a coal or nuclear power plant. For steel, the ratio of material for a solar compared to a coal energy system is about 12:1, while it is about 17:1 for a nuclear energy system (light water reactor). For concrete, a solar plant requires about sixty times that of a nuclear energy system. The basis for comparison is per unit electric energy generated over the plant lifetime of thirty years (Caputo 1977). In Chapter 9, which deals with the WELMM aspects, such comparisons are elaborated in greater detail.

The construction and maintenance of a solar system of global scale would thus require large amounts of materials, unless material-efficient designs are achieved. In order for sunlight to be translated into a globally interesting energy option, we must develop systems that are inherently low in mass or of extremely long lifetime or that allow a high use of recycled materials. This suggests that technological breakthroughs that permit low mass, high environmental resistance, and long lifetime are not just desirable, but ultimately essential, even if we consider only the plant replacement rate beyond the initial buildup period.

We should note that these observations on material requirements for the installation of solar power in the TW range are fully consistent with the notion of consumptive and investive uses of resources as developed in Chapters 4, 21, and 25. Indeed solar "fuel" is free, but it requires large-scale investments of materials—that is, resources—to have that solar "fuel" collected and transformed into a viable secondary energy carrier, be it electricity or hydrogen. These investments of resources then continually pay off by providing such secondary energy. What has to be considered, then, is the size of the investment, the rate of depreciation, and the rate of providing secondary energy. The investive use of resources has to be compared with consumptive uses such as a level of mining fossil resources that would be comparable to the yearly depreciation associated with the investive uses of resources. In fact, Figure 5-11 was conceived and should be read with such a comparison in mind.

ENVIRONMENTAL AND CLIMATIC IMPACTS

The potential consequences, both environmental and climatic, of deploying a global solar energy system are of special concern. From experience in the field of fission power, we know that in the beginning of the technological development period, the large-scale aspects of a technology are often not thoroughly examined (or even perceived). Only when large-scale activity commences do such considerations become visible and important. From hindsight we realize that the development of a strong, systems-oriented technology assessment of the fission option, including social valuing integrated with the political process, probably would have made a substantial contribution to the recognition and resolution of problems that are now inhibiting the use of such technologies.

While solar energy conversion systems are relatively benign, they will be no exception to the rule that the large-scale use of any new technology bears unexpected and often undesired consequences. Although there appears to be a popular mythology that the use of sunlight is completely "clean," this mythology will fall when the large-scale operations associated with solar power are fully appreciated. Of principal concern are the environmental impacts that are connected with the provision of the large amount of materials discussed above.

Davidson and Grether (1977) have shown that on the average, the additional effluents will be negligible even for a bullish solar economy in the United States when compared with the total impact of all activities in the economy. Still, steelmaking and the like are highly local activities, where the burden of pollution is felt directly. The air of Gary, Indiana, may be fouler because STEC plants keep the air clear in New Mexico. Solar fuels may warm houses in northern France at the expense of widespread disruption of desert ecosystems in Spain. Another study estimates the life cycle health effects of a central solar electric baseload power plant to be two orders of magnitude lower than those for "clean" coal electricity—that is, coal mining with U.S. 1969 dust standards enforced and 99^+ percent of sulfur removal prior to combustion (Caputo 1977). This estimate includes fuel acquisition and operation as well as the indirect activities involved in plant construction and acquiring construction materials.

A second principal concern is with conceivable impacts on the climate, for possibilities of climatic modification arise when we consider covering upwards of a million square kilometers of sunny land with solar conversion machines (Williams, Krömer and Weingart 1977). An anomaly in one part of the total climate system, which is highly complex and nonlinear, may be expected to trigger a series of changes in other variables, depending on the type, location, and magnitude of the initial anomaly. When considering the impact of large-scale deployment of solar-thermal electricity generation on climate, we are concerned with anomalies introduced in the interaction between the land surface and the atmosphere. The physical characteristics of heliostat arrays can influence several climatic boundary conditions, in particular the albedo, surface roughness, and hydrological characteristics of the land surface (Jäger, Chebotarev, and Williams 1978). However, since there is no direct observational evidence of such anomalies, discussion must be based on observations of analogous situations in the climate system or upon the results of numerical models of climate. At this point we will not report on energy and climate, which is done in Chapter 10, but rather simply refer to that chapter, where we study these problems more fully.

CONCLUSIONS

First, it is clear that when one considers possible, sustainable global energy systems, a menu of solar energy technologies has its place alongside nuclear breeder reactors. Both sorts of systems provide essentially inexhaustible long-term energy sources for mankind.

Second, we have made a distinction between soft and hard solar power, where the former refers to mostly local and indirect uses of solar power and has a limited potential of a few TWyr/yr (see also Chapter 6), while the latter refers to direct and mostly centralized uses of solar power having a practically unlimited capacity potential. It is expected that future energy systems will be made up of a mixture of both types of solar power uses.

Third, a global solar option would exhibit enormous heterogeneity, reflecting the great variations among different regions in terms of physical resources and climate.

Fourth, for large-scale solar power, land availability is not expected to be a binding constraint in the end.

Fifth, for the application of solar power on a large scale, material requirements (e.g., steel and concrete) will be unusually large and may prove a serious constraint.

Sixth, large-scale storage capacity will probably turn out to be the key requirement for significant, continuous, and reliable uses of solar power. Hydrostorage may be an early, but intermediate solution. Eventually chemical storage, such as hydrogen, will be needed.

Seventh, for solar energy to take over a significant market share of the world's primary energy demand will probably require, on average, a few decades. Not more than a few TWyr/yr should be expected before 2030. Thereafter, solar energy could make a significant contribution.

Eighth, high capital costs appear as a more immediate obstacle to the early introduction of solar energy. However, there is room to expect technological breakthroughs that could improve the capital cost situation significantly.

Ninth, although the environmental consequences of such large-scale use of sunlight will not be entirely benign (since, for example, they include the health effects of material-intensive industries), they appear manageable and lower than those of conventional fossil systems.

Tenth, the emergence of a global solar energy system could perhaps bring with it an unprecedented international interdependence and cooperation and a substantial potential for development and growth in many poor but sun-rich regions.

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6 RENEWABLE ENERGY SOURCES

HISTORICAL OVERVIEW

Since their origin, homo sapiens have met their energy needs from renewable energy sources. Fuelwood, and later the sail and the windmill, in use for millennia now, are prominent examples. These represent a group of energy technologies that obey the principle of collecting and exploiting what nature would "waste" in any case. The step away from the age-old principle of "collection" to that of "production" of energy from finite resources was taken only with the first industrial revolution, basically in the nineteenth century. This step is not complete yet, nor does it indicate that the principle of collection is out of date.

Before we focus on the potential of renewable energy sources, it is helpful to reflect briefly on the situation at the time modern energy systems came into being. Coal was then the dominant energy source. The key to understanding this process lies in the densities of energy demand and supply. This subject is discussed in detail in Chapter 23; here, we consider it only briefly.

Population densities in the past were limited by the amount of food that could be produced on a given area of land (Marchetti 1979). Wood, the main source of heat in nonindustrial societies, was (and still is) abundant in areas where a stable population deploys a nonintensive type of agriculture. There is always more indigestible hydrocarbon substance in the structural body of plants than digestible human food. Although solid trunks were preferred, farm wastes and bushes growing on fallow land provided a source of energy if forests were not abundant. Thus, for millennia the cultivation of food did not force the population to enter a parallel enterprise of cultivating energy. Harvesting natural forests was sufficient in most areas to maintain a renewable energy source.

Many times in recorded history, however, the technique of civilization brought into being large population centers, such as ancient Rome and Babylon. The densities of habitation outstripped the local capabilities to renew forests. The response of going farther afield for wood and converting it to charcoal for greater ease of transport and end use was also invented many times and is the prototype of fuel conversion technology. But inevitably, the forests became depleted over an increasing radius, and "fuelwood crises" developed—unless they were averted by population destructions brought about by war or pestilence.

In the early nineteenth century in Europe, two developments coincided that dramatically raised both the demand for energy and the density of that demand. Improved agricultural techniques solved the pressing food problems, and local populations grew. Mechanical devices were invented, and early industrialization boosted the process of urban concentration. This concentration called for technical responses as soon as villages became towns—that is, when urban agglomerations containing tens of thousands of people become common. Fuelwood in the developing areas of Europe became scarce and expensive within a few decades; in addition, water to run mills was in short supply in some places. The fixed productivity of local forests forced exploitation of forests far away from areas of demand. Transport difficulties arose: only wood of a certain minimum quality, or charcoal, could be transported (usually using rafts of limited payload). Thus, many parts of Europe had fuelwood crises in the second half of the nineteenth century. These crises were solved by the large-scale development of coal, coupled with the buildup of railway systems.

The key problem was energy demand density, which overtaxed local renewable resources and forced the development of both conversion processes and transportation systems. Along with the alleviation (for a period) of the nineteenth century energy crisis, these developments also paced the formation of today's advanced society, with its characteristic features of interdependence, specialization, and conurbation. Importantly, they also foreshadowed the increasing share of energy needed to run "the system," for both conversion and transportation are energy intensive.

Technology has made tremendous progress since then. We are in a much better position than our great-grandfathers to convert and transport energy effectively. But the central problem of renewable energy sources remains—the low energy supply density. Along with this is the need for land and the potential environmental interference that could occur (as the fuelwood crisis now being experienced in many less-developed regions testifies). Low energy densities also mean large demands on labor and harvesting devices for the initial step of energy collection: technologies without such a step have an important economic advantage.

As the discussion of the problems of fuelwood has illustrated, the prospects of renewable energy sources are determined by three essential conditions—availability of land, environmental acceptability of the diversion of power from a particular subsystem of the natural environment, and economic viability with respect to other energy supply systems. These conditions must be fulfilled simultaneously. The potential of renewable energy sources is not proportional to any one of the above factors independently. The most favored applications today—solar heated homes, waterpumps driven by a windmill, or biogas plants for farms or villages—represent cases where the relevant factors coincide—the right energy form at the right place, available roughly at the right time.

There are numerous opportunities for renewable energy sources to be deployed successfully. The major question is not whether these exist, but how much they can contribute, relative to the demands of society.

ENERGY FLOWS IN THE ENVIRONMENT

We consider first the global aspects of renewable energy sources. The numerous devices falling into this family of energy technologies have one universal feature: they divert some of the natural energy flows present in the environment to serve a useful purpose.

Before we address specific technologies, a brief survey of natural energy flows is in order. Following a concept developed by Hubbert (1971), Figure 6-1 lists the mean annual throughput of energy—that is, the average power flows through the atmosphere, the hydrosphere, the bedrock of the earth's surface, and the biosphere.

The environment receives energy from three independent primary sources —sunlight, geothermal energy, and planetary motion in the solar system. The dominating inflow of power is the sunlight arriving at the upper layers of the atmosphere. The extraterrestrial power density is 1.35 kW/m^2 perpendicular to the direction of the sun. The total energy flow of sunlight intersected by the earth is 178,000 TWyr/yr.[a] Part of the solar radiation is scattered on its way through the atmosphere, and part is absorbed. On clear days up to 80 percent of the initial intensity is measured in places like the Sahara and the southwest United States. In midlatitudes, the power densities measured on a horizontal area reach a maximum of 35 to 45 percent of the extraterrestrial value. The yearly averages calculated on a twenty-four-hour day are 250 W/m^2[b] in central areas of the Sahara with up to 4000 h of sunshine per year and about 100 W/m^2 in Central Europe with 1500 h of direct insolation. The area densities referred to here are per unit of horizontal area. Mirrors that can be oriented so that they always face the sun (heliostats) can see larger energy densities per unit mirror area—up to 350 W/m^2.

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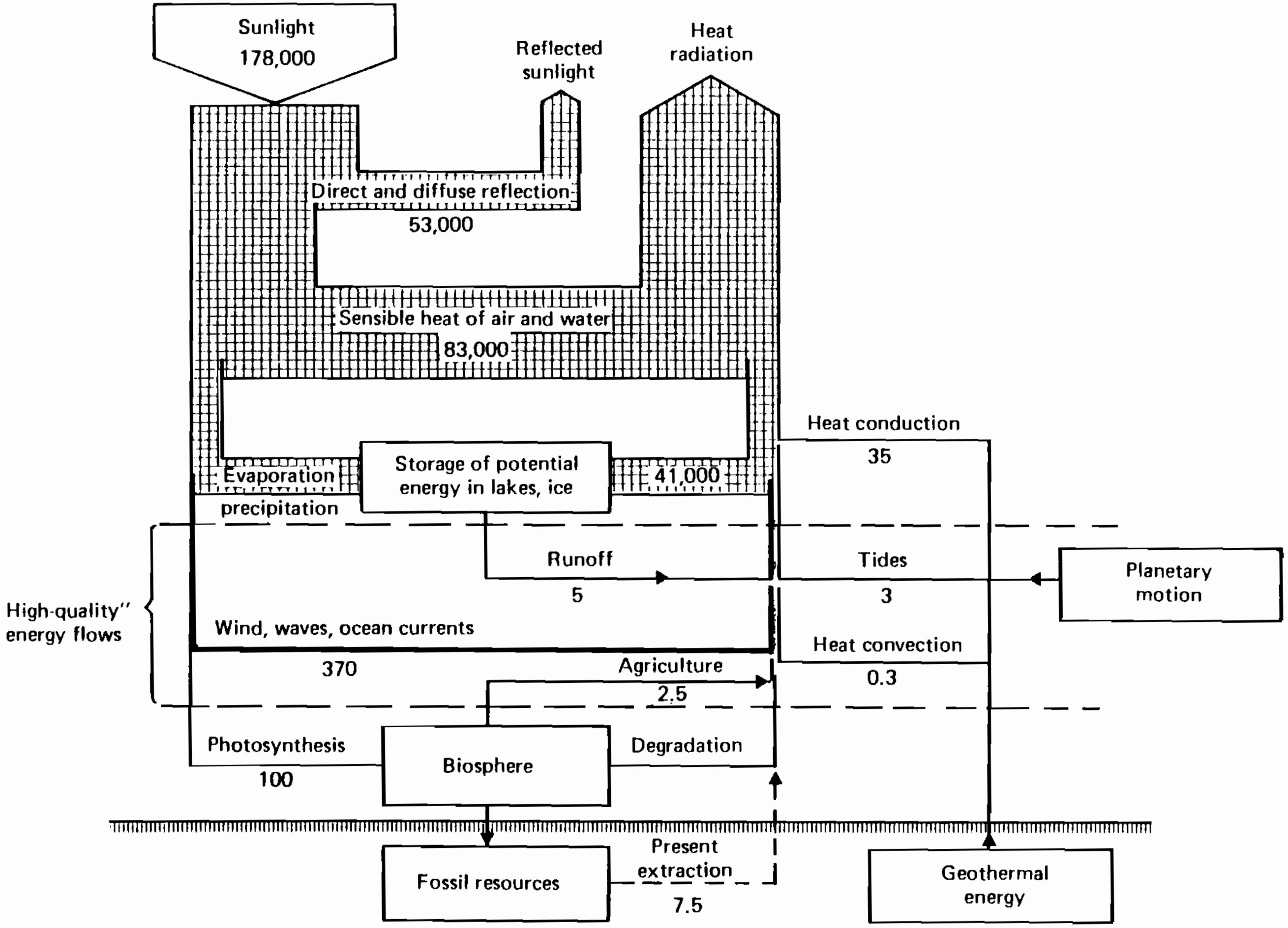
[a] Throughout this book energy flows are given in TWyr/yr, although in the literature they are usually given in units of power (i.e., TW).

[b] Throughout this book energy flow densities are given as power densities.

Figure 6-1. Energy flows through the environment (power levels in TWyr/yr). In many of the numerical presentations extra significant figures beyond what is significantly valid are listed. This is done to make arithmetic identities valid. In many cases the numbers are appropriately rounded off in the text.



About 30 percent of the incoming radiation leaves the earth directly after reflection at the cloud, the dust particle, and the surface levels; about 70 percent is absorbed. Of the amount absorbed, approximately 83,000 TWyr/yr are found as sensible heat of air and water and 41,000 TWyr/yr as latent heat from the evaporation of water from the oceans and the wetland surface. This latent heat in the atmosphere is eventually released upon condensation. The absorbed solar energy leaves the earth finally in the form of infrared (heat) radiation.

The natural power flows generated by sunlight and the two other sources in man's "direct" environment (i.e., the thin boundary layers between the atmosphere, land, and the oceans) are much smaller than the direct energy transfer from sunlight. The continental runoff dissipates potential energy into heat via friction at a rate of only 5 TWyr/yr. Winds, waves, and the kinetic energy of ocean currents dissipate roughly 370 TWyr/yr, the majority being contributed by wind at high altitudes. The net conversion rate of solar energy to biomass is of the order of 100 TWyr/yr (Bolin 1979; Woodwell et al. 1978). (For comparison, sylviculture and agriculture currently draw a net power flow of some 2.5 TWyr/yr from this subsystem.)

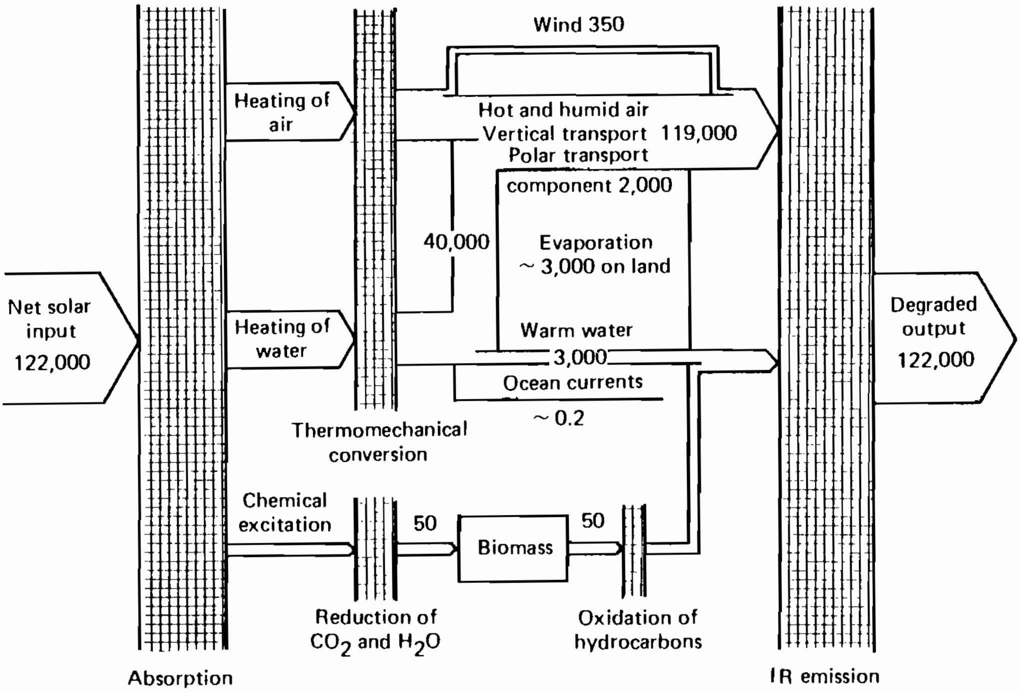
The second primary source of energy, geothermal energy, feeds a comparatively small power flow to the accessible environment. By means of heat conduction, 35 TWyr/yr enter the atmosphere and the oceans from the bedrock of the earth. Only 1 percent of this amount comes by way of volcanoes or active geothermal fields through convection mechanisms, giving rise to significant temperature differences above the ambient conditions.

The third primary source, causing a still lower power flow, is planetary motion in the solar system. Approximately 3 TWyr/yr are dissipated through tidal movements in the oceans.

Within man's direct environment, only a few natural power flows are both large and valuable enough to be suitable for exploitation at a significant level, using global primary energy consumption of roughly 10 TWyr/yr as a reference value. The most important flow is solar irradiation absorbed at the land surface: this amounts to 25,000 TWyr/yr. The available natural transformed "secondary" power flows—wind at accessible heights over the continents, formation and degradation of biomass, continental runoff, and wet geothermal sources—add up to about 150 TWyr/yr. If one includes the ocean surface as an environment accessible to man for harvesting, this figure would roughly triple. However, these natural power flows in the atmospheric, biologic, and hydrologic system cannot be diverted beyond a certain point without causing major environmental changes. The underlying feedback mechanisms leading to potentially detrimental instabilities are a result of the thermodynamic principles governing the various energy conversion steps in the environment. To illustrate this, we rearranged the energy balance given in Figure 6-1.

Figure 6-2 allocates the dominant natural power flows through the environment in relation to the main natural energy conversion processes. The data are rough estimates and are averaged over a multitude of interlinked subphenomena (see, e.g., Vonder Haar and Oort 1973; Bolin 1979).

Figure 6-2. Major thermodynamic processes of the global environment (power levels in TWyr/yr).



The absorption of sunlight at ambient temperature is the most significant natural conversion step in the environment. The thermodynamic quality of sunlight would theoretically allow for a conversion into mechanical, electrical, or chemical energy, with an efficiency of more than 90 percent. It is for this reason that we considered the direct use of sunlight separately in Chapter 5. This capability is almost quantitatively lost in the absorption stage, however. Water and air, upon incremental heating, change their specific gravity. In the gravity field of the rotating globe, this gives rise to slow vertical and horizontal movements of both air and water. The atmosphere and the hydrosphere act like coupled thermodynamic machines, operating between the small temperature differences of the air-water and the air-land interface and the upper layers of the troposphere and, in part, of the stratosphere. Air and ocean water function simultaneously as working media and as inert "pistons," producing their own mechanical motion, which leads to convective heat transport. The most sensitive coupling between different types of energy flows is to be found in the oceans.

The ratio between the mechanical energy of the warm ocean currents and the heat they carry poleward is of the order of 1:10,000. The total kinetic energy of the ocean currents is about 0.2 TWyr/yr, and any significant harvesting of it would block a much larger heat flow and create a major climatological problem.

The kinetic energy produced and dissipated in the atmosphere is much larger than that in the oceans. Most of the energy is caused by the vertical turbulent motions in the cloud systems. Per unit of mechanical power, air transports thirty to forty units of sensible and latent heat. The large-scale wind fields transporting hot and humid air poleward and cold and dry air toward the equator have an average mechanical power of the order of 350 TWyr/yr. The net heat carried poleward averaged over the year is roughly 8000 TWyr/yr. Because of this ratio—about 1:25—an interface with the wind pattern is not so dramatic as in the case of the ocean currents.

We find an analogous situation in the biosystems. A few percent of the sunlight absorbed by plants is converted via the photosynthetic process into chemical energy of hydrocarbons; the rest is transformed into heat at ambient temperature. The changes in the physical power flows caused by the present agricultural practice, which produces 2.5 TWyr/yr of useful products, not counting the energetic values of farm and forestry residues, are of the order of 25 to 100 TWyr/yr. These changes are mainly because of changes in the albedo and the evaporation rates, which in turn are caused by the change in the physical characteristics of the ground cover. The ratio—between 10:1 and 40:1—relating change in the power flow through the system to the power flow of useful products withdrawn, is of the same order of magnitude as the ratio for wind.

Figure 6-2 illustrates that the appropriate reference figures against that one has to compare man's energy needs are the "high quality" power flows—that is, mechanical energy and chemical energy, rather than the heat flows, occurring at ambient temperature. Except for the direct use of solar energy, only wind provides a comfortably large figure (350 TWyr/yr) and not too large a catalytic effect on nature's machine if it were to be harvested. However, most of the wind is not accessible for man. The most favorable wind fields are in high altitudes and over the oceans. Up to a height of 200 m above ground, where technical plants can be built, wind dissipates a few tens of terawatts through friction mechanisms with the land (see, e.g., Corby 1969).

This observation leads to the question of what fraction of various natural power flows is really accessible. A corollary question, then, is how much of what is accessible can be harvested without disturbing the natural system too much. A third question is how much of that is likely to be technically and economically producible. In the following sections we examine the various potentials of these energy sources.

THE TECHNICAL POTENTIAL OF RENEWABLE ENERGY SOURCES

Renewable energy technologies interlink with natural power flows through the environment and man's specific energy needs, which are tied to his general activities in space and time. For the consumer, an ideal source of power would have the following characteristics—high power density, continuous availability, and delivery as an energy form that can be converted easily into all forms as useful energy with minimum losses. To the extent that these characteristics are not satisfied, there is a corresponding restriction on the application of a technology. For example, a discontinuously available source that does not produce a storable product can be used only for an intermittent application.

In industrially advanced societies, a high degree of interconnection of energy sources and a variety of options available for many types of application soften some of these restrictions. For example, an intermittent electrical source, such as wind power in certain locations, can be absorbed easily into an electrical network that has an appreciable amount of backup capacity in the form of thermal stations or stored hydroelectricity. Similarly, the possibility of oil, gas, or electrical domestic heating makes it possible to save energy by solar heating, without the risk of freezing during a cloudy spell. Thus, the technical potential of renewable resources, most of which have some defects when measured against the ideal, is maximized in a society that is highly developed technologically and has an infrastructure of commercial energy forms within which renewables can be embedded. Later we shall discuss how to "balance" this technical potential: in such technologically differentiated societies, the opportunities for exploitation of a given energy technology may be restricted by the competitive economies of other energy technologies.

The situation is different in less developed societies. There, the standards of utility are not as high. The definitions of "continuous" availability and "easy" convertibility into useful energy are less demanding when the alternative is no availability and/or no applicability. Conversely, deliverability takes on greater importance in the absence of integrating networks and backup supply options. All in all, this tends to reduce the technical potential of renewable energy sources. Nevertheless, the lack of alternative options improves the economic potential of specific technologies in developing regions.

Thus, in addition to technical potential there are other levels of potential for renewable energy sources—application potential and economic potential. Technical potential imposes upper limits everywhere, while application potential and economic potential reduce these limits. The types and degrees of restrictions imposed by application limits and by economic factors vary among regions, countries, and districts.

Table 6-1 groups different kinds of renewable energy technologies according to their suitability to meeting the requirements of an ideal supply as just defined. The first group comprises solar technologies that divert power from the environment before the high thermodynamic quality is lost in the normal absorption process of sunlight. With a total flow of 25,000 TWyr/yr arriving at the land surface, the technologies of Group I divert energy from the only nonexhaustible renewable resource. Solar technologies are discussed in Chapter 5 and are mentioned here only for completeness.

The natural power flows supporting Group II, technologies for indirect

Table 6-1. Characteristics of main groups of renewable energy technologies.

Diverted Energy Flow	*Thermodynamic Quality*	*Natural Transformation into Acceptable Power Densities*	*Storable and Transportable Natural Energy Carrier*	*Conversion Technology*	*Auxiliary Technology*	*Accessibility*
Direct solar radiation (Group I)	High	No (but relative simple concentrations possible)	No (but areas exist with high availability)	Photovoltaic	Electrical grid additional generating capacity	Widespread
				STEC		In sunny regions, preferably deserts
				Solar chemical	Pipeline network	
				Heat collection	Backup supply Storage	Widespread
Indirect solar use (Group II)	High	Good	Poor	Waves	Electrical chemical fuel conversion	Mostly along coastal areas with adverse climate
		↑	↓	Wind	Electrical grid and/or additional generation	
				Hydroelectricity	Electrical grid	Widespread
		Poor	Good	Biomass (wood, farmwaste)	None	
Indirect solar use (Group III)	Low	Good	No	OTEC	Electrical chemical fuel conversion	Along warm tropical ocean currents
		↓ Poor		Water Soil Air } Heat pumps	Increasing demand for high quality feed power backup	Widespread
Geothermal (wet) (Group IV)	Medium	Yes	Very limited	Power plant District heat	Electrical grid District heating, grid	Along geological folding lines
Tides (Group V)	High	Yes	Very limited	Power plants	Electrical grid	Along a few coastlines

solar use, are much smaller in absolute terms than the natural power flow associated with direct sunlight. Also, the average power densities characterizing waves, wind, precipitation, and photosynthetic activities are lower than those for Group I. Local concentration of power flows in the atmosphere, the ocean surface layer, and storage in hydrosystems as well as in biosystems compensate in part for this disadvantage. Group II comprises the old combination, wood plus hydroelectric power, that was substituted for by oil plus electricity. Wind and waves, also in Group II, offer a much larger physical potential (see Figure 6-1) than hydroelectric power and biomass, but this potential is reduced by the fact that only a small fraction of their energy is directly accessible in the first few hundred meters of the air or in the immediate coasts of the continent.

The technologies mentioned in Group III, indirect solar use, are defined in order to understand their contexts. Heat pumps do not really tap direct natural power flows; they use the thermal storage of water bodies, the ground, or even the ambient air. In order to be effective, heat pumps must provide extremely low temperature heat; thus, they suffer from the poor transportability of sensible heat. Consequently, they must operate as close as possible to the point of energy demand and are dependent on local reservoirs of a suitable temperature level. As they require substantial amounts of mechanical power, supplied from elsewhere, heat pumps must be viewed more as an energy-conserving device than as an energy source.

Ocean thermal electric conversion (OTEC), is the main entry of Group III. OTEC is considered in two ways—as a way of diverting part of a natural energy flow, from warm surface waters to cooler deep waters of the oceans, and as a way of tapping energy stored from a past energy flow, the storage of solar heat in the upper layers. OTEC's limits are both environmental (How much could be tapped before major changes in energy flows are initiated?) and technical—the heat stored is of very low thermodynamic quality.

Geothermal energy, Group IV, is usually considered only with regard to wet sources, principally steam or hot water near the earth's surface. Such sources arise from geothermal anomalies and are present only in a few districts. The temperature of geothermal water or steam is high enough to use for electrical generation at moderately low efficiencies (as compared with fossil- or nuclear-fueled thermal units). It is high enough to be useful for many direct applications of low temperature heat, domestic or industrial, but only if it can be applied near the source. There are developments aiming to use dry geothermal heat from deep boreholes (several kilometers) or from dry geothermal anomalies. As with OTEC, these developments are schemes for mining past heat storages, rather than for diverting a natural heat flow. To be precise, the time required to deliver geothermal heat in quantity to a large body of rock, so as to heat it to a useful temperature, is large compared to the time over which that heat might be extracted.

For the sake of completeness, Table 6-1 also contains tidal energy as a separate group, V. Tidal power plants exist in France, with an installed electrical capacity of 240 MW(e), and also in the Soviet Union.

We now review in slightly greater detail the considerations affecting the technical potential of the various renewable resources.

Biomass

Of the approximately 100 TWyr/yr of fuel equivalent biomass (net) produced from solar energy, about 23 TWyr/yr are fixed in swamps, grasslands, and tundras; 29 TWyr/yr in forests; 10 TWyr/yr in cultivated land; and the remainder in the oceans (Bolin 1979). Direct human food consumption is about 0.4 TWyr/yr (four billion (10^9) people at 2000 kcal per day), while the consumption of animals is crudely estimated at 0.6 TWyr/yr. About 0.8 TWyr/yr are estimated to be withdrawn from forests as harvested wood (FAO 1975). We estimate that about 0.7 TWyr/yr of the net carbon product is associated harvest from field and forest products that is returned to the soil; this would be the rate of production of agricultural and sylvicultural "waste" associated with human harvesting activity.

How much of this biomass can, or should, be harvested is a matter for speculation. In Europe, perhaps half of the total land that was available in primitive times is now being harvested, with acceptable degradation of the biosphere. In tropical forests, there are indications that even this much harvesting would bring about considerable soil degradation and loss of photosynthetic potential. A harvest of 40 percent of the 62 TWyr/yr of land biomass fixation would probably be the maximum that we can prudently cultivate. This is still an impressive 25 TWyr/yr. Of this, by the year 2030 a world population of eight billion people, double that of today, would demand about 1 TWyr/yr to be in food (not food crops) and 1 TWyr/yr in lumber and paper crops (producing between them about 2 TWyr/yr of "waste"). With these crops, there would be a need for about 10 TWyr/yr of associated production in cultivated land. Under these subtractions, the 25 TWyr/yr reduces to 11 TWyr/yr of available production, plus about 2 TWyr/yr of waste, or a total of 13 TWyr/yr. Of this, at least half would be lost in collection and conversion processes: some would be preferably returned to the soil as a conditioner, and some (leaf and twig losses in forests, stubble in field crops) would be uncollectable (the efficiency of conversion of wood to charcoal is about 50 percent, the efficiency of conversion of sugar or cellulose to fuel is less than 30 percent, and so on). By this process we arrive at a total of 6 TWyr/yr of fuel, equivalent on the average to high quality coal, that would be technically available from biomass.

This is the sort of limit we can contemplate when we "turn planet earth into a garden." It implies a sophisticated, very careful management of the "photosphere." The 6 TWyr/yr subsumes such uses as the formation of biogas from animal residues, the use of wood as fuel directly in villages and in forest products operation, and a residual fuel value of nonrecyclable waste paper and wood. These may be important locally, and the use of wood as a cooking fuel in particular seems to double the amount of primary energy available. However, this last increment is illusory, as the efficiency with which heat is delivered to food that is cooked over wood is generally much lower than when (even) charcoal is used.

Hydroelectricity

Of the 5 TWyr/yr of mechanical power available from continental runoff of water, no more than 3 TWyr/yr can be relied on technically. The remainder is considered technically unavailable for one of several reasons:

- Some fraction of the water flow energy must still be allocated to overcome the frictional losses of stream beds; otherwise, the water would evaporate without going downstream.
- A certain water velocity must be retained in natural stream beds in order to maintain riverine ecologies.
- Even if other uses of land and water were possible, it seems virtually impossible to channel all the water for hydroelectric power; some of the flow energy appears in myriad small streams at headwaters or in "lazy" rivers near their outlets.

Because of these aspects, even such advanced projects as those of the Tennessee Valley Authority (TVA) and the Bonneville Power Authority (BPA) in the United States actually capture much less than half of the runoff potential of their respective river basins, and it is unlikely that a larger fraction could be harvested anywhere else in the world.

The potential of glacier power—tapping the hydro potential of glaciers (Partl 1977, 1979)—is small and can be considered as having been included in the hydroelectric power total.

Wind

We estimated the technical potential of wind by considering the wind energy available at heights up to 200 m above ground level. Geographically, we limited the areas to continental regions within 1000 km (on the average) of coasts running from 50° northern to 50° southern latitude. We excluded polar regions and high mountain, uninhabited areas. This exclusion may be considered an intrusion of the economic sphere on the technical potential since, at least for the generation of network electricity, it seems economically impractical to get the product competitively to the consumer.

There are a number of both pessimistic and optimistic assumptions in our estimate, which amounts to 3 TWyr/yr of wind power. On the pessimistic side:

- We assumed that total capture of the low level wind energy at coasts would create a several hundred kilometer zone of lower wind velocities

in its lee. In other words, the windmills would act like a chain of low hills. Thus, we could not expect to capture more than the total low level wind energy entering the coast.
- We ignored the smaller contributions of winds in the interiors of continents.

On the optimistic side:

- We assumed that wind machines could be emplaced whenever the average wind fields are favorable, ignoring the difficulties of doing so in regions where these machines might be particularly vulnerable to destructive storms.
- We assumed that large wind machines can be used. As far as the technical potential is concerned, 200 m wind machines capture more of the wind energy than do smaller machines.

One must not forget that wind power (as also hydroelectric power) generates high quality energy. Its product is electricity or stored mechanical energy (as with pumped water). To the extent that this high quality energy can be used, it is worth about three times as much as the same energy in low quality heat.

Ocean Currents and Waves

The contribution from ocean currents and waves is very small (0.005 TWyr/yr). As noted, the kinetic energy of ocean currents is only 0.2 TWyr/yr, and this kinetic energy plays a major role in shaping climates. Any significant harvesting of it cannot therefore be considered.

There are many schemes proposed for harvesting the energy of waves, particularly in the United Kingdom, where wave power is estimated as high as 8 to 9 GW. The main problem is that devices must be able to convert energy, with high efficiency, from 3 m waves while being able to withstand the onslaught of 30 m waves. This observation pertains essentially to all coasts where wave power has significant potential. No devices with this capability are yet in the offing.

Ocean Thermal Electric Conversion

OTEC would tap a heat source of extremely low thermodynamic quality, but it would provide access to extremely large quantities of such heat. Although OTEC is a speculative technique, it requires a closer look for two reasons: first, it could provide a significant source of energy once the technological difficulties were overcome; and second, through its analysis we can see how estimates of the theoretical or the technical potential of renewable energy sources depend on assumptions about how much interference with the mechanisms of the earth system can be tolerated.

We first review the thermal phenomena of the oceans, as they form the basis for understanding how OTEC would perturb the global system for distributing heat energy.

About 3000 TWyr/yr of solar energy is directly absorbed by the oceans, the largest part of this being in the equatorial zone between the two tropics. This heat is transported poleward by the giant ocean currents, such as the Gulf Stream and the Japanese (Kuroshiu) Current. Almost all the heat is delivered to the atmosphere in the temperate and subpolar zones, which are thereby blessed with much more moderate climates than would otherwise be the case. Some small fraction of the heat is delivered to polar seas, as a source of energy to melt ice. About 50 TWyr/yr is ultimately dissipated by convective mixing with cooler deep layers of the ocean (Wick and Schmitt 1977). It is this energy dissipation that, at low efficiency, is converted into the approximately 0.2 TWyr/yr of kinetic energy in the ocean currents.

Simply to complete the physical description, we note that there is also a delivery of heat from the earth's mantle upward into the ocean. This geothermal energy is converted into chemical-free energy in the ocean, but at such low efficiency as to be essentially dissipated. The depths of the ocean remain cool, in spite of heat deliveries, by the mixing of very cold saline waters delivered from polar regions, compensated in mass balance by the mixing of water across the thermocline.

Specific OTEC systems suggested in the literature transfer heat from the warm surface water of tropical or subtropical oceans directly to deeper cold water. The efficiency of conversion to electricity is extremely low–about 3 percent when the warmer tropical water is used exclusively. Technical difficulties in capturing all the heat in surface waters (because of having to discharge water so that it is not drawn back into the system and so forth) limit the electric power capability to 0.25 W/m^2 of tropical ocean surface (ASA 1975c). Taking the area of the tropical oceans to be 90 million km^2, this translates into a technical potential of 22 TWyr/yr of electricity and a diversion of 720 TWyr/yr from differentiated surface layers of the ocean to greater depths.

If all of this 720 TWyr/yr were subtracted from the heat transported north, the climatic impact would be very severe indeed. There would, of course, be compensating "induction" effects. For example, if the result would be the cooling of the ocean currents, so that at the beginning of their poleward migrations their temperatures would be, say, 18°C instead of 25°C, they would lose less heat on their journey and pick up some more heat from the sun. Nevertheless, one would still expect a major impact.

Taking a completely different viewpoint, Wick and Schmitt (1977) used the rate of heat transfer across the thermocline to develop a yardstick for estimating the technical potential of OTEC. The natural transfer between these two reservoirs is equivalent to a thermal power flow of 50 TWyr/yr across a temperature gradient of 12°C. Taking the same technical efficiency for OTEC systems as above, we arrive at a technical potential for OTEC systems of 1 TWyr/yr—only 4.5 percent of the nonequilibrium value of 22 TWyr/yr. In fact, harvesting this potential would be most practical at locations where cold water is warmed in any case; these are regions of upwelling with smaller available temperature differences—and corresponding lower heat-to-electricity conversion efficiencies.

We are faced with a dichotomy between less than 1 TWyr/yr of electricity recoverable from possibly nonperturbing sources of OTEC and over 20 TWyr/yr of electricity that might be associated with large perturbations. We selected 1 TWyr/yr as the proper value to use for estimating the technical potential of OTEC for a number of reasons, not the least of which is that we shy away from schemes that would draw on the heat stored in all the tropical ocean surface. Even 1 TWyr/yr would be a gigantic undertaking; and in view of the need to study the systematic side effects of going further, that seems to be a prudent upper limit for a few generations.

OTEC is an almost perfect example of the difficulties in arriving at responsible estimates for the global technical potential of renewable energy sources. It highlights the need for a much more intimate knowledge of the hydrosphere, the atmosphere, and the ecosphere before these systems are tapped on a grand scale. The problems of environmental disruption seem to depend as much on the amount of energy tapped as they do on the type. But for some of the natural flows, the problems are more complex than they are for most types of manufactured energy.

Heat Pumps

Heat pumps appear in Table 6-1 in the same group as OTEC (Group III). This placement refers to the characteristic of storing solar energy in land or fresh water or as heat in air. Unlike OTEC, heat pumps do not actually produce net energy. Their function is to permit mechanical energy to be transduced into low quality thermal energy at high efficiency; this is done by "running a refrigerator backwards" to dump the cool fluid into a reservoir and use the warm fluid—air or water—for specific purposes such as domestic heating or low temperature industrial heat. Water, soil, or air that is not too cold is such a reservoir. The amount of heat that can be made available in this way is two, three or more times as much as the mechanical energy that is expended.

Today's heat pumps do not approach their maximum theoretical efficiency, and large amounts of heat can be generated by them only if the reservoir is water. Their use on a global scale cannot be large, but they may become important locally. As envisaged, they represent to us an efficient way of utilizing high grade energy (electricity) for applications that would otherwise consume fuel. We therefore did not include heat pumps in our list of energy sources. In the discussion of the IIASA High and Low scenarios in Part IV of this book, we bear in mind that heat pumps are a possible way of conserving fuel. They could be subsumed under the conservation factors that are implicit in the future evolution of energy demand.

Geothermal Energy

Our estimate of the total geothermal energy potential considers only the wet heat sources that are known to exist in populated regions. We have already discussed dry sources and their speculative potential. There does not seem to us to be any chance that dry sources would be available to any large extent within the next fifty years. In any case, these resources are not renewable, although they are very large (Armstead 1978). (The total heat stored within the top 6 km of the earth's crust at temperatures above 200°C was estimated as being far greater than the energy content of all global fossil fuel resources; but practically, there is no reason to expect that a large-scale technology to fracture deep rocks around boreholes and to extract heat over long enough periods of time before the fractures are healed can be developed and emplaced where desired.) Other speculative resources, such as the geopressured brines of the Gulf of Mexico coast of the United States, are also excluded.

The Geothermal Resource Group (1979) conducted studies of the geothermal potential of the United States, which seems to have a somewhat better than average resource of wet geothermal energy. Rapid development of U.S. resources could yield of the order of 0.7 TWyr/yr by 2010. The reference report did not consider resource depletion, but we assumed that this power is close to the maximum that could be extracted on a steady state. By multiplying by four to account for a whole world resource, we arrived at 3 TWyr/yr.

Another estimate of geothermal potential (see Wick and Schmitt 1977) suggests that only about 0.1 TWyr/yr of electrical power, corresponding to 0.5 TWyr/yr of heat, plus some tenths of a terawatt for direct application, is all that could be sustained. From this, we might infer that up to 1 TWyr/yr of heat might be considered available. We averaged the two estimates to propose a technical potential of 2 TWyr/yr for wet geothermal heat.

Tidal Energy

From the total of 3 TWyr/yr of dissipated tidal power, a very small fraction is accessible for operating turbines: only a few coasts have a form that transforms the kinetic energy of the global tide wave into sufficient tidal levels. In the few favorable coastal areas the scarcity of basins for intermediate water storage (i.e., natural bays which can be closed off by dams) reduces the technical potential of tidal power to a very low level on a global scale—about 0.04 TWyr/yr (ASA 1975c; Wick and Schmitt 1977).

Total Technical Potential as Secondary Energy

The technical potential of the renewable resources previously discussed is listed in Table 6-2. The total, some 15 TWyr/yr, is quite impressive—almost twice the current rate of total global primary energy consumption. Achieving

Table 6-2. Technical potential (as secondary energy) of renewable resources.

Type	*Power (TWyr/yr)*	*Comment*
Biomass	6	Requires cultivation of virtually all of the productive land of the world.
Hydropower	3	A high quality product, equal to three times as much fuel. Includes minor potential from glaciers.
Wind	3	High quality energy but utilization must deal with difficulties of energy storage.
Waves and ocean currents	0.005	Minor quantities are available, but they do not add up to anything significant.
OTEC	1	Potential is greater if ocean heat can be diverted on a gigantic scale. Still speculative.
Geothermal (wet)	2	Much more stored heat is available for "mining" but technology is not available.
Tidal	0.04	Very localized potential.
Total	≐15	

this technical potential would be possible only if the world organizes itself around renewable energy—arranging settlement and industry patterns so as to concentrate them even more than at present around energy resources rather than around other resources or cultural and environmental benefits, and disregarding any cost problems that might arise in considering the competition among fossil, nuclear, solar, and other renewable energy supplies.

APPLICATION POTENTIALS

Certain types of renewable sources are in widespread use simply because there are no alternative energy supplies available. The use of biomass as a cooking and heating fuel in subsistence economies is one example; the use of run of the river water power for gristmills and sawmills is another.

There is another class of technologies that can provide a large amount of energy, but it is available in such a form that only a small fraction can be used. One example is the use of direct sunlight as a small-scale heat source, which can provide domestic hot water as well as supply building heat as needed.

The common features of these applications are that they are user oriented and demand limited. By user oriented we mean that the renewable energy source is collected as needed by the user and applied directly to his purposes. By demand limited we mean that the amount of energy harvested in these applications is dictated by demand rather than by supply.

User orientation bypasses most of the infrastructure and/or the networking of commercial energy systems. To some degree, and depending on the local economic conditions, this frees the user from the costs of maintaining the infrastructure and networks. This economic benefit must be balanced against the costs of capitalizing the required, small-scale equipment. When the balance is positive, and when other conditions (e.g., convenience and maintenance) are favorable or neutral, it is then a rational decision to adopt the user-oriented technology.

This justification, although phrased in marketplace economic terms, may also be applied to subsistence economies. For such economies, infrastructural costs are high; long distance transportation, for example, is very costly compared to income, and indeed the concept of "long distance" is reduced to 100 km or less. And for such economies, capital is essentially labor. The investment in a user-oriented energy system is often a decision to invest labor in such activities as wood chopping, charcoal burning, or dung collection.

The notion of user orientation is central to the concept of soft energy systems, discussed in Chapter 24 of this book. Here, we examine only the feature that user orientation implies demand limitation. The reason is that there are only specific economic settings and energy applications for which user orientation is appropriate. We have, in fact, mentioned the two most important cases—fuelwood for cooking in subsistence economies and insolation for space and water heating. (Interestingly, these represent almost the economic extremes of the world, for fuelwood is the energy source of the world's poor people, while solar heating is of greatest value to the affluent countries of the north.) Even when we expand the notion of user orientation to consider a village or a neighborhood as "user," we do not expand the applications very much. Mechanized transportation, most urban functions, and specifically industry require concentrated energy, as is provided by commercial fuels and electricity.

Renewable Energy Densities

The key point in considering application limitations is energy supply density. Any user-oriented collection system must provide enough energy in a limited space. Apart from direct insolation, only the natural flows of Group II—waves, wind, hydroelectric power, biomass—are concentrated enough to supply reasonably heavy demand densities. The situation is reviewed semiquantitatively in Figure 6-3.

The figure lists two types of power densities. On the left-hand side, the densities of natural power flows averaged over global or continental areas are displayed. For example, the 0.02 W/m^2 for hydroelectricity represents the average rainfall, minus evaporation, collected at the average height above sea level of the continents. These are the inputs for harvesting. On the right-hand side, the collection densities of various technologies for favorable, but not unusual, cases are listed. For comparison, the center of the figure also gives power demand density ranges for urban areas and for the seven IIASA world regions.[c]

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[c] See Figure 1-3 for the definition of these regions, and Appendix 1A for the list of the countries in each of the regions.

Figure 6-3. Energy supply densities.

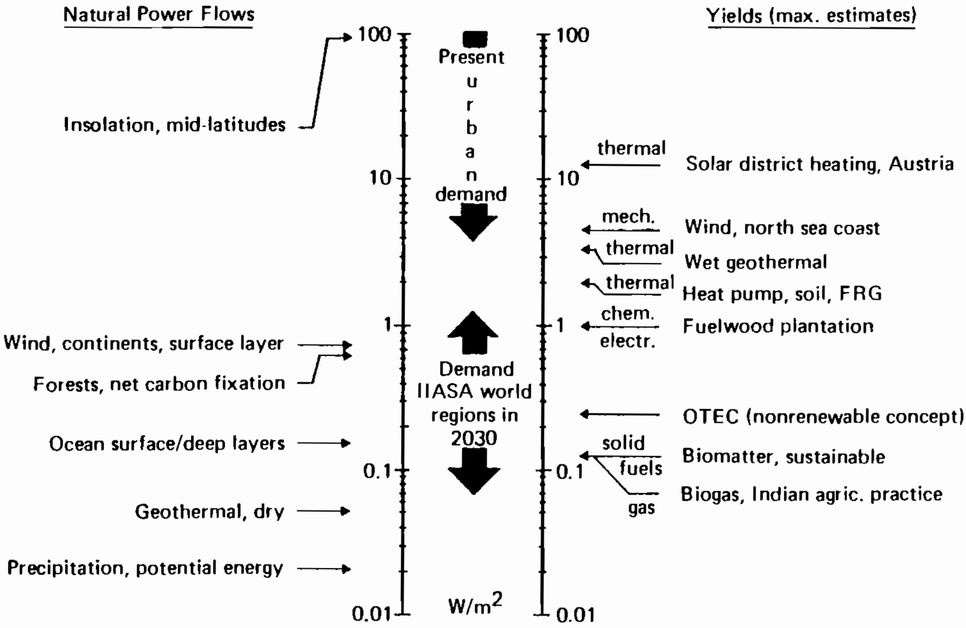

Figure 6-3 suggests that renewable energy sources might meet local energy demand in certain parts of the world, particularly in rural areas with low demand densities. For urban areas, only direct sunlight has a proper density. Other renewable energy sources require collection, concentration, and transmission or distribution from the large and favorable areas to the more concentrated demand centers.

Biomass in Rural Areas

Although some contribution from wind, water power, and even geothermal energy in selected locations can be counted upon, the dominant renewable energy source in rural areas is fuelwood. If we broaden the term to include "biomass," we can also accommodate straw, dung, and biogas in the total.

Khan (1980) estimated the possibilities of utilizing renewable sources on a local basis for all developing regions except China and other Asian, centrally planned economy countries (IIASA world region VII). His basic assumptions about total energy demand and total energy supply potential coincide largely with those of Revelle (1979). Including towns and cities as potential users of local renewable sources, Khan arrived at a renewable contribution of 1.0 TWyr/yr out of an assumed total energy demand of 6.2 TWyr/yr for a developing world population of 4.7 billion in 2030. Adjusting Khan's results by adding a proportional contribution for region VII, one is able to scale up the socially and practically achievable limits to an application potential of 1.35 TWyr/yr out of the 4 TWyr/yr production potential given by Revelle for the whole developing world. Of this, of the order of 0.1 TWyr/yr would be electricity from hydro and wind; only about 0.1 TWyr/yr would be user-collected solar heat; and the remaining 1.15 TWyr/yr would be biomass–mostly charcoal, but including biogas from wastes.

The figure for user-collected solar heat is smaller than many might think. This is because there is little or no demand for comfort heating in most of the developing countries; virtually all the direct solar energy goes for hot water heating. Solar cooking has been introduced repeatedly but has failed to gain acceptance. Khan's figures include a considerable consumption of biomass fuels, principally charcoal derived from wood, by small industries.

In reviewing Khan's results, we are struck by the similarity between the uses he assumed and those (except for comfort heating) made by the industrialized world before the coal era. If industrial development recapitulates the experiences of the IIASA world regions I (NA), II (SU/EE), and III (WE/JANZ), the application potential of user collected energy in developing regions would not increase.

We conclude that there is an application limit on user-collected energy in the developing regions that is about 1.35 TWyr/yr. Any further energy supplied by renewables must enter commercial channels and be considered for its economic and social merits.

Forest Product Biomass

An interesting application of user-harvested energy is being made by the technologically advanced forest products industry of North America and Europe. In the course of processing commercial forests to turn wood into lumber and paper, a very large amount of scrap is generated. Of this, what cannot be turned into secondary products such as fiberboard is potentially available as fuel.

According to industry spokesmen, they anticipate using this scrap as fuel for their own industrial operations. The amount of usable scrap would be just about enough to satisfy the energy demands of the lumber and the pulp and paper industries and would allow them to be free of purchasing large blocks of commercial energy.

We estimated how much energy this might be in the following way. In 1974, the commercial energy used by the U.S. lumber industry and the pulp and paper industry combined was 0.04335 TWyr/yr (derived from information from the U.S. Bureau of the Census 1976). This energy is, of course, in secondary energy carriers–industrial oil and, to a lesser extent, electricity. In 1974, some energy was self-generated from scrap, leading us to round the number upward to 0.05 TWyr/yr. For comparison, based on information from the U.S. Bureau of the Census (1976), an estimate was made of available primary energy in the scrap of these industries equivalent to about 0.06 TWyr/yr, which is commensurate with the assumption that the scrap could fuel these industries.

If increasing per capita demand is balanced by increased energy efficiency of the industry from now until 2030, we can associate 0.05 TWyr/yr with 200 million people in the United States in 1974 and then scale the number up to the corresponding energy demand of the 1600 million people assumed to inhabit regions I (NA), II (SU/EE), and III (WE/JANZ) in 2030. The result is a demand of 0.4 TWyr/yr associated with the forest products industry of the north temperate zone. This, from its method of estimation, is secondary energy equivalent. If we now assume that regions IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA) together could ultimately achieve an equal forest products industry (or, basically, that the tropical forests could match the outputs of the temperate zone ones), we get a figure of 0.8 TWyr/yr for the total secondary energy potential of wood used in this way.

An estimate of the wood harvest that went into products in the United States in the year 1978, based on information from the U.S. Bureau of the Census (1976), translates into approximately 0.12 TWyr/yr. For purposes of this crude estimation, it thus appears that for each terawatt year actually harvested annually, some two-thirds become products and one-third becomes the source of energy to make the products. If we extrapolate to a self-generated energy consumption of 0.8 TWyr/yr for the forest products industries of the world, this would come from harvesting 2.4 TWyr/yr of wood, of whch 1.6 TWyr/yr would be lumber, paper, and other nonfuel products. This is more nonfuel wood product than was assumed in the first assessment of the technical potential of biomass.

Renewable Energy in an Affluent Society

The case study, *Distributed Energy Systems in California's Future* (U.S. Department of Energy 1978), documents an investigation of how an affluent society might use renewable energy. It is important because, as the title indicates, the thesis of the study was to get the maximum out of distributed (but not necessarily noncommercial) energy sources.

California represents a very favorable case for renewable energy sources: it has a moderate population density; it is endowed with both a nearly optimal climate and a wealth of renewable sources; and it has an advanced economy with an unusually large service sector. These characteristics persist through the study period, which assumes continuous economic and population growth up to 2025. A considerable conservation effort was also assumed, paced by energy prices that were taken as four times the present values in constant dollar terms: the total energy demand was therefore held to today's value, in spite of a twofold increase in population and a factor of 3.1 increase in gross state economic product.

The study concludes that California could become nearly self-sufficient in energy by 2025 by producing 0.13 TWyr/yr from biomass, wind, solar heat, geothermal sources, and hydroelectricity—all of which are renewable sources. Solar electricity from centralized utility collectors was not taken as needed, since the postulated electrical demand could be met by other sources that were already in existence (e.g., hydroelectricity) or considered more desirable (e.g., wind, geothermal). Photovoltaic solar systems were not considered because of the uncertainty of their economic prospects. All biowaste from present forestry and agriculture, 50 percent of all noncommercial forests, conversion of bush and grassland into wood plantations, and installation of wind energy farms using 6 percent of the land of the state would be required, in addition to exploitation of California's considerable hydroelectric and wet geothermal potential. A shortfall in the liquid fuel supply of 0.023 TWyr/yr still persisted; it was suggested that a partial or total answer to this fuel shortfall might be achieved by adding harvesting of "kelp farms" off the coast to the arsenal of renewable supplies to be used. Table 6-3 summarizes the supply characteristics of the California study.

Interpreting these data for estimating user orientation requires some definitions and assumptions. While the California study emphasized the distributed nature of the sources—a characteristic of all renewable energy supply systems—it also involved centralized processing of most of these sources. In fact, virtually all the biomass energy was used to make liquid fuels that are destined to enter into the commercial distribution system for motor fuels and industrial feedstocks. To a rather good approximation, the user orientation of this source is zero. The same is true of the electricity generated by wind, geothermal, and hydropower. These systems form an excellent commercial supply mix, using geothermal for base loads and accommodating fluctuations in the wind system generation through the storage and peaking capabilities of the hydroelectric system. Thus the concept is clearly one of supplying electricity through a utility network and, indeed, a large one: the user orientation is, again, zero. Interestingly, in this study the fraction of end use that is taken up by electricity rises from about 10 to 29 percent in 2025.

Table 6-3. Supply characteristics of the California study.

Source Type	*Source*	*Energy Supplied in 2025 (TWyr/yr)*	*Energy Form*
Biomass	Municipal and agricultural wastes	0.016	Liquid fuel
	Energy farms	0.021	Liquid fuel
Insolation	Solar heat[a] collection	0.052	Heat
	Cogeneration	0.006	Electricity
Wind	–	0.025	Electricity
Geothermal	Wet fields	0.011	Electricity
Hydroelectricity	Storage dams	0.005	Electricity

[a] Approximately 40 percent of the solar heat is used in the residential, commercial, and agricultural sectors at low temperature. About 25 percent of the solar collection is used for on site, high temperature industrial heat, and most of the cogeneration is associated with this. The remainder is low to medium temperature industrial heat.

Source: Based on data from U.S. Department of Energy (1978).

Only with regard to insolation is user orientation observable. Apparently all the solar heat that is collected is applied to user purposes at the point of collection. Cogeneration of electricity is indicated whenever a solar heat source is required to produce high temperature heat or steam, but not all this electricity is consumed by the industry that generates it. We therefore made a further assumption that one-third of the cogenerated electricity is user oriented. We end up, then, with an estimate of 0.052 TWyr/yr or solar heat and 0.002 TWyr/yr of solar electricity that are used by the person, community, or firm that collects it, without passing into commercial channels.

We must make some heroic extrapolations to use this information for estimating the user-oriented contribution that direct insolation might make to the energy supplies of the whole of regions I (NA), II (SU/EE), and III (WE/JANZ). These regions are essentially classified under a single assumption that the population density of use, postulated for the year 2025 for California in the study, is the same for all of these regions asymptotically. There are a number of balancing features.

- California is sunny, on the average more consistently than most of the inhabited parts of these regions (favorable to heavy use in California).
- California would still be more affluent (favorable).
- California is, relatively, closer to the equator and solar intensity is higher (favorable).
- The California climate is mild, requiring less building heat (unfavorable).
- The study assumed an unusually strong degree of conservation (unfavorable). The term "unusual" is introduced here in the context of other studies only and is not intended to reflect on the realism of this assumption.
- California has a greater than average supply of other renewable energy sources (unfavorable).

Taking our advanced region population projections (see Chaper 14) of 1562 million people by 2030 and dividing it by the 38.6 million population used in the California study, we arrive at a normalization factor of 40.5; and applying this to the results of the California study, we then get 2.1 TWyr/yr of direct insolation heat and 0.08 TWyr/yr of electricity as the user-oriented contribution that might be inferred for insolation in regions I (NA), II (SU/EE), and III (WE/JANZ).

Total User-Oriented Renewable Energy Supplies

We are now in a position to estimate how much of the 15 TWyr/yr of the technical potential of renewable resources, as augmented by user-oriented solar energy collection, can be considered user oriented. This division is important because it is the user-oriented portion that is least vulnerable to the competitive economics of commercial energy forms. Our results are summarized in Table 6-4.

Table 6-4. User-oriented supplies of renewable resources.

Technology Type	*Application*	*Energy Forms*	*Quantity (TWyr/yr)*
Biomass	Subsistence fuel[a]	Charcoal, biogas	~1
	Small-scale industry	Charcoal, biogas	~0.15
	Forest products	Industrial fuel	0.8
Hydroelectricity	Rural electricity	Electricity	~0.05
Wind	Rural electricity	Electrical equivalent	~0.05
Insolation	Domestic and industrial heating	Low to medium quality heat	2.2
	Self-generated electricity (cogenerated)	Electricity	0.08

Totals by Source Type (TWyr/yr)		*Totals by Application Category (TWyr/yr)*	
Biomass	1.95	Secondary industrial solid fuel	0.8
Hydroelectricity	0.05	Other secondary fuel	1.15
Wind	0.05	Electricity or equivalent	0.18
Insolation	2.28	Comfort and process heat	2.2
Total	4.33	Total	4.33

[a] Although charcoal is the dominant secondary form, the "biomass" total for subsistence fuel also includes the more versatile form, biogas, as well as miscellaneous uses of wood, straw, and crop residues as fuel.

Several caveats must be repeated at this point. The second, and even the first, decimal place in the totals is not meant to imply precision: it is there only as an exhibition of proper addition. Even the first significant figures are not firm—they are only approximations to potential values. Finally, the numbers in Table 6-4 are potential values. They are meant to provide the basis for exploring limits. We do not think they will be exceeded, but there are many possibilities for shortfalls. For example, the major category of the biomass of the forest products industry, which is a surrogate for industrial uses of cultivated wood, could be less if the industry is more conserving in energy use than has been assumed. It could also be less if the industry finds more profitable uses for its wood waste, continuing a trend that has been apparent for a long time. Similarly, the major category of user-collected insolation could be much smaller if the cost of solar panels does not become considerably less than it is today. (This subject is treated in the subsequent section on economics of renewables.) Finally, the uses of subsistence fuel would shrink if a large fraction of the poorer countries succeed in improving their material circumstances; grids and commercial fuels are far more convenient than self-collected wood and charcoal.

After these gloomy warnings, two potential additions should be noted. If photovoltaic cells reach a cost level that places self-generated solar electricity within the cost range of delivered electricity, then they add greatly to user-oriented supplies. However, we judge that this would require a technical breakthrough and therefore did not consider this in our calculations. Among other things, the costs of such cells would have to include compensation for the diseconomies that would be introduced into the commercial grid, which would still be needed for backup; these diseconomies include the provision of generation and distribution facilities that operate at a low load factor. Alternatively, the self-generated electrical supply cost must still be economical when costs of electricity storage are included.

Another potential addition could come from direct uses of sunlight in the developing regions—IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA). Here most of the population live in climates that have little need for comfort heating in homes and offices. When the annual energy demand for this purpose is small, meeting the need by electric resistive heating or by fueled stoves is economically preferable to active solar heating and would probably remain so even if the price of solar panels is greatly reduced. This is indicated by a very small quantity—about 0.1 TWyr/yr—that Khan (1979) included in his estimate for the contribution of direct insolation; only that amount appears in the summaries of Table 6-4. But there are industrial opportunities for using solar heat, and these may ultimately be adopted in industrially developing countries. High capital cost for solar heating systems would, however, inhibit rapid installation of such systems, and their use before 2030 would undoubtedly be very limited.

ECONOMIC POTENTIAL OF RENEWABLE ENERGY SOURCES

Achieving the 15 TWyr/yr technical potential estimated in Table 6-2 would imply not only building up each technology to its maximum practical level in each locality, but also installing a number of secondary systems for storage, transportation, and distribution. Otherwise, one could imagine inefficient matching of production with consumption in specific localities (e.g., wind power for heating or wood for electrical generation). The degree to which these considerations limit the exploitation of resources depends on the level of the infrastructure put into place by other energy technologies and also on economics. Economic considerations are also of importance in determining whether renewable systems can compete with more concentrated forms of manufactured energy, when the choice is available. Sophisticated efforts to assess the realistic chances of renewable energy sources must therefore deal with economic questions.

The question of what is economical and what is not is open ended. Economic conditions throughout the world vary at least as much as the technical potential for harvesting energy from the environment. Among others, three factors introduce a major uncertainty into cost comparisons of energy supply technologies. First, oil and natural gas, the "reference" energy sources of today, have prices that are administered and thus provide a potentially unstable basis for comparison. Second, research and development are likely to bring down the cost level of renewable sources and also of competing sources such as coal, nuclear energy, and unconventional hydrocarbons: research could also create new competitors, and in the long run even a new reference energy carrier. Finally, many localized renewable sources are distributed unequally, require significant amounts of land, and constitute a real environmental burden and specifically a burden not necessarily borne by the energy users. As with nonrenewables, "social costs" and royalties should be charged to compensate, changing the relative price of the unit of energy finally delivered by the technology in question.

The situation is reflected in widely different estimates of the future costs of renewable energy found in the literature. Thus, a serious analysis cannot hope to produce more than rough estimates. For the sake of transparency, we present a comparison of the economic situation of renewable energy sources on one cost factor only. Table 6-5 uses the investment costs relative to the achievable energy output per year as the main yardstick.

Since renewable energy sources do not consume resources, operation and maintenance costs are in principle the only additions to the fixed capital charges to arrive at the total energy costs. The fixed 10 percent charge on

Table 6-5. Electricity from renewable sources: examples of capital costs and contributions to electrical cost.

Technology	*Plant Capacity*	*Investment Costs (1975$ /kW(e))*[a]	*Assumed Duty Cycle (hr/yr)*	*Contribution of Capital Cost to Electricity Cost*[b] *(U.S. cents/kW per hr)*	*Technical Status*
Hydroelectricity					
High head	250 MW(e)	800	4000	2.0	Mature, deployed
Low head	250 MW(e)	1400	4000	3.4	
Tidal Power	1.6 GW(e)	400	2000	1.95	Under design, experience with large pilot plants
Wind	6 kW(e)	1600	2500	6.4	Some commercial experience, projects, studies under way
	3 MW(e)	450	2500	1.8	
OTEC	100 MW(e)	650	6500	1.0	Studies
For comparison					
Direct solar[c]	100 MW(e)	3000	6000	5.0	Prototypes
Oil fired (including oil well and transport)	300 MW(e)	650	4000	3.0	Mature, deployed

[a] These cost levels refer to layouts used to estimate technical potentials. The layouts were evaluated for cost as though each technology were mature. No storage or transportation systems are included.

[b] Evaluated using 10 percent fixed capital charge.

[c] Heliostats at 2 × U.S. Department of Energy cost targets; includes nine to twelve hours of energy storage, southwestern United States.

Sources: Based on data from ASA (1975b, 1975c, 1975d).

capital investment is a benchmark figure only. Both monetary interest rates and the lifetime of plants are variable, and both higher and lower percentage rates can apply in reality even for a specific technology. The economics of a hydroelectric power plant in Africa cannot be compared directly to those of a plant of a similar size in, say, Canada.

Table 6-5 compares technologies that produce electricity from renewable sources. Examples were chosen to illustrate what we believe to be typical cases. The cost data are based on a priori estimates of construction costs for plant layouts considered in ASA (1975b, 1975c). They pertain to the North Sea-English Channel area with regard both to geographical and to economic setting. The assumed factors were determined by natural conditions, rather than by consumers' habits. No transportation and storage costs are included. For orientation, long-term storage of electricity, necessary in the case of load factors of much less than 4000 h per year, might add a complete hydro-storage cycle and consequently raise the investment costs by an amount close to the entries for hydroelectricity in this table.

Table 6-5 displays the well-known fact that hydroelectricity has long been competitive in cost with fossil-fueled electricity. Long lifetimes of plants, minimum requirements of operating personnel, and built-in storage capacity do not significantly increase the production costs over and above the 10 percent capital charge rate given. Tidal power, given favorable conditions, makes economic sense if the expected low investment costs are achieved. High investment costs for small units make wind power much more attractive in large units. The capital charges for wind power could be higher, however, if the wind systems require frequent repair and/or replacement, as has been experienced. Finally, OTEC too, if it is demonstrated to be technically reliable, is economically very promising.

Both higher and lower investment costs than those offered in Table 6-5 can be found in recent studies. However, this table is not intended as source material for Delphi studies—as estimates of most probable values. Its value, for technologies that have not been thoroughly commercialized, is to demonstrate that the order of magnitude of cost targets proposed for these technologies brings them into the region of economic interest. For OTEC in particular, and also to some extent for wind and tides, only time will tell whether these targets will have been realistic.

Table 6-6 lists technologies that provide material energy carriers, either fuels or hot water, for consumption locally. In contrast to that in Table 6-5, the cost comparison in Table 6-6 is made at the point of final consumption and not at the first collection step. This is done because hot water and steam cannot be transported over large distances and because fuels derived from renewable sources are also localized. Two different standards of costing are given in Table 6-6, depending on whether investment or operating charges are dominant.

The first three sources—fuelwood, biogas, and wet geothermal energy—compare favorably with the retail price of light fuel oil today. The cost figures for fuelwood include its conversion into charcoal, to allow for comparable efficiencies with the other sources in heating systems. Fuelwood and

Table 6-6. Cost levels for favorable cases: heat from renewable sources.[a]

Technology	*Investment Costs, 1975$/kW of Average Power*	*Fuel Costs (FC) or 10% Capital Charge on Investments (CCI) (1978$/bbl equivalent)*	*Assumed Load Factor (hr/yr)*	*Remarks/Technical Status*
Fuelwood: plantation, improved forest	180	5–24 (FC)	Rotation of land, continuous	Institutional changes, technically feasible
Biogas: farm wastes	480	15 (FC)	Continuous	Without labor costs during operation
Wet geothermal	100	7 (FC)	6000	Geyser fields, Iceland; cost of delivered hot water as fuel equivalent
Hot dry rocks, geothermal anomalies	400 extraction (+)1000 (distribution)	28 (CCI)	2500	Feasibility study
Heat pumps: electric schemes	2100 (high estimate) 800 (low estimate)	42 (CCI) 16 (CCI)	1700	One-third of heat supplied by electricity if water is available as a heat source
Solar panels: residential heating	7500[b]	150 (CCI)	1700	50 percent fossil fuel backup
For comparison				
Light fuel oil	100–200	20 (FC)	Negligible storage costs	Retail price (1976)
		70 (FC)	1700	Cost of delivered hot water from district heating system, as fuel equivalent

[a] The cost levels refer approximately to those layouts that were chosen to estimate the technical potentials in Table 6–2. They are not meant to represent expert opinions about achievable costs for the most favorable competitive circumstance.

[b] For Central Europe.

Source: Based on data from ASA (1975a, 1975d).

biogas data are based on an extremely low labor cost allocation, a circumstance that exists only in some developing countries. There is room for compensation, however, by institutional changes—for example, land reforms could in some cases provide cheap land, suitable for more efficient wood plantations. Industrial exploitation of active geothermal fields provides economic advantages that were already justifying such operations at a time when oil prices were much lower.

The remaining technologies—geothermal district heating, small-size heat pumps, and residential solar heat panels—provide residential and small commercial hot water and comfort heat only. These data are based on information from ASA (1975a, 1975d). The reference figure of $20 (1978) per barrel of oil consequently must be replaced by $70 per equivalent barrel of oil as heat delivered to a residential heating system. The relatively low capital charge figure for geothermal was taken from a feasibility study for exploiting a local geothermal anomaly in the vicinity of a large town in the Federal Republic of Germany (ASA 1975d): hot, dry rocks, which were excluded from Table 6-2, are more frequent than wet geothermal fields, but the cost of exploiting them is likely to be many times greater. Heat pumps appear cost effective where electricity is cheap and ground water can be tapped, but not elsewhere. In regions of mild climate and corresponding low annual heating demand, heat pumps compete with resistance heating, which has a low investment cost. Solar panels are expensive and require an incremental investment for a full capacity backup system; the cost of the solar part of the system must be reduced by a very large factor before this economic difficulty is overcome.

REALIZABLE POTENTIAL

It is now possible to combine the considerations of technical potential, the generally more favorable economic prospects of user-oriented supplies, and the broad economic aspects of renewable energy systems into a summary estimate of their realizable potential. By this we mean the rate at which renewable energy can actually be expected to be harvested under generally favorable conditions and within a fifty-year time span.

In considering economic factors, the notion of generally favorable conditions is not violated. There is a great range of economic driving forces in the world, both within the IIASA world regions and, especially, intraregionally. Thus, for any given technology we can expect that, ceteris paribus, very favorable economic circumstances will exist in some regions and very forbidding ones in others. For the world as a whole, the fraction of technical potential that can be realized, even given generally favorable prospects, would be neither very close to zero nor very close to unity for any specific technology. What economic factors provide is some shading in between.

An estimate such as is attempted here is necessarily subjective; we see no other way to do it. But some confidence can be derived from statistics: by adding up contributions source by source, biases would tend to cancel to the extent that they are not all slanted in the same direction.

Biomass

A technical potential of 6 TWyr/yr is given for biomass (see Table 6-2). This is secondary energy. The 1.15 TWyr/yr listed in Table 6-4 as usable in poor rural areas is also secondary energy—charcoal and biogas. The 0.8 TWyr/yr listed as self-harvested by the forest products industry is also, from its method of estimation, secondary energy. Thus, after these two sources are subtracted, there remains a further potential for 4.05 TWyr/yr of secondary energy to be commercially processed from biomass. How much of these three components—energy in poor rural areas, energy used in the forest products industries, and commercial energy—can be called "realizable"?

The main practical problem in poor rural areas is the mismatch between the supply of the main resource—wood—and the population distribution. Many countries already face a fuelwood crisis, while others have forests that are waiting for exploitation at a commercial scale. In region V (Af/SEA) in particular, the amount of fuelwood contemplated for harvesting of energy could consume almost half the annual growth of existing forests; and most of the region's forests are in Africa, while most of its people live in Southeast Asia. The situation could be improved by reforestation in the form of cultivated community woodlands; but in many cases these would be competing with food crops for the land. Yet the economic prospects for the use of fuelwood are excellent in these areas: the only alternatives are subsidized supply of electricity or commercial fuels, both of which are very expensive in this setting.

We adopted the judgment that for such areas, in balance, more than three-fourths of the application potential of biomass is likely to be called upon. The balance would have to be supplied commercially. Arbitrarily, we assigned 0.8 TWyr/yr of the resulting 0.9 TWyr/yr to the solid secondary energy carrier, charcoal, and 0.1 TWyr/yr to biogas.

We see no reason to reduce the 0.8 TWyr/yr gathered and used by the forest products industry. To the extent that some commercial energy (e.g., electricity) might be purchased, reductions of supply within the industry might be compensated by increments to world electrical generation that could come from wood as a fuel for this purpose in favorably situated districts. Of the 0.8 TWyr/yr, we consider 0.7 TWyr/yr as coal equivalent and 0.1 TWyr/yr as electricity.

We could only guess the fraction of the commercial 4.05 TWyr/yr of biomass energy that could actually be exploited. The limiting considerations are, in a broad sense, those of competitive land use and of economics. As to land use, we take it as a theorem that the best and most accessible farm and forest land will be cultivated for food crops and for timber. The basic demands of a world with eight billion people necessitate it. Energy farming would be lower priority land use. This, though, would imply that most of the land that could be made available for energy crops would be relatively far from demand centers. In turn, this emphasizes the need for an efficient conversion system to transform biomass into liquid fuels that can be transported easily.

Let us examine once again the realizable biomass potential in a more refined way. In a world of eight billion people, we have suggested that 1 TWyr/yr might be from food crops and 1 TWyr/yr might be from agricultural waste. Animal consumption might take 0.6 TWyr/yr. Between the agricultural waste and the droppings of domestic animals, perhaps 0.2 TWyr/yr of biogas could be generated. This subsumes the biogas generation already suggested as a target for poor rural population (0.1 TWyr/yr). Associated with all this is 10 TWyr/yr of biomass production in cultivated land.

The other major growths of biomass are in swamps, which are now considered to play too great a function as an "ecological kidney" to tamper with, and in grasslands. One might contemplate some extension of energy crops into existing grasslands, but few of those that remain in the world are likely to be profitable. In the United States, for example, the grasslands of the western plains are being withdrawn from cultivation as too vulnerable to dust storms that accompany periodic droughts. It is difficult to conceive of more than 1 TWyr/yr of energy crops—probably grasses for straw, for the most part—coming from this source.

Of the 29 TWyr/yr of forest biomass growth, harvesting 25 percent of the primary growth, rather than the 40 percent suggested in assessing technical potential, would be an audacious goal in itself over the next half-century. Actually, recovering much more than half of the biomass in living trees could be a task in itself. The 6 TWyr/yr of primary energy equivalent seems therefore to be an upper limit for practical withdrawals. Of this, however, 1.6 TWyr/yr has been accounted for as the withdrawal in poor rural areas to make 0.8 TWyr/yr of charcoal, and 2.4 TWyr/yr has been counted as the withdrawal of forest products industries, of which 0.8 TWyr/yr is used to provide energy—equivalent in this case to coal energy—for those industries. This leaves not more than 2 TWyr/yr of further, collectible primary energy from forests.

From all these sources, then, we obtain:

- 1.5 TWyr/yr of coal equivalent, whose consumption is already earmarked (poor rural areas, forest products industries);
- 0.1 TWyr/yr of electricity whose use is likewise earmarked;
- 0.15 TWyr/yr of biogas;
- 3 TWyr/yr of wood and straw for use as seen fit.

Urban Waste

Although urban waste is not really from a source different from biomass, it is nevertheless a resource that must be considered incrementally. The reason is that most urban waste comes from that part of the biomass that was not specifically harvested for energy purposes or processed into energy carriers. The principal component as far as energy content is concerned is paper, but lumber and food wastes are also a part of it.

Not more than one-fourth of the 1.6 TWyr/yr that goes into paper and wood products would, after recycling, end up as urban waste. But such matter is difficult to use as a fuel, even as a substitute for or additive to coal. Rather than use half of 0.8 TWyr/yr, or 0.4 TWyr/yr, that would be inferred from our comparison to forest waste, we use three-fourths of the latter number, or 0.3 TWyr/yr, and consider this to be "charcoal equivalent."

Hydroelectricity

There are a variety of water requirements that compete with the ability to develop fully all of the energy that is technically available–irrigation needs, preservation of scenic and special ecological values, and maintenance of navigation. There are also technosocial restrictions that apply–loss of land value to storage impoundments and allocation of water and power rights. All of these are estimated to constrain the total hydroelectric potential to half of what is technically available before economic factors are considered; it is assumed that economics is, in general, favorable for the amount of hydroelectricity (1.5 TWyr/yr) that is considered realizable here.

Wind

Economics, aesthetics, and competing land values are reinforcing constraints. Siting wind farms either far from urban centers (in order to cut down on television reception interference and to remove competition with other urban land use) or far from scenic and recreational areas reduces the number of potential sites and increases investments in transmission. Also, we assume that electricity generated from wind is integrated into a system that has a major storage capacity or that can permit the thermal baseload to be maneuvered according to demand. Under this latter circumstance, the wind system would have to be assessed with at least part of the cost of suboptimal use of that baseload. Even including uses of wind for dispersed rural energy, principally for water pumping and for very small-scale electrical demands, it does not seem reasonable to expect that more than one-third of the technical potential of wind power (1 TWyr/yr) can actually be realized.

Geothermal

Of the two estimates mentioned previously that were averaged to estimate the technical potential of (wet) geothermal, we have taken the lower one as being more likely to be realized. One-half of the 1.0 TWyr/yr so estimated is expected to be used as low temperature heat, while the other half is assumed to be used for generating electricity at 20 percent conversion efficiency.

User-oriented Solar Heat Collection

Although this technology was discussed, qua technology, in Chapter 5, its application context is more appropriate to that of other renewables, and it is therefore included here. Table 6–4 lists 2.2 TWyr/yr of user-oriented (user-collected) solar heat as an upper bound because of application limitations. Of this amount, we assume that about half of the solar heat is for residential-commercial purposes (comfort heat and hot water) and about half is for industrial purposes (heat at various quality levels, including heat of sufficiently high quality that electricity can be cogenerated from it).

Table 6–6 illustrates the essentially uneconomic position of solar heat when existing solar panel technology is the basis for costing. Under these conditions, it is difficult to imagine direct, small-scale solar heating capturing a large share of its potential market. Low temperature agricultural heating is a very favorable market, and low and medium temperature industrial heating is a moderately favorable one; high temperature industrial heating, on the same economic basis as for comfort residential and commercial heating, would be a poor market.

We have therefore applied the following factors to the end uses of solar heating recorded in the California study, on which our solar application potential estimate was based—space heat (0), water heat (1), agricultural heat (1), industrial low and medium temperature heat (0.5), and industrial high temperature heat (0). Using these factors as weights, we find that just about 40 percent of the total solar energy projected for the California study has a good chance of being realized worldwide. This rounds off to 0.9 TWyr/yr of direct use of solar heat.

Other Renewable Resources

Here we include ocean currents, waves, tides, and OTEC. Of these, the first three have an almost negligible technical potential. OTEC has extremely speculative economics and is in such an early stage of development that probably not all problems have been identified. The realizable potential figure for OTEC systems envisages realizing half of what was listed as the technical potential of OTEC and amounts to 0.5 TWyr/yr of electricity.

Soil storage and other heat reservoir schemes involving heat pumps are not included since they are not ways of using renewable energy as an energy source. Instead, they work by using natural energy flows as catalysts to improve the efficiency of applications of manufactured energy.

This is not to say that these schemes are unimportant; quite the contrary. Their influence on the quantity of manufactured energy needed, particularly to operate low temperature heat delivery systems, could be very great. And indeed, there is a whole continuum of ideas combining solar heat storage with heat pumps that spans a range from almost no contribution to a very significant contribution of solar energy to the heat delivered.

In this sense, the presentation offered here has underestimated solar heating potential. The same could be said about passive solar heating—an ancient device, exemplified by Gothic cathedrals and American Indian adobe pueblos alike, for using solar heat storage to minimize even seasonal heating requirements. Modern technical knowledge makes it possible to employ a variety of architectural and structural devices to do the same for less massive buildings.

But by insisting on treating all these methods as demands rather than as supplies, we avoid double counting, for treatments of conservation indeed usually already incorporate their effects on the demand side.

Tabulations

Tables 6-7, 6-8, 6-9, and 6-10 present the numbers just derived in a more organized form. Table 6-7 presents the realizable potential of renewables by source, and Table 6-8 organizes the data in terms of energy form. Table 6-9 presents conversions to equivalent primary energy forms. The potential for renewables is equivalent to that from 14-15 TWyr/yr of fossil fuels or nuclear power (if it is assumed that one must make an equivalent mix of secondary energy carriers).

These tabulations indicate that renewable energy sources, collectively, have promise of the same order of magnitude as fossil fuels or nuclear power. One should not underestimate them, nor should one overstate their case. The 6.6 TWyr/yr of potentially realizable secondary energy from renewable resources and the 3 TWyr/yr additional primary energy from biomass plantations must be interpreted as an upper bound to the practical. It is a figure to be used for exploring limits, in the same spirit as 10 TW(e) of installed nuclear power was used in Chapter 4.

Table 6-7. Realizable potential of renewables, by source.

Source	*Application*	*Quantity (TWyr/yr)*	*Energy Form*
Biomass	In poor rural areas	0.8	Charcoal
		0.1	Biogas
	Other farm waste	0.1	Biogas
	Forest products industries	0.7	Coal equivalent
		0.1	Electricity
	Energy plantations	3.0	Primary energy to be processed
	Urban waste	0.3	Coal equivalent
Hydroelectricity		1.5	Electricity
Wind		1.0	Electricity
Direct solar heat		0.9	Low temperature heat
Geothermal (wet)		0.5	Low temperature heat
		0.1	Electricity
Other renewable resources (mostly OTEC)		0.5	Electricity
Total		≐9.6	

Table 6-8. Realizable potential of renewables, by energy form.

Energy Form	*Quantity (TWyr/yr)*
Coal equivalent (solid fuel)	1.8
Electricity	3.2
Gaseous fuel	0.2
Heat	1.4
Primary energy to be processed	3.0
Total	≐9.6

Table 6-9. Primary energy equivalents of renewable energy potential.

A. If made from oil, conversion factors used are:
(1 unit primary fuel = 1 unit primary oil)
1 unit charcoal = 0.8 units oil
1 unit electricity = 3.0 units oil
1 unit gas = 1.2 units oil
1 unit heat = 0 units oil (could be waste heat from electricity)

$$\begin{array}{r} 1.8 \times 0.8 + 3.2 \times 3 + 1.2 \times 0.2 = 11.28 \doteq 11.3 \text{ TWyr/yr} \\ \underline{+\ 3.0} \\ \doteq 14 \quad \text{TWyr/yr} \end{array}$$

B. If made from coal, conversion factors used are:
(1 unit primary fuel = 1 unit primary oil)
1 unit charcoal = 1 unit coal
1 unit electricity = 3 units coal
1 unit gas = 1.4 units coal
1 unit heat = 0 units coal (could be waste heat from electricity)

$$\begin{array}{r} 1.8 \times 1 + 3.2 \times 3 + 1.4 \times 0.2 \doteq 11.7 \text{ TWyr/yr} \\ \underline{+\ 3.0} \\ \doteq 15 \quad \text{TWyr/yr} \end{array}$$

C. If made from nuclear energy, conversion factors used are:
(1 unit primary fuel = 1 unit primary oil)
1 unit charcoal = 1 unit nuclear
1 unit charcoal = 1 unit nuclear heat
1 unit electricity = 3 units nuclear heat
1 unit gas = 5 units nuclear heat
1 unit liquid = 4 units nuclear heat
1 unit heat = 0 units nuclear heat (could be waste heat from electricity)

$$\begin{array}{r} 1.8 \times 1 + 3.2 \times 3 + 0.2 \times 5 = 12.4 \text{ TWyr/yr} \\ \underline{+\ 3.0} \\ \doteq 15 \quad \text{TWyr/yr} \end{array}$$

Table 6-10. Comparison of technical and realizable potential.

Source	*Technical Potential (TWyr/yr)*	*Realizable Potential (TWyr/yr)*	*Constraints*	*Comment*
Biomass	6	5.1	Land use	Partial mismatch between sources and customers. The only renewable source of reduced carbon.
Hydroelectricity	3	1.5	Ecological, social	High quality product (electricity). Very small fraction available from self-collected sources.
Wind	3	1.0	Land use, economics	High quality product (electricity), but must be used mostly in conjunction with grids or hydro. Small fraction could be self-collected (for water pumping).
Geothermal (wet)	2	0.6	Resource uncertainty	Relatively low temperature heat. Best used for comfort and process heat, but convertible to electricity at ±20 percent efficiency.
Direct solar heat[a]	Enormous	0.9	Economics	Only self-collected applications counted; mostly hot water in sunny locations.
OTEC	1	0.5	Economics, market penetration	Still speculative.
Tides, ocean currents, and waves	0.04 0.005	0	Computational[b]	Amount available insignificant compared with uncertainties of other estimates.
Total	≐15	≐9.6		

[a] Not included in Table 6.2. For general discussion see Chapter 5.

[b] The number is so small that it rounds off to zero at the significant level of the table.

OBSERVATIONS

The global supply figures just inferred, amounting to about 9.6 TWyr/yr of potentially realizable energy from renewable resources and representing an equivalent of about 15 TWyr/yr of primary heat energy, show that renewable energy sources must be given the same consideration as fossil fuels, nuclear power, or centralized solar power. But there is one difference: this large sum does not come from a single source or from a single technology. Instead, it is derived from adding up a number of smaller sources and technologies. This affects our thinking in two ways that have opposing implications. On the one hand, it is easy to consider, say "only 1 TWyr/yr of wind power" and conclude that it can make only minor contributions to solving world energy problems. When this is done on a source-by-source basis, the promise of the renewable supplies can be lost in the statistical "noise" of the energy problem. On the other hand, when the addition has been made, it is all too easy to look at the total complacently, without realizing that to achieve the promise, it will be necessary to pursue not one, but a whole host of separate research, development, commercialization, and marketing activities that differ in scope and character.

Under these circumstances it is necessary to emphasize that the large potential we have listed for renewable energy supplies has the same significance, in this study, as the similarly large potential for, say, nuclear power. In both cases, they are explorations of the limits of the possible. Almost certainly, what the world will achieve will be less. We must therefore examine here what caveats must be considered, what problems have been set aside in our previous discussion, and what structural and infrastructural changes are implied if the world is to harvest all this energy from renewable sources.

Energy Density Revisited

A general understanding of the impact of the harvesting effort on the world can be gained by comparing energy densities of our 9.6 TWyr/yr estimate of potentially realizable energy with those derived from the California study and from the Revelle (1979) study of rural energy. A descriptive summary is presented in Table 6-11.

The California study represents an all-out effort by a society that probably has the means to make such an effort and has, besides, unusually favorable resources to work with. A very remarkable output of 0.3 W/m^2 is achieved, but one might characterize the land use as virtually total.

The Revelle study also portrays an all-out effort, but with a lower level of technology. At that level, the 0.09 W/m^2 that are made available are also contingent on the total commitment of land use. From this perspective, the "world" column in Table 6-11 could also be described as a near total commitment of land, hydro, wind, geothermal, small-scale solar, and intensive cropping of all accessible grass and forest land; the 9.1 TWyr/yr supply from renewable resources would be more in the spirit of an upper limit than an expected early achievement. Doubling the energy yield to the level suggested by the technical potential shown in Table 6-2 would entail both advancing into marginal areas of economic and technological feasibility and assuming that the whole world can reach the level of sophistication that California hopes to reach by 2025.

We can also reverse the question to ask: What population densities could be sustained on an energy density of 0.1 W/m^2? The energy use that we take as a target for modest standards of living in rural areas is 1 kW per capita. (For reference, bare subsistence requires about 0.3 kW per capita.) Thus, a population density of one hundred people/km^2 could be sustained. However, many parts of the earth are expected to have a much higher population density by 2030. The inference is that these geographic regions, which

Table 6-11. Renewable energy supply: a comparison of limiting cases.

Case	*California (in 2025)*[a]	*Rural Developing World (in 2025)*[b]	*Possible World in 2030*
Population in territory (year 2025 or 2030)	38.6×10^6	$3{,}250 \times 10^6$[c]	$8{,}000 \times 10^6$
Inhabitable area of territory (10^6 km^2)	0.4	43	80
Yield from renewable resources (TWyr/yr)	0.13	4	9.1[d]
Land use implications	100% of commercial forests and agricultural land plus 50% of noncommercial woods, brush, and grassland; wind, solar, hydro, geothermal	All forests plus wastes from doubled agricultural yields plus hydro, wind, solar heat	Nearly total land dedication or dedication of a major part plus advanced technology for all available sources
Population density (inhabitants per km)	97	76[c]	100
Energy supply density (W/m^2)	0.3	0.09	$\doteq 0.11$

[a] USDOE (1978).
[b] Based on data from Revelle (1979).
[c] Excluding urban population in cities of more than 100,000 inhabitants in same territory.
[d] Excluding ocean-based sources.

include Europe, South Asia, and the Far East,[d] must have a large fraction of their energy needs supplied by high density energy carriers even after maximum use is made of renewables. In Southeast Asia and China, even survival conditions could not be met with the use of renewable resources only.

We can characterize these two energy density considerations by two observations. First, the potentially realizable renewable supply goals require taking a big step toward "cultivating" the entire globe. Second, the variable population densities in different parts of the world do not permit total reliance on renewables, even if modest standards of living are assumed.

Market Penetration

Up to now we have not considered the constraints on the buildup of new technologies that are classified under the heading "market penetration." With regard to two energy sources, we can be secure on this point. Hydroelectricity is a mature technology and one whose penetration is still much

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[d] These regions, as used here, are defined according to the U.N. Statistical Bureau.

more limited by the matching of resource availability to demand than by any other institutional factors. Biomass in rural areas (fuelwood, dung, and agricultural waste) already supplies 7 percent of the world's energy needs, although most of the biomass being used now is noncommercial. If we talk of a 40 TWyr/yr, high energy demand world, biomass requires only about 10 percent of the market share to correspond to 4 TWyr/yr of supply. Thus, biomass needs only to increase its market share gradually as energy demands grow.

The other, relatively major, technologies may have more difficulties penetrating markets. This would be particularly problematic with two electricity-generating technologies—wind and OTEC. These technologies differ from existing ones in supply characteristics: wind is still considered to be a sporadic source of energy and will be treated as such until its continuity of supply is better understood; and OTEC requires either transmission of electricity from an offshore base to load centers on land or, conversely, the migration of specialized electric consumer industries (such as aluminum refining) to the sea. In both cases, not merely the technologies but also new infrastructures are required if they are to be deployed on a grand scale: they occupy specialized niches in the ecology of energy supplies.

Other Institutional Factors

We have pointed out that new infrastructures would certainly be needed if OTEC is deployed on a large scale: manufacturing industries might have to learn how to migrate to the oceans, along with their labor forces and materials-handling structures. In this sense, OTEC might only be a part of a much larger, very futuristic development—the resettling of a part of the human race in floating cities. This might ultimately become desirable or necessary in any case, but the entire development would take a very long time.

Similarly, the infrastructural problems of embedding wind into electrical utility systems have been mentioned. These problems might be more acute if user-collected photovoltaic electricity comes into use. Among other things, they involve questions of equity. Who pays how much for the cost of lowered capacity factors within the electrical grid?

Finally, the large-scale use of biomass would require many institutional adjustments in view of both land use allocations and a heightened need for a global ecological monitoring program, probably also associated with a global ecological control program. This will be discussed later in this section.

The global nature of this bundle of supply systems is immediately apparent when we consider the "world as a garden"—as implied by an emphasis on biomass, by the extraterritoriality of OTEC, by the potential continental-scale effects of harvesting wind or of capturing water on a grand scale, and by the ecological or climatological constraints on several of the renewable energy sources. As with oil, coal, and nuclear power, matters of global organization could be the real limiting factors of renewable resources.

This observation is reinforced by the "lumpiness" of many renewable resources (i.e., the nonhomogeneous distribution worldwide of wind, hydropower, and geothermal in particular) and also by the fact that the renewable supply systems have their maximum capability when they are coordinated with other sources of grid energy and with transportable energy. The theme keeps recurring: no single supply system can meet our needs as a "stand alone" system. Each has features that support the others. Even if one or the other could supply all the world's energy needs, the energy system would work better when all the resources are used. Each resource would then be able to serve the market in which it functions best; more importantly, the resilience of the energy system would be maximized.

By considering the energy system in this way, one is able to see the role that economics plays. Economics allocates human activity. It balances inputs of labor, capital, and resources according to the values that people place on these inputs, in order to produce outputs whose value is set in some way. So it is with the energy system. The competitive nature of various energy supply options is resolved by comparing costs. Of course, external costs must be incorporated, and the art of doing this is not completely developed. And costs may be different on the average than at the margin. When costs are compared, they are always based on the context of an existing system—and they will continue to be compared in that way.

Where these economic factors will lead us depends on future developments. All that is certain is that some of the renewable energy supplies will turn out to be too expensive to achieve the realizable potential we have estimated and some will exceed that potential.

Research, Development, Commercialization

There is an extensive literature documenting the research and development of each of the new renewable energy systems. Therefore, it is only necessary to point out that for most of the renewable energy systems the real problem, qua supply system, is commercialization: getting enough examples into operation so that decisions can be made on technical, economical, and environmental information, rather than just on forecasts.

There is one exception which must be repeated here. Ecologically and environmentally, the whole is more than the sum of its parts. At he level of many terawatts of energy supply from natural energy flows, it becomes mandatory to understand fully all the feedbacks: how "nature's machine" works, and what affects it. To put it succinctly, achieving the realizable potential of renewable energy sources requires a flowering of the earth sciences (oceanography, meteorology, hydrology, geology, etc.) and of the biological sciences. The required level of research completely transcends that which is currently devoted to these fields.

The Significance of Biomass

Of all the renewable energy supplies, only biomass (including urban waste) produces fuel. The others supply other secondary energy forms—hot air, water, or electricity. We have observed in studying uses for coal that there is an irreducible demand for storable fuels, particularly for liquid fuels. In the discussion of the coal option in Chaper 3 we noted that in the long run, the global constraint imposed by the carbon dioxide problem sets a limit on the amount of coal that can be used for making liquid fuels; in Chapter 22 we specify a preferred technology wherein coal is hydrogenated with energy and hydrogen coming from nonfossil sources.

The significance of coal is that it is by far the largest fossil resource of reduced carbon. But biomass is a nonfossil resource of reduced carbon. It also has the property that biomass carbon is accumulated from atmospheric carbon dioxide, so that after some period of equilibration, the use of biomass as fuel has a net effect of zero on atmospheric carbon dioxide buildup. From this point of view, biomass is an exceptionally attractive energy source.

In the long run, then, it seems especially desirable first, the stimulate maximum biological production of reduced carbon and, second, to develop efficient and economical ways of making liquid fuels from this biomass. The classical route for this second step is natural sugars to alcohol, via fermentation. Alcohol from sugar cane, or from grain, represents existing technology. However, over the long run, agricultural land devoted to crops for energy is likely to be preempted by the higher value of using agricultural land to produce food. Thus, we are naturally led back to wood as the chief source material for "bioliquids." One route being developed is the biological degradation of cellulose, which is a sugar polymer, to its constituent sugars, followed by fermentation.

But in the long run, we must reckon with the fact that fermentation is not efficient in its use of carbon. The energy for the process is actually supplied by biological burning of some of the sugar, as is evidenced by copious production of carbon dioxide; and less than 30 percent of the original energy content actually appears in the liquid fuel that is produced. Moreover, natural alcohol is rather expensive. For example, its present cost is more than twice that of gasoline from oil, on an energy content basis, when taxes and subsidies are eliminated.

The example of coal provides a more efficient possibility whose adaptation to biomass only needs to be sketched out here. An initial step, pyrolysis of wood, essentially reduces the wood to charcoal, with by-product liquids also produced (methanol, turpentines). The charcoal is now substituted for coal in the allothermal route to methanol (see Chaper 22). We simply recall here that, in this route, heat energy and hydrogen are both added to the carbon, so that the resulting liquid fuel has about twice as much energy content as the carbon from which it was made. Thus, with pyrolysis carried out using an external heat source (e.g., concentrated solar or high temperature nuclear heat), the result is the total conversion of biomass carbon to liquid fuels and an increase in its stored energy as well.

Given this promise for the long-run use of biomass, we must take a closer look at what it means to harvest around 20 TWyr/yr of contained primary energy for the food, fiber, and partial energy needs of eight billion people; this is about the sum of the cultivated biomass that is needed when one adds up food, fiber, energy, and associated cultivated land. This is of the order of one-third of all continental biomass production. Including wood as an energy resource, it also subsumes one-quarter of all wood production. If we consider the concept of "the world as a garden" to include the preservation of a reasonable fraction of the world in its natural state, then 20 TWyr/yr by the year 2030 indeed requires commitment to a garden world.

The deployment of a biomass-based liquid fuel system on the scale being discussed here demands active control for global ecological stability. The control of soil erosion, the management of water systems, the stabilization and management of the nitrogen cycle and the phosphorus cycle, and the decreasing resistence of cultivated plants against pests are well-known problems today. With a further sizable reduction of the naturally stable ecosystems, a successful deployment of biomass energy will eventually depend on a globally instituted environmental and ecological control system. What quantitative limitations will thus be imposed can hardly be guessed at now. The limitations can be accentuated only by the further limitations that the ecological side effects of other renewable energy systems (wind, hydroelectricity) will require. The need for macroecological research becomes an overriding constraint.

SUMMARY

There are a variety of natural energy flows from which energy can be captured for human purposes. They include, in addition to the direct energy from the sun, the energy content of biomass, flowing streams, wind, waves, ocean currents, and tides. They also include the turnover of heat from the oceans' surface layers to the depths and the heat flowing from the earth's interior to the surface. Our ability to make use of this energy depends on the energy densities in the various forms, their locations, and the extent to which they can be diverted without significantly affecting climate and ecology or adversely affecting high value land uses. The technical potential estimated in consideration of these constraints is about 15 TWyr/yr of secondary energy.

There are additional factors that serve to restrict the amount of energy that can be harvested from these resources. Some resources can be used only at or near their point of collection and are thus application limited. On the other hand, user orientation—that is, the ability of the user to collect his or her own supply—is a favorable indicator that the resource will in fact be used. Examples of user orientation can be found in the use of biomass as fuel in poor rural areas and, separately, in the use of wood waste as an energy source for forest products industries. Application limitation is seen in the use of direct insolation, which is a vast resource, for domestic and industrial heating. This special aspect of direct solar energy has been incorporated in the discussion of renewable resources because of its similarity to biomass as a supply mode for user-oriented collection systems.

Other limitations arise from economic considerations, from more detailed supply-demand mismatches of sources and consumers, from detailed ecological and social factors, and from prudence in deploying unevaluated or not-well-developed sources. Even with these constraints, about 9.6 TWyr/yr of energy from renewable sources can be considered to be practically realizable. This is equivalent to about 15 TWyr/yr of primary energy from fossil fuels or nuclear heat to provide an equivalent mix of secondary energy forms. The mix is 1.8 TWyr/yr of solid fuels, 3.2 TWyr/yr of electricity, 1.4 TWyr/yr of low temperature heat, 0.2 TWyr/yr of gaseous fuel, and 3 TWyr/yr of primary biomass. The contributions of the various sources are biomass, including waste, 5.1 TWyr/yr; hydroelectricity, 1.5 TWyr/yr; wind, 1 TWyr/yr; geothermal, 0.6 TWyr/yr; solar heat, 0.9 TWyr/yr; and waves, tides, and OTEC together, 0.5 TWyr/yr.

The maximum use of renewable sources presupposes the fulfillment of two major general conditions. First, renewable sources must be used in conjunction with other energy supply systems that will still be needed to provide reserve supplies and base loads in grids and/or to supply poorly endowed regions and districts; this will ensure stability and resilience of the total energy system. Second, since the use of renewable sources represents a large potential ecological disturbance, a global ecological monitoring and control system is indicated. This, in turn, must be based on much-improved knowledge of how the natural energy flows affect the globe—a knowledge that can only be gained by a commitment to large-scale research in the pertinent disciplines.

Among the renewables, biomass is especially important because it could be a self-renewing source of fixed carbon for use in producing liquid fuels. If economic obstacles can be overcome and ecological conditions satisfied, biomass could displace coal for liquid fuel production.

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7 A REVIEW OF ENERGY SYSTEM CONSIDERATIONS

In the preceding chapters of this part we discussed opportunities and limitations of several energy systems. By and large, these were examined individually. We compared some of these systems with possible levels of demand and looked at how various supply strategies might translate potentials into realities. We now put these individual essays together, which involves elements of review as well as comparisons, categorizations, and judgments. Here, we examine some peripheral issues, such as the economic status on which many decisions are made and the roles of reference energy carriers in stabilizing energy systems.

FOSSIL FUELS

Within the period covered by this study—up to the year 2030—there will be a slow but continuous transition from the present use of relatively cheap and clean gas and oil to an extended period of using fossil fuels that cost more to extract and process and have larger and larger environmental impacts. We call these "dirty" fuels.

Translated into expectations for the ultimate recovery of fossil fuels, we estimate that conventional oil fields are capable of delivering 420 TWyr of energy, including the effects of enhanced recovery; unconventional oil (heavy oil and tar sands), another 420 TWyr; shale oil, 60 TWyr (on the

Table 7-1. Estimated recoverable fossil fuel resources.

Type	*Amount (TWyr)*	*Comments*
Conventional oil	420	Includes anticipated additions to reserves via secondary recovery, offshore exploration, and exploitation of smaller fields.
Unconventional oil	420	Heavy oil and tar sands; must be processed before "oil" is recovered.
Shale oil	60	A huge resource, but one whose exploitation has possibly insurmountable environmental problems.
Natural gas	350	Requires heavy investments to deliver to consumers (e.g., new pipelines, liquified natural gas, supertankers).
Coal	2400	About half in easily recoverable formations; perhaps an additional 1200 TWyr, beyond the 2400 TWyr listed, could be obtained from exotic deposits (i.e., permafrost areas).
Total	≐3650	Less than half is in "cheap to recover" formations or locations.

assumption that environmental problems will be very difficult); natural gas, 350 TWyr; and coal, 2400 TWyr. Table 7-1 presents these data with comments.

The resource base of fossil fuels is large, but only if it includes resources that will cost much more than they do now. About half of the conventional oil and natural gas are recoverable inexpensively. The rest comes from a variety of sources that are associated with higher production costs—poorer fields that require drilling more holes and capitalizing drilling and land costs against smaller product yields; production from continental shelves, deeper basins, and polar regions; and secondary and tertiary extraction. All these activities are, moreover, associated with larger environmental impacts than are used now. If we assume (as we probably must) that cleaning up spills, reclaiming mined out lands to useful purposes, and arranging for disposal of pernicious effluents are all operations whose costs must be internalized, then these dirty fuels become even more expensive.

Coal represents at least two-thirds of our estimated recoverable fossil fuel resources. But mining coal is not a "clean" operation at best, and the more coal that is mined, the more land that has to be torn up and reclaimed. Just as with oil, as the best sources are used up, one must further accept poorer grades, work harder to extract them, and process and ship what is mined. And some of the environmental impacts of using coal, such as large-scale mobilization of toxic materials in slag and ash piles, may persist for millions of years.

The standard observation of resource economists—that one never runs out of a resource but simply reaches a point where it is cheaper to use a substitute—is entirely correct in the case of fossil fuels. We can postulate fossil resources lasting from one to a few centuries, depending on how they are used. So, there is no imminent danger of running out of coal and oil. But we can begin to see the point at which we simply will choose not to use them.

Much before this point is reached, we expect to see a transition in the way fossil fuels are used. Within half a century, and indeed around 2030, we see fossil fuels being used principally for applications where there are no acceptable substitutes—that is, transportable and storable fuels. For such uses we see no substitutes for liquid fuels. For these, we envisage an asymptotic market up to twice as large as the total fossil fuel consumption today. It would be supplied by converting coal and/or heavy oil to gasoline, kerosene, and methanol.

In order to see some semiquantitative features of the situation, we categorized the entries of Table 7-1 in a simpler way. Table 7-2 lists the recoverable resources of fossil fuels dichotomously into "cheap" and "expensive" oil and gas and "cheap" and "expensive" coal. If globally, on the average, 10 TWyr/yr of "cheap" oil and gas were used, then the supply would run out in forty years. Since the world is nonhomogeneous, there would be some regions where local "expensive" oil and gas would be used or "cheap" coal would be substituted for oil, in order to avoid importing oil from other regions. As a result, fifty years from now we can contemplate a world that still has some "cheap" oil and gas left, but also has begun to tap "expensive" oil and gas and to substitute some of its cheap coal for oil.

Prudent resource management would be supported by the increasing price of fossil fuels, so that an era of their restricted use as liquid fuel carriers could last several centuries. Their use in this form might also be required by another possible limitation—the buildup of carbon dioxide in the atmosphere. The effects of this buildup are uncertain, but until there is evidence that they are not severe, prudence dictates keeping carbon dioxide release within reasonable bounds. The projected order of magnitude of liquid hydrocarbon combustion—10 TWyr/yr—seems to be within reason on the basis of what we know now. There is the proviso that if the liquid fuels are to be derived by the hydrogenation of coal, then the hydrogen should, over the long run, be supplied exogenously (in the allothermal method as mentioned in Chapter 3). Processes for burning coal to supply the energy for hydrogen production can be considered only transitional while the proper technological structure is being built up.

The resource base of coal is large enough so that the use of coal as a chemical reagent for producing liquid fuel could continue for several cen-

Table 7-2. Fossil resources, dichotomized.

Resource	*Amount (TWyr)*
Cheap oil and gas	400
Expensive oil and gas	850
Cheap coal	1200
Expensive coal	1200

turies. Other high quality uses of coal, such as its use as a chemical reagent for reducing iron ore, also could be accommodated. Any attempt to build up coal consumption to global levels approaching 25 TWyr/yr or more—that is, to make coal the principal energy source of a high-energy-consuming world—would very much shorten the time over which "liquid coal" could be used; it would also raise the rate of carbon dioxide emissions to above that now considered prudent. Plans for a coal future should therefore emphasize applications and processes that are compatible with the strategic role of coal as a source of liquid fuels.

BIOMASS AND/OR COAL AS LIQUID FUEL?

After the "cheap" oil has run out, the next obvious step for getting a continued supply of liquid fuels is to use "dirty" oil. Following that step, or perhaps avoiding it if environmental factors are favorable, is the synthesis of liquid fuels from coal. But if we recollect that coal, too, is ultimately a depletable resource, albeit a very large one, we can speculate about what might happen when the coal runs out. At that point, the only available source of chemically reduced carbon would be biomass.

If eventually, then why not now? Could biomass supplant coal sooner? Should we be looking harder now at liquid fuels from biomass as a more desirable route than coal? We do not see any clear indication as to the preferable route. There are advantages both to coal and to biomass, summarized in Table 7-3.

Coal's advantages are all intrinsically technological. Indeed, they are the same as those that led to the replacement of wood by coal during the industrial revolution. The advantages of biomass are generally environmental and thus reflect more recent global concerns.

Vitiating the advantages of coal are two factors. First, the existing infrastructure of coal use is a decaying one. New life must be breathed into coal mining, coal hauling, and coal burning. Case studies dealing with the revitalization of coal use have shown that institutionally, coal must be treated as a new industry. Second, with the shifts from burning coal directly to using it as a synthesis chemical, the amount of necessary preprocessing increases.

The advantages of biomass cannot be taken for granted either. Very large land areas are needed for a harvesting effort capable of providing, ultimately, up to 6 TWyr/yr of liquid fuels globally. Added to the needs of humanity for

Table 7-3. Coal versus biomass as a liquid fuel.

Advantages of Coal	*Advantages of Biomass*
More concentrated	Limited CO_2 problem
Needs less preprocessing	Renewable
Disturbs less land, per TWyr extracted	Land disturbances less severe
Uses existing infrastructure	More equitably distributed relative to population

food and natural fiber, fully one-third of the biomass grown on land would then be under cultivation. Even if we assume for biomass, as is recommended for coal, that the maximum of process heat and hydrogen is derived from nuclear and solar origins, then about 25 percent of all forests would have to be harvested. Completely autothermal processes, such as fermentation or processes that rely on wood burning to produce heat and charcoal for further steps, would require a much larger number (about 40 percent). Harvesting even 10 percent of forest growth requires taking a step from ecological responsibility (always necessary) to ecological engineering. Centuries of experience would probably be needed to harvest 40 percent (or perhaps even 25 percent) in a truly benign way. For example, the introduction of fast growing monocultures in an attempt to improve biomass yields and to achieve true "cultivation" of energy crops is an ecological risk that requires generations of experience to evaluate.

Our rather superficial study of how to make liquid fuels from biomass suggests that forests, rather than fields, are the more likely source and that chemical synthetic process routes (e.g., destructive distillation and oxidative hydrogenation to methanol) are more attractive than anaerobic fermentation routes (e.g., the alcohol route). In both of these judgments, the chief concern is to have maximum yields of liquids so as to minimize both land requirements and, in particular, the intrusion of energy harvesting on land needed to grow food and fiber, to provide recreation, and to preserve natural habitats.

The wood-coal dichotomy should be studied in more detail. In particular, the conversion of wood to liquid fuels should be treated as a separate area of research involving both systems aspects and process development. Under these circumstances, we cannot recommend for coal or for wood. Perhaps the biomass harvest would not be sufficient; but even if it were, we can forecast that different regions and countries would opt to prefer one or the other—coal supplies, the suitability of forests for exploitation, and the demand for imported liquid fuels would vary from place to place. And of course, we cannot equate to zero the contribution of field crops such as sugar cane or grains to local liquid fuel supply or that of biogas to local gas supplies. There are, and will continue to be, opportunities of time and place for these sources, even though they are unlikely to loom large in the total energy picture.

Biomass and coal are part of a continuum—living biomass to dead biomass to peat to lignite to coal. At each step of the chain there is both a loss of carbon and a concentration of carbon. In looking for ways of substituting biomass for coal, we are really posing a challenge to human cleverness. Can we be more efficient than nature has been in turning biomass into concentrated energy supplies?

NUCLEAR ENERGY

Potentially, nuclear fission energy can contribute significantly and durably to global energy supplies. Up to now its principal use has been as a source of central station electricity, but fission energy can be used also as a source of low temperature urban or industrial heat, as the energy source for ship propulsion, and as a source of high temperature industrial process heat. This latter application would be favored by the commercialization of high temperature reactors, whose technical feasibility has been proved by several examples. The running of a "hydrogen economy" with fission energy is possible either by direct thermochemical splitting of water or, as is technically feasible now, by electrolysis.

Because nuclear has an extremely high energy content of stockpiled fuel, it is the most portable of all energy sources. Therefore, for many countries, only the large-scale use of this technology offers complete and permanent relief from continued large fuel imports. Deployed fully or only partially, nuclear power could be a backup option for these countries. Similarly, even though reactor types may be chosen that require continued imports of fuel, both the costs and the supply logistics problems are so small compared to those of fossil fuels that nuclear fuels would be preferred in international commerce. For example, such countries as the United States, which might be in a position to export either uranium or coal, would be under much greater pressure to export the uranium.

However, several political factors make a large nuclear supply contribution questionable. A number of issues currently surround nuclear power—notably, the issues of reactor safety, high level waste disposal, and low level radiation standards. Most proponents of nuclear power are convinced that these issues revolve around problems that are technically solved or solvable. Yet these issues have given rise to a sociopolitical antinuclear movement that has had considerable success in delaying the implementation of technical solutions and in slowing the development of nuclear power in many countries. A condition on the widespread use of nuclear power is therefore the resolution of these issues with enough consensus, particularly among the technical communities who are expert in the field, that the political opposition loses its impact. We believe there is more to the problem than this—that the roots of the political opposition stem from the association in many people's minds of nuclear energy with nuclear warfare. This being the case, a further condition on the use of nuclear power (at least as a major or dominant energy resource) is the general realization that the threat of nuclear war and nuclear terrorism is not coupled with nuclear power and is therefore not diminished by banning it.

If the political opposition to nuclear power loses its impact by, say, 1990 or 1995, nuclear could become a principal energy source for the world by 2030 and permanently thereafter. A requirement for realizing that potential is the deployment of fissile material breeding before a significant fraction of the world's high grade natural uranium is used up in less resource-efficient nuclear reactors and fuel cycles. Herein lies the basic dilemma of nuclear fission energy at present. If reactors are installed today at a maximum rate, with the goal of diversifying the global energy resources and solving existing problems with existing technology, then we must build light water reactors (LWRs) based on once-through fuel cycles that consume uranium relatively rapidly. Unless there is an early switch in reactor types and fuel cycles—

especially to breeder reactors but also to more advanced converter reactors employing efficient thorium cycles—the world might be forced into burning "yellow coal"—that is, using uranium from low grade ores whose mining and processing would be expensive economically and environmentally. Alternatively, the nuclear contribution would peak and decline until breeder reactors could build fissile fuel supplies back up. Unfortunately, this latter alternative might occur just at the time when the energy contribution of nuclear fission could be of maximum importance—when fossil fuels are reduced to their asymptotic role.

The rate at which the nuclear option can be built up is limited technically, although this limit is not severe. A global nuclear energy contribution of 17 TWyr/yr could be achieved by 2030 in a high-energy-consuming world whose total primary energy demand would be some 40 TWyr/yr. The 17 TWyr/yr corresponds to an installed electrical capacity of 10 TW(e), operated at a capacity factor of two-thirds and a heat-to-electricity conversion efficiency of 0.4. It requires only normal growth of the nuclear supply industry starting from present technical capabilities and a traditional rate of market penetration (about 5 percent per year) of this new technology into the energy system.

A conceivable limitation on the buildup rate of nuclear power could be the magnitude of the natural uranium resource. We therefore estimated the amount of natural uranium that might be mined from deposits of reasonable uranium concentration globally, 500 ppm or more. Our estimate, 24.5 million tons, is based on the concept that the United States, which has been well explored, is a representative sample of the earth's land mass. This is really just an extrapolation, but it lends credence to the idea that 10 to 15 million tons of natural uranium are likely to be available for building up a high nuclear demand world by 2030. If this uranium cannot be found in concentrated deposits then, it could conceivably be recovered from "yellow coal." However, we consider this latter possibility a last resort.

We explored a number of strategies for building up the high nuclear demand world (17 TWyr/yr) by 2030, paying particular attention to total uranium requirements and the distribution of reactor types that would eventuate. Table 7-4 presents data for two such strategies. The most important finding is that the natural uranium needed to reach the 17 TWyr/yr target by 2030 is, at the maximum, 15 million tons—which is within our estimate of what might be available without resorting to "yellow coal."

After the buildup period, no uranium mining would be needed for a very long time, and the nuclear system could continue to operate at 17 TWyr/yr or even at a slowly escalating level. A number of auxiliary facilities would be needed; these are outlined in Table 7-5. The safety factors and confinement factors—that is, the degree to which the radioactivity associated with nuclear fission energy must be retained in the various facilities and fuel cycle operations—were analyzed and found to be technically achieved or achievable with development.

Our discussion of the nuclear option did not touch on fusion except peripherally. It does not seem to be a major factor within the period of our

Table 7-4. Nuclear strategies (for 17 TWyr/yr from reactors of 10 TW(e) equivalent of installed electrical capacity in 2030).

Requirement	*Converter-Breeder Strategy*	*Multipurpose Strategy*
Total natural uranium[a]	15 million tons	12.5 million tons
Breeders by 2030	4300 GW(e)[b]	3500 GW(e)
Other reactors by 2030	5700 GW(e)[b]	6500 GW(e)
Breakdown of other reactors	All advanced converters on a $\mathrm{Th}^{233}\mathrm{U}$ cycle	5000 GW(e) HTGR, $\mathrm{Th}^{233}\mathrm{U}$ 1000 GW(e) LWR, $^{238}\mathrm{U}^{233}\mathrm{U}$ 500 GW(e) special purpose "pure burner" reactors

[a] This is the quantity of natural uranium that must be mined, cumulatively, up to the point where the breeders produce enough fissile material to keep the whole system fueled.

[b] Actually, by the year 2035 for this strategy. In it, breeders continue to substitute for converters after the year 2030. In consequence, the converter-breeder strategy has a slightly better potential for further growth than does the multipurpose strategy.

Table 7-5. Fuel cycle facilities for a 17 TWyr/yr nuclear industry, 2030.

Operation	*Number of Facilities*	*Individual Facility Capacity*
Fuel fabrication	94	1500 tons of uranium oxide per year
Spent fuel reprocessing	94	1500 tons of spent fuel per year
Liquid high level waste storage tanks	650	1000 m^3 of aqueous high level waste
Waste solidification	94	285 tons of fission products, 1.5 tons of high activity actinides per year
Waste disposal	47	145 tons of fission products and high activity actinides per year, 2850 tons of radioactive materials, equilibrium inventory

study, even if technical and economic problems were solved. The market dynamics would be too slow. Fusion might, however, contribute to the breeding of nuclear fuel, as might the technology of "accelerator breeding." Current prospects for these technologies do not seem to us to be particularly favorable, although it is too early to judge their value.

LARGE-SCALE ELECTRICITY GENERATION FROM RENEWABLE ENERGY SOURCES

Renewable energy sources, including sunlight, have low energy densities. The energy must therefore be collected from a considerable area if large-scale uses are contemplated. This fact generally makes for siting of renewable energy collectors at some distance from centers of demand; otherwise, severe land use conflicts would arise. The opportunistic location of sites reinforces remote siting: hydroelectric and wind power must be generated where conditions are right for efficient collection of energy, and solar energy is much more economic if collected in regions of high, reliable insolation. Thus, most renewable energy forms must be converted into forms that can be transmitted or shipped over considerable distances.

With the exception of biomass, the renewable sources are collected either as heat (solar thermal, geothermal, OTEC), as mechanical energy (hydroelectricity, wind, waves, and tides) or as electricity (photovoltaic). Since neither heat nor mechanical energy can be transmitted efficiently, they must first be converted into electricity. Even transmitting energy in the form of hydrogen requires the production of hydrogen by electrolysis.

Electricity is therefore the proper secondary energy carrier for renewable energy sources, with only three exceptions—biomass, in which energy is stored as chemical binding energy; small-scale uses of direct insolation; and some (wet) geothermal energy, which provides local heat.

Electricity from renewable energy sources can be categorized according to the nature of the source; the service characteristics of the electricity (base loads, intermediate loads, multipurpose, or energy contribution); the rate at which they can be built up to realizable potentials; and the magnitude of that potential. These categorizations are summarized in Table 7-6.

From the properties listed in Table 7-6, we constructed a strategy for building up electrical supply from renewable sources. The strategy is only precise enough for a word description. It assumes, of course, the existence of favorable economic circumstances.

The approximately 3 TWyr/yr electrical supply capability from renewable sources that might be in place by 2030 would satisfy a large fraction of the global requirements for final electric energy. For example, the IIASA High and Low scenarios (see Chapter 17) project about 4.7 and 3 TWyr/yr, respectively, as the global demands for electricity in 2030. The buildup would be paced by the quick development of hydroelectric power and wet geothermal energy to something approaching full realizable potential, the slower insertion of wind power, and the more deliberate installation of large-scale solar electric supplies.

Both wind and solar energy require operation within maneuverable systems, and wet goethermal energy requires peaking capacity. When large-scale hydroelectric power is available, it is possible to store energy and to deliver peak energy within rather broad limits. But hydroelectric power is not always conveniently located near good wind, solar, or wet goethermal supply sites. Also, in some regions it is not economically possible to meet electricity demands by renewable energy sources only (e.g., in Western Europe, Japan, central and eastern United States, areas of Asia). In such cases fossil or nuclear sources of electricity would continue to be required, at the global level of perhaps 2.5 to 3 TWyr/yr of electricity.

This leads to a potential oversupply of electrical energy or to a use limitation on renewable energy sources. Or, if one looks to opportunities, this situation indicates a future role for electricity as a reference energy carrier. We would have to alter our viewpoint about reference energy carriers, as

Table 7-6. Electricity from renewable sources.

Source	*Continuity, Application*	*Deployment Rate*	*Realizable Potential by 2030 (TWyr/yr)*	*Ultimate Potential (TWyr/yr)*
Hydro	Reliable and storable. The only renewable really applicable for base, peak, or any other load service.	Limited only by economic factors. Could be built to full potential by 2030.	1.5	1.5
Wind	Fairly stable, but less reliable; usable for baseload but only if sufficient reserve is available. Otherwise, it must be considered an energy input only.	Limited by general rules of market penetration starting now from a very low level.	≐0.4	1.0
Geothermal (wet)	Reliable and stable for baseload.	Limited only by economic factors. Could be built to full potential by 2030.	0.1	0.1
OTEC	Reliable and stable. Suitable for baseload.	Limited by economic factors and by institutional factors (bringing market to source).	<0.1	0.5
Terrestrial solar (with limited storage)	Intermediate load matches need in sunny areas; requires reserve in less favored areas.	Limited initially by cost as function of location.	≐1	Very large
Space solar	Baseload, extremely reliable.	Cost problematic in view of large infrastructure requirements. Likely to be still in experimental stage by 2030.	<1	Very large
			≐3	

Notes: Sources such as waves, tides, ocean currents, glaciers whose total potential is < 0.1 TWyr/yr by 2030 are omitted. Also such possible conversions as biomass to electricity are omitted. Numbers cited are electrical energy production rates—e.g., secondary energy and, except for transmission and distribution losses, final energy.

is discussed subsequently in this chapter. With electricity as the reference energy carrier, for example, the "hydrogen economy" becomes a virtual corollary, and the concept of an oversupply of electricity becomes meaningless.

Once we have accustomed ourselves to the notion of electricity as a reference energy carrier, it becomes possible to think of much larger energy supplies than a few terawatts coming from sunlight. The amount of available energy is enormous. Its cost targets, although somewhat higher than those for advanced nuclear systems (i.e., fast breeder reactors), are not so high that we can now make a value judgment on economic grounds between these two potential competitors. Since neither breeder reactors nor solar installations represent mature commercial systems, it is still to be determined how realistic these cost targets are. Finally, if public opposition prevents the breeder reactor from being fully deployed regardless of economics, central station solar electricity would probably become the principal global energy source.

Because of very large material requirements, large-scale solar installation could not be achieved as quickly as, say, nuclear power. Nevertheless, we can envisage a global economy in which the chief primary energy form is sunlight, converted to electricity and hydrogen, which is then fed by pipeline and wire to the consumer. This is an analogous situation to the high nuclear demand world outlined earlier.

USER-COLLECTED RENEWABLE ENERGY SYSTEMS

Natural energy flows can be transformed and transduced on both a small and a large scale. Sunlight, wind, and biomass can in principle be captured, transformed, and utilized locally by the final energy consumer. The condition that the consumer be located at the transformation point severely limits the contribution of local energy sources to global energy supply

Consider, first, wind. The windmill has been a picturesque and utilitarian feature of both European and North American life for some time. Its major use has been for pumping water, both for drainage and for irrigation. It is appropriate for this purpose, since pumped water is a "stored" product, and the intermittent operation of the pump is therefore tolerable. Windmills also were commonly used to provide rural energy, but were largely abandoned for this purpose when rural electrification became a reality and liquid fuel deliveries became reliable. Today, windmills may be coming back into rural use for two reasons—improvements that lower their cost and increasing costs of delivered energy. They have never been suggested for urban and industrial use except through the intermediary stage of electric utility operation.

Even so, wind energy might make a respectable supply contribution for the rural population, except for one important fact: only a relatively small fraction of the world's rural population lives in regions where the wind has the characteristics of strength, consistency, and mildness (e.g., low frequency of destructive storms) that are needed to make profitable use of wind energy. Thus, only a small amount of wind energy—less than 0.2 TWyr/yr—is expected to be generated globally by individual user windmills.

Next, consider biomass, which is also a traditional energy source. Fuelwood has been the source of domestic energy for every preindustrial society and of industrial energy in the early stages of the modern industrial era. Its rise and fall coincided with overexploitation of woodlands, leading to fuelwood crises and to substitution of other fuels. Today, fuelwood is used as an incidental form of domestic comfort heating in some industrialized countries, in its traditional campfire role, and as a fuel for cooking in preindustrial societies.

Harvesting biomass and in particular fuelwood for energy need not lead to sylvan disaster. Woods and farms produce a large amount of waste biomass. Although much of this must be returned to the soil in order to retain nutrients and retard erosion, some fraction (perhaps up to half) can be gleaned. And more importantly, properly managed woods and fields can be harvested. The key to successful harvesting is low intensity—for example, for woods—of the order of 2 or 3 percent of the stand per year. Following these principles, woods and fields could be exploited by low density populations up to a level of 1 TWyr/yr. However, this whole process makes large demands on labor, which means a loss of opportunity for more productive work; this can be equated with the abandonment of biomass as an energy source, in favor of more convenient fuels, as income rises. Let us not forget that coal was much cheaper than oil and gas in the United States at the time it was essentially abandoned as a domestic heat source.

Finally, consider sunlight. Solar panels for domestic hot water and comfort heating are a popular topic in the United States and Europe and a growing industry. While there is hope that solar comfort heating will become economic, the point is still debatable; yet as we have seen, this market is not influenced completely by cost. Thus, one can predict a growing use of solar heat in the more industrialized, cooler climates of the world.

Nevertheless, the use of solar heat cannot be large on the global scale for several reasons:

- Much of the world's population lives in warm climates where neither comfort heating nor hot water is a significant energy demand.
- Increased energy conservation in cool zone residences cuts into the required energy inputs that solar power must make.
- Solar energy devices seem to require more user sophistication and more capital than do more conventional forms of energy. The one exception is passive solar uses (storage of heat from direct illumination in internal building structures or, conversely, appropriate shade for cooling), which we did not count as supply modes, but instead incorporated into reductions in demand by conservation. Thus, solar energy devices are less easily adapted for use by the poor than by the rich.

We conclude, therefore, that these sources might make a useful contribution of somewhat less than 2 TWyr/yr, or of the order of 5 to 10 percent, to global primary energy supplies.

ECONOMIC CONSIDERATIONS

We have frequently referred to the ultimate importance of economics in choosing among energy supply alternatives, but have refrained from detailed attention to the specific costs of various options. Economics measures the capacity to invest for future values or to consume for current wishes. What costs more reduces these choices.

Detailed cost comparisons are difficult for several reasons. First, costs can vary greatly from place to place. Capturing wind energy by locating a windmill in a poor area need not cost any more than using one in a good location, but the cost allocated to a unit of energy output would be much higher. The cost of coal varies greatly according to the method of mining, the wage rate of the labor force, and the distance of the user from the mine. Comparisons must therefore be at the local level; even aggregating the world by regions gives a tremendous spread in economics that cannot be described by region-averaged prices.

Another problem of cost comparisons is that both technologies and the economic setting change. Only a few of the technologies we have discussed are technologically mature—LWRs and fossil-fired electrical generation, hydroelectric power, oil, and gas-fired industrial boilers. Some of the most interesting technologies have only cost targets at present: one cannot buy today an economic breeder reactor or a solar-electric converter.

Changes also occur in the economic setting. For example, the relative values of labor and materials evolve with time. Whether coal that is economic when mined by a poorly paid labor force will remain so when that force finds other opportunities for employment is purely speculative. Conversely, a materials-intensive technology (e.g., central station solar power or OTEC) is sensitive to the cost of the materials it uses, while the high use of a material leads simultaneously to an increased price in a sellers' market.

Because of these difficulties, we can categorize systems only by tendencies and qualitative statements. With this apology, such categorization follows.

There are two basic components of cost—those due to the charges on the investment of capital and those due to continued impacts of labor, materials, and fuels. Different evaluators place different relative values on these cost components, and there are unresolved differences, down to the level of economic ideology, as to what these charges should be.

First, we examine capital costs. By and large, the capital costs required to produce fossil fuels, or mineral fuels such as uranium, are low. Therefore, when such fuels are easily available and usable without conversion, there is not much capital contribution. This explains why natural gas, which is both inexpensive to extract and directly usable for many applications, is the fuel of economic choice in gas-producing regions.

There are capital costs associated with transportation and conversion.

These costs have been relatively low for the conversion of oil to final hydrocarbons but will increase as heavier oils come into use. They are low for coal directly used as a fuel (e.g., for electricity generation) in the mining district. They become higher as coal is transported to a distant site and higher still if the coal must be converted to liquid fuel.

The largest capital costs are associated with the conversion of primary energy sources to electricity. The capital costs of gas- or liquid-fueled power plants are lowest; followed by those of coal-fired plants; followed closely by LWRs; by HWRs; then by biomass forms, hydroelectric power, and wind; then by breeder reactors; and finally by direct solar energy conversion. The target costs for breeder reactors are, however, in the range of HWR costs or a bit lower, while the target costs for direct solar electric conversion are competitive with the other solar options. A summary of capital cost considerations is given in Table 7-7.

Table 7-7. Capital cost considerations.

For Fuels Extraction (land, equipment)		
	Source	*Cost*
	Oil or natural gas	Low
	Coal	Moderately low
	Uranium	Moderately low
	Biomass	Moderately high
For Fuel Transportation (rail, pipeline costs)		
	Source	*Cost*
	Uranium	Extremely low
	Oil	Low
	Natural gas	Moderately low
	Coal	High
	Biomass	Very high
For Conversion to Final Energy Fuels (gas or refined liquids)		
	Source	*Cost (of conversion plant)*
	Natural gas	Negligible
	Oil	Low
	Coal	High
	Biomass	Very high
	Uranium	Very high (final energy form as reactor fuel assembly)
For Electrical Generation		
	Source	*Cost (of power plant)*
	Natural gas	Very low
	Oil	Low
	Coal	Moderate
	Biomass	Moderate
	LWR	Moderate, but greater than coal
	HWR	Moderately high
	Hydro Wind	High per unit of output
	Breeder reactor Direct solar	Very high, pending development

Table 7-8. Operating costs of electrical generating systems.

Source	*Cost*
Wind	Very low
Solar	
Hydro	
Natural gas	Low
Oil	Low
Coal (near mine)	Moderately low
LWR, HWR, breeder reactor	Moderate
Coal (far from mine)	High
Biomass	

A second category, that of operating costs, must now be examined. These are all costs involved with processing fuels or with converting fuel to electricity, but do not include the fuel itself. We list these only for electrical generation. They include labor and material costs in mining, transportation, and fuel preparation. For the nuclear option, they include the operating costs of fuel purification, enrichment, fabrication, reprocessing in certain fuel cycles, and waste disposal. For the coal option, they include transportation, boiler feed preparation, stack gas cleaning, and waste disposal. Operating costs are listed in Table 7-8.

A final category is fuel costs, taken as the "economic rent" on the fuel. By this we mean the price commanded by the original owner of the fuel in view of its demand and its scarcity or abundance of supply. These are given in Table 7-9.

Finally, Table 7-10 presents in qualitative form our estimates of the economic position of various energy options. This table is not to be considered a detailed ranking of the supply systems, especially when referring to any specific location. But it does indicate the major features of the existing economic competition. Thus, under "fuels" we find the use of coal near the mine, or the direct burning of biomass, to be cheap wherever the application permits. Oil products such as gasoline or jet fuel are moderately expensive

Table 7-9. Fuel costs of electrical generating systems.

Source	*Cost*
Breeder reactor	Negative
Wind	None
Direct solar	
Hydro	
Biomass	Low
HWR	Low
LWR	Moderately low
Coal	Moderate
Natural gas	Moderately high
Oil	High

Table 7-10. Qualitative costs of energy alternatives.

Source	*Cost*	
Fuels		
Natural gas	Low	
Coal, direct use near mine	Low	Restricted in application
Biomass, direct use	Low	
Coal, direct use further from mine	Moderate	
Crude oil	Moderate	
Oil products (e.g., gasoline, jet fuel)	Moderately high	
Liquids from biomass	High	
Liquids from coal		
Heavy oil products		
Electrolytic hydrogen	Very high	
Electricity		
Hydro	Very low	
Coal, near mine	Low	
Wet geothermal (when available)	Low	
LWR, HWR	Moderately low	
Natural gas (when available)	Moderate	
Coal, further from mine	Moderately high	
Biomass (local)		
Wind	High (can be low in good locations)	
Oil	Very high	
Direct solar	Not currently economic; development could lead to major cost reductions	
Breeder reactor		

and therefore should be used only when the application demands them. Synthetic liquids and gases are currently uneconomic. Similarly, hydroelectric power, wet geothermal, and coal near the mine are the cheapest sources of electricity. When they are not available (i.e., when the demand is not located near such sources), conventional nuclear power (LWRs and HWRs) is the next preferred source. Wind energy in favorable locations can be competitive. Other sources are currently more expensive.

A TRANSITION TO ELECTRICITY AS THE REFERENCE ENERGY SYSTEM

Oil and natural gas taken together produce most of today's global primary energy (5.3 TWyr/yr out of a total of 8.8 TWyr/yr in 1975, including 0.6 TWyr/yr of noncommercial energy; see Table 7-1), with oil contributing the larger part (3.6 TWyr/yr). So dominant is the role of oil that when its price was multiplied by a large factor in 1973, the prices of coal and natural gas followed suit, even though neither of these fuels was controlled by a world cartel. This phenomenon is what defines a reference energy system.

We have seen that the structure of the global energy supply system in the future is likely to be very much changed from today's. At some point, conventional oil must ultimately be replaced by other liquid fuels, elaborately processed (shale oil) or essentially synthesized from carbon (coal- or biomass-derived liquids). As this transition occurs, liquid fuel production and use would become more expensive and would therefore be limited to irreducible application—as transportation fuels and storable energy supplies for sporadic use in dispersed locations. When this happens, it will no longer be possible to consider oil or liquid fuels as dominant energy carriers—what we have called the present reference energy system.

We have also seen that virtually all of the asymptotic energy forms lend themselves to electricity generation. This includes solar power, nuclear fission power, and the most quickly deployable renewables—hydroelectric power, wind, and wet geothermal. Looking ahead to technological possibilities, we again see a variety of systems that generate electricity—fusion, space solar power, OTEC, dry geothermal. The only alternative to electricity that appears possible is hydrogen produced thermochemically from sunlight, but such processes would have to compete with electrolytic hydrogen production, which could turn out to be cheaper.

From these qualitative observations we can see the outline of the future reference energy system in which the reference energy carrier is very likely to be electricity. That is, the price of other forms of energy would be determined by the price of electricity. It seems that the associated secondary energy carrier would be hydrogen. This is in contrast to the present system, in which natural gas and electricity are associated secondary energy carriers.

In discussing electricity from renewable energy sources, we observed that there would be an oversupply if the potential of these sources were developed along with the fossil and/or the nuclear power required to complete and stabilize the electrical system. We also observed that we would have to change our way of thinking about oversupplies of electricity and view this extra capacity as means for generating hydrogen. In other words, we would have to develop a new reference energy system. The change in viewpoint is completely analogous to what Kuhn (1972) has called a new paradigm in scientific thinking as the result and indicator of a scientific revolution. Old questions become irrelevant and new ones become important. In that spirit, we can speculate about the types of new questions that would replace older ones. We divided these questions into three levels—a global level, which comprises the broadest problems and concerns; an industrial level; and a level at which changes in personal attitudes and actions might develop (see Table 7-11).

At the global level, regions and countries that are now grappling with problems of procuring fossil fuels from distant places would shift their attention to questions of whether nuclear or renewable sources of electricity are more appropriate. Concerns about the distribution of oil resources would be replaced by concerns about the distribution of hydroelectric, wind, and usable solar resources and about the possible economies of using the flexibly sited nuclear resource. The growing concern about the carbon dioxide problem is almost certain to be replaced by concerns about land use allocations, and other problems of air pollution would be replaced by

Table 7-11. Old and new energy supply system problems.

	Old Problems	*New Problems (electricity as new reference energy system)*
Global level	Geographical distribution of fossil fuel resources CO_2 emission Environmental pollution from fossil fuel use Structure and power of international oil companies	Geographical distribution of renewable energy resources Land use allocation Radiation health and safety aspects of nuclear power Structure of electricity distribution and transmission institutions
Industrial level	Generation of electricity Gasoline economy of automobiles Cogeneration of electricity Natural gas delivery Metal smelting	Manufacture of liquid fuels Battery and fuel cell efficiencies for electric vehicles Industrial uses of incidental heat Hydrogen pipeline construction Electrical and/or hydrogen reduction processes
Personal level	Operation of gasoline service stations Building cooling as an added convenience factor to comfort heating Cooking with fuels	Battery charge and repair stations Building heating and cooling as a normal result of heat pump operation Microwave cooking

concerns about radiation health and safety. Questions about the structure of the international oil trade would be replaced by questions about the proper way of operating the electricity grid in the public interest. The new questions seem to be easier to face than the older ones, but this may be simply because they are newer questions and can therefore be addressed without having to consider so many existing institutional factors.

At the industrial level, we again see a substitution of processes and associated problems. Just one example will serve as an illustration of the force of new ways of thinking—the "cogeneration-industrial parks" dichotomy. Today, cogeneration is a popular concept—popular because it promises to recover additional electrical energy from heat sources used in industrial processes. If electricity is the reference energy supply, then we must think of associated heat as a by-product to be used at maximum efficiency rather than discarded. Cogeneration is thus turned around, and the electrical generating station acts doubly as a source of thermal energy for industrial parks. Rather than making electricity while burning fuel, we reverse the concept to providing heat while making electricity (with some of the electricity being used to make fuel).

Only a few examples are cited for the personal level. To stimulate related ideas, we call attention to a potential change in the nature of automotive service stations—the transformation of the gasoline pump into a battery-charging station. Likewise, there would be a fundamental change in the

Table 7-12. Resources, production potentials, and constraints.

Energy Type	*Maximum Production Level (TWyr/yr)*	*Product*	*Resource (TWyr)*	*Constraints*
Biomass	~5	Primary and secondary fuels, mostly charcoal	∞	Land use, economy, environment
Hydro	1.5	Electricity	∞	Land use, environment
Other renewables	2 (by 2030)	Electricity	∞	Land use, environment, economy, infrastructure
including solar	1.5	User-collected heat and fuel	∞	Economy, stage of industrial development
Oil and natural gas	8–12	Liquid fuel	1000	Resources, economy, environment
Coal	10–14	Solid fuel	2400	Society, environment, economy
Nuclear				
Burners	4 (by 2030)	Electricity	300	Resources, public acceptance
Breeders	< 17 or < 7 (by 2030)	Heat Electricity	300,000	Buildup rates, resources, public acceptance
Fusion	< 1 (by 2030)	Electricity	300,000	Technology, buildup rates

mechanical nature of automotive maintenance, requiring chemical skills (for the batteries) and electrical skills (for the motors).

A SUMMARY TABULATION

Our best guesses—which we hope can be called informed ones—as to long-term energy supply capabilities are shown in Table 7-12. There has been a great deal of rounding off of numbers that were previously exhibited, which more correctly reflects the low precision of most of the numbers. As can be seen from the table, there are many resources that are either vast, or effectively infinite, or truly infinite. What we are not as sure about is whether these resources can be produced at a rate commensurate with our needs. Taking into account maximum production levels for 2030, the global rate of secondary energy supply by the year 2030 seems to be certainly less than 40 TWyr/yr—perhaps much less. Coal, oil, and natural gas burned at a combined global rate of 18 TWyr/yr would produce carbon dioxide emissions at three to four times the present rate; the production of energy from biomass and renewable sources requires resolution of enormously important land use and environmental problems; and nuclear power production at a thermal global rating of 17 TWyr/yr requires public support that is not visible now. About 25 TWyr/yr of secondary energy of high quality (electricity and liquids), recovered from about 40 TWyr/yr of primary energy, provide the energy services of a high energy demand world of 2030. It would not take much shortfall of our expectations to miss this objective by the year 2030. So if there is a need for energy, failure to have developed diligently all of the sources could result in severe problems, even fifty years from now. Ultimately, very large amounts of both nuclear and solar power could be supplied, but only well after 2030.

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III CONSTRAINTS

8 MARKET PENETRATION

INTRODUCTION

In this chapter we examine a simple method for describing the evolution of the energy system that gives insight into patterns of future energy use. The analysis is based on the concept of energy sources as commodities competing for shares of the market. It is assumed that primary and secondary energy sources, and energy supply systems, are subject to market demand in the same broad sense as, say, steel production technologies and household detergents. In adopting this concept, we modify and apply a number of mathematical models that have been used to project patterns in which one technology may arise to substitute for another. The technique offers a new way of describing the likely evolution of future energy systems in that it shows the shares of the energy market held by successive fuel systems over time.

For understanding the evolution of future energy systems, a first and obvious step is to examine historical trends of energy consumption. We analyzed primary energy consumption of the world and of individual regions and countries, starting at the middle of the nineteenth century. Our findings show that if the contributions of different energy sources are expressed as fractional shares of total energy consumption, then the evolution of energy systems can be described as a continuous substitution of new for old energy technologies.

In the following sections we discuss models of technological substitution for two competing technologies and then describe the evolution of energy systems using a similar approach. We explain our analysis of historical substitution patterns and takeover times, indicating how these data can be used for estimating a realistic buildup rate for new technologies. Finally, we use this approach to provide additional insight into the projections of the two IIASA energy demand and supply scenarios for the year 2030 (which are described in Part IV of this book) and present a theoretical discussion of our method and our conclusions.

A LOGISTIC SUBSTITUTION MODEL

The initial working hypothesis of this study, proposed by Marchetti (1975), is that primary energies resemble the behavior of different technologies competing for a market. Consequently, the pioneering analysis of technological substitution by Mansfield (1961), later extended by many others, is also applicable to energy systems. Mansfield's work, as well as numerous other studies of the technological substitution process and market penetration of the technological innovation, is based on the logistic function. The logistic function, although not the only S-shaped function, is perhaps the most suitable one for analyzing growth processes both because of the ease in interpreting the meaning of its parameters and because of the simplicity in estimating the parameters from the observed phenomena. Another S-shaped function, the Gompertz curve, also has been used frequently, particularly to describe population, plant, and animal growth (see, e.g., Richards 1959).

The widespread empirical applications of the logistic function as a means for describing growth phenomena also originated in studies of human population, biology, and chemistry. The first reference to the logistic function can be found in Verhulst (1838, 1845, 1847). Pearl (1924, 1925) rediscovered the function and used it extensively to describe the growth of population, both human and biological. Since then, numerous studies have been conducted, only to confirm the logistic property of most growth processes. Robertson (1923) was the first to use the function to describe the growth process of a single individual. Later, the function was advanced for use in bio-assay (see, e.g., Emmens, 1941; Wilson and Worcester, 1942; and Bergson, 1944), in studies of growth of bacterial cultures in a feeding solution, for autocatalyzed chemical reactions, and so forth.

Griliches (1957), in his study of the diffusion of the hybrid corn seed in the United States, was one of the first to use the S-shaped curve to describe technological substitution. He showed that hybrid corn replaced traditional corn seed in different states in a very similar way, the S-shaped substitution being only displaced in time by a few years and lasting for longer or shorter periods in different states.

Following the work of Griliches, Mansfield (1961) developed a model to explain the rate at which firms follow an innovator. He hypothesized that the adoption of an innovation is related positively to the profitability of employing the innovation and negatively to the expected investments associated with this introduction. Mansfield substantiated the theoretical implications of his model by analyzing the diffusion of twelve industrial innovations in four major industries.

Mansfield's findings were further extended by Fisher and Pry (1970),[a] who considered only fractional shares of a market controlled by two competing technologies. They postulated, on the basis of their analysis of many substitution processes, that the rate of fractional adoption of a new technology is proportional to both the fraction of the market penetrated by the new technology and the fraction of the market held by the old technology still in use. They assumed that this substitution proceeds to completion once it has progressed as far as a few percent of the market.

THE FISHER-PRY MODEL

Mathematically, the Fisher and Pry assumptions can be written as the differential form of the two parameter logistic function:

$$f'(t) = \alpha f(t)\ [1 - f(t)]$$

where $f(t)$ is the fraction of the market that the new technology has penetrated at time t; $[1 - f(t)]$ the amount of old technology still in use; and α the factor of proportionality—or in Mansfield's language, the rate of adoption. This differential equation shows two convenient properties of the logistic function. The function has both the property of exponential growth—that is, the proportionality to the amount of growth achieved, $\alpha f(t)$—and the property of constrained growth—that is, the proportionality to the amount of growth left to be achieved, $\alpha[1 - f(t)]$. It is limited by two asymptotes, one from above and one from below, $0 < f(t) < 1$; and the maximal rate of growth $f'(t_o) = \frac{\alpha}{4}$ is achieved at the inflection point t_o where $f(t_o) = \frac{1}{2}$.

This differential equation is solved by rearranging the terms and integrating both sides of the equation:

$$\ell n \left[\frac{f(t)}{1 - f(t)}\right] = \alpha t + \beta \text{ or } f(t) = [1 + exp(-\alpha t - \beta)]^{-1}$$

where ℓn is the natural logarithm and β is the constant of integration.

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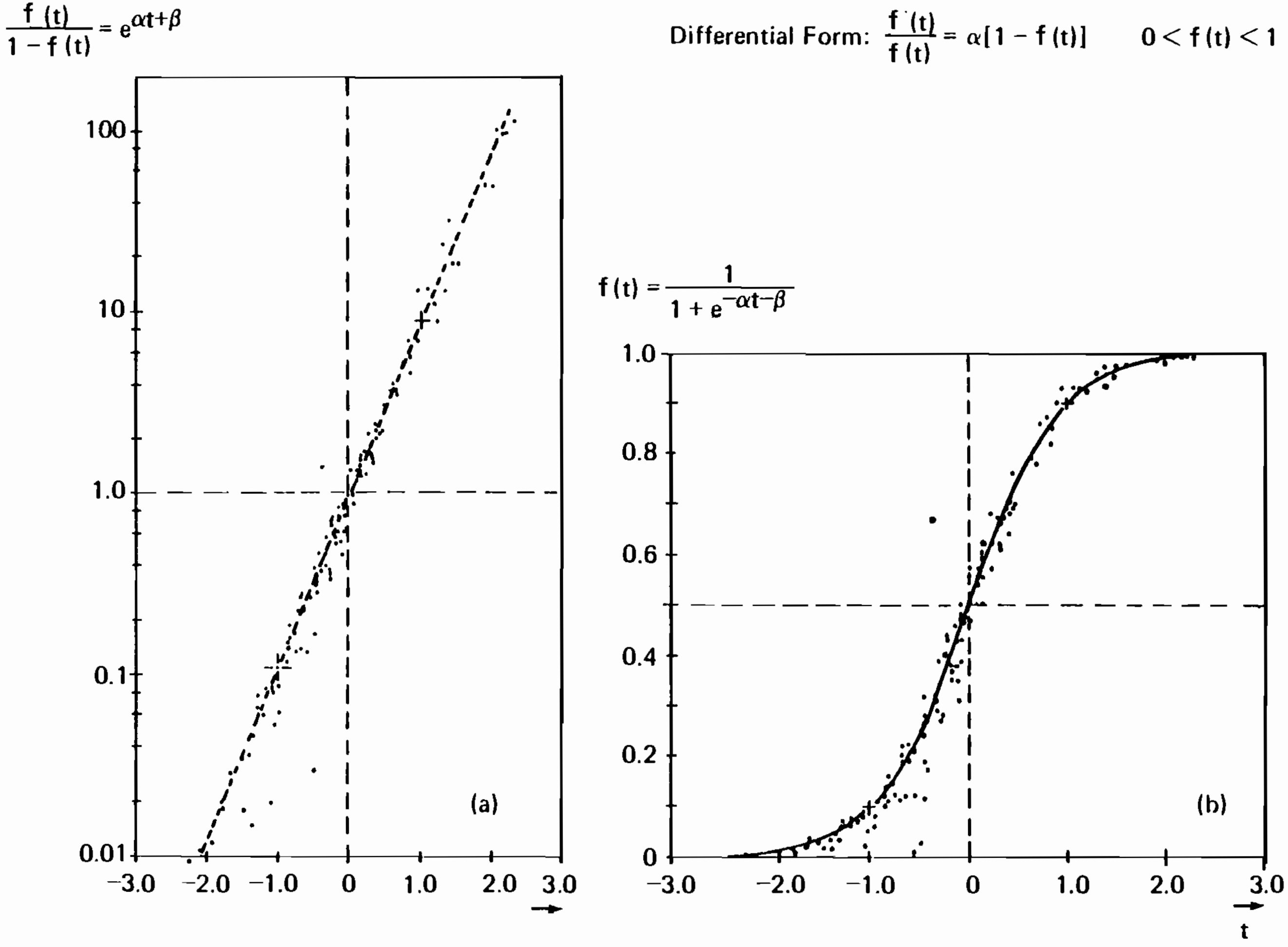
[a] We deal here with the Fisher-Pry model in somewhat greater detail because it is a standard reference in the field of technological substitution and because it has properties that we found useful for describing the substitution of different energy sources. Fisher and Pry did not deal with energy substitution, but there have been other applications of the logistic function in the energy field. Hubbert (1962) used the logistic function to estimate the cumulative proved discoveries, cumulative production, and proved reserves for crude oil and natural gas for the United States. Penner and Icerman (1974) extended this approach by considering the cumulative proved discoveries as shares of the ultimate cumulative proved discoveries.

Figure 8-1. The logistic function: exponential growth in a limited environment. The fit of the logistic function to the substitution data for seventeen cases against normalized units of time. *Source:* Adapted from Fisher and Pry (1970).



$$\frac{f(t)}{1-f(t)} = e^{\alpha t+\beta}$$

$$\text{Differential Form: } \frac{f'(t)}{f(t)} = \alpha[1 - f(t)] \qquad 0 < f(t) < 1$$

$$f(t) = \frac{1}{1 + e^{-\alpha t-\beta}}$$

The Fisher-Pry formulation implies that, in fractional terms, the substitution path of a new for an old technology over time tends to take the form of the logistic function, perhaps the simplest of all S-shaped functions. This type of fractional substitution is characterized by slow initial growth followed by more rapid growth, which decreases thereafter in a phase of slow growth and eventually saturates when the final level of adoption of an innovation is achieved. In the Fisher-Pry model, the substitution saturates in a complete takeover of the market and not at some lower fraction.

The characteristics of the logistic function describing fractional substitution are illustrated in Figure 8-1 which shows the seventeen substitution cases studied by Fisher and Pry and the logistic fit of these data as a smooth line. The plot on the right-hand of the figure shows the S-shaped form of the function and the scatter of the observed data around the trend line. The plot on the left-hand side shows another convenient property of the logistic function for empirical analysis. When a sample of data points is plotted in this way, the scatter of these transformed data points has a straight line trend, provided that these points can be described by the logistic function. In Figure 8-1 this is the case, the straight line being the logistic fit of the data. On both curves the time has been normalized at the inflection point (t_0) of the curve, where the fractional share equals 0.5 and the slope of the curve is the steepest.

Such plots illustrate how the logistic function can describe technological substitution, not only for very different products and technologies, but also for different types of economies. However, this aggregated representation makes individual substitution processes indistinguishable from each other. Figures 8-2 and 8-3 highlight some of the examples analyzed by Fisher and Pry. The plots show the remarkable regularity of these substitution processes.

ENERGY SYSTEMS AND THE LOGISTIC SUBSTITUTION MODEL

Over the previous 115 years, global primary energy consumption (including commercial use of fuelwood) increased exponentially at an average growth rate of 2.2 percent per year. Yet during this period energy consumption did not draw equally from all sources, nor did the use of all energy sources increase equally.

Figure 8-4 gives the global primary energy consumption since 1860, according to five major primary energy sources[b]—wood, coal, oil, natural gas, and nuclear. Energy consumption is plotted in terms of absolute shares in tons of coal equivalent (tce) per year. Figure 8-4A gives consumption according to these five energy sources on a linear scale; Figure 8-4B gives

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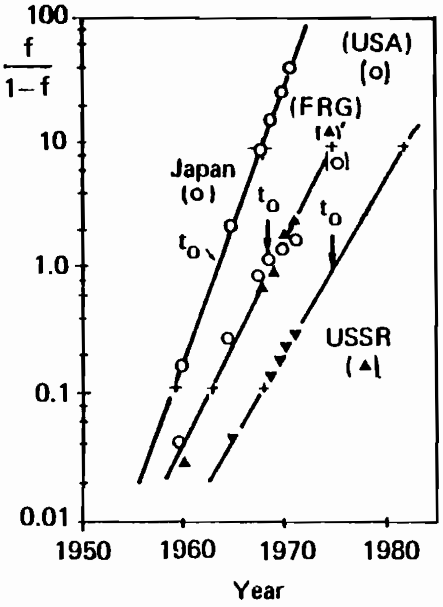
[b] Although hydroelectric power is also an important energy source, it has remained a relatively constant fraction of total supply; for our purposes here (the analysis of the dynamics of energy substitution) its inclusion would only complicate the analysis unnecessarily—hydroelectric power never exceeded a market share of a few percent.

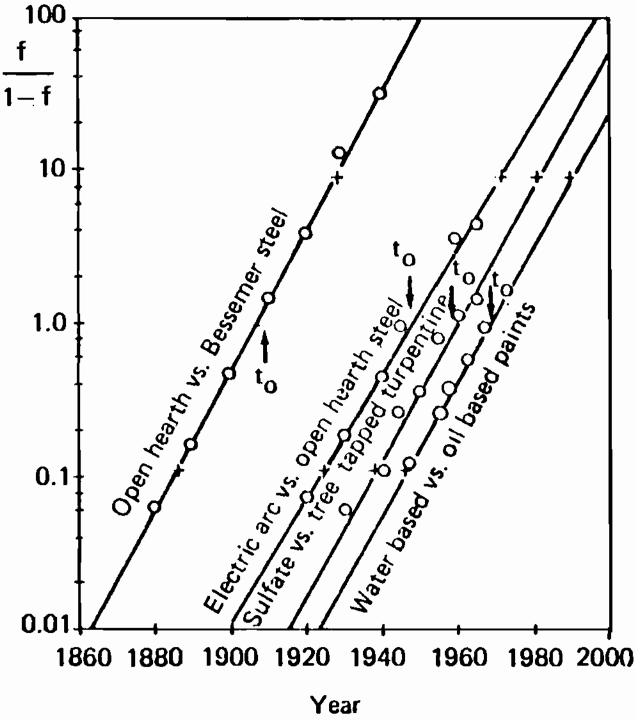
Figure 8-2. Substitution of basic oxygen furnace for open hearth and Bessemer steel production expressed by fractional market share (f) for Japan, the FRG, the United States, and the USSR. The triangles and the circles on the middle line respresent, respectively, the FRG and the United States. Source: Pry (1973).



consumption on a logarithmic scale. It is evident from these two plots that the initial growth of energy sources is exponential, but that many features apparently related to economic and political events influence energy consumption. The consumption of coal, especially during the time when coal held the largest share of the market, is subject to great fluctuations that coincide with the two world wars and the intervening period of worldwide economic depression.

Figure 8-5 shows the fractional shares of the market taken by these five energy sources, again on a linear scale and a logarithmic scale, respectively. In the logarithmic plot the fractional shares (f) are not plotted directly but as the straight line fransformation of the logistic curve, as $f/(1-f)$. (The properties of this transformation are illustrated in Figure 8-1.) Two important characteristics of energy systems can be seen from these plots. First, the enormous fluctuations of the absolute consumption levels of coal after the turn of the century have in part disappeared from the plot of fractional shares. Second, the presence of some straight line trends on the logarithmic plot indicates where the fractional substitution of energy sources follows a logistic curve. Thus, we can observe that energy substitution is similar at least in one respect to the technological substitution patterns observed by Fisher and Pry. This plot lends strong support to our approach of treating energy sources with the logistic substitution model. Figure 8-5

Figure 8-3. Technological substitution expressed by fractional market share (f) in production of steel, turpentine, and paint. t_0 represents the 50 percent substitution mark; crosses indicate, respectively, 10 percent and 90 percent marks. Source: Fisher and Pry (1970).



also shows that in the case of multiple competition, logistic substitution is not preserved in all phases of the system. This point is well illustrated by the substitution path of coal, which curves through a maximum from increase to decline of its market share.

In order to describe this substitution system by a logistic model, Marchetti and Nakicenovic (1978, 1979) modified the Fisher-Pry assumptions, introducing the constraint that all market shares sum to one—a constraint that, for the case of only two competitors, is implicit in the Fisher-Pry model. In order to satisfy this constraint, they made certain assumptions about the behavior of a competitor in transition from logistic growth to logistic decline. The rules determining this competition process are phenomenological. Basically, it is assumed that the market share of the oldest still-growing technology—for example, coal—can be defined as a complement to one of the sums of other fractional shares following logistic substitution paths. Thus, the oldest still-growing technology takes the residual of the market, but eventually its share starts to decline and becomes logistic again. Subsequently, the next newer technology—oil in this example—would undergo this transition from growth to decline.

THE LOGISTIC SUBSTITUTION MODEL (MARCHETTI AND NAKICENOVIC 1978, 1979)

Without going into details, the logistic substitution model may be illustrated by the following simplified analytical treatment:

Let there be n competing technologies expressed in terms of their historical market shares

$$f_i(t) = [1 + exp(-\alpha_i t - \beta_i)]^{-1}, i \neq j, i = 1, \ldots, n$$

and assume that they are ordered chronologically in the sequence of their appearance on the market. After the coefficients α_i and β_i have been estimated over a certain historical interval for the technologies in the logistic substitution phases, one gets n logistic equations. Now choose the oldest still-growing technology, j, to enter the residual phase and let its market share be defined by

$$f_j(t) = 1 - \sum_{i \neq j} [1 + exp(-\alpha_i t - \beta_i)]^{-1}$$

where j is identified by the fact that $\alpha_{j-1} < 0$ and $\alpha_j \geqslant 0$.

One needs only $n - 1$ sets of coefficients α_i and β_i, because the estimated coefficients are not required to determine the fraction of technology j.

The transition from growth to decline would be completed for technology j and would begin for technology $j + 1$ when the function $f_j(t)$ becomes logistic on its way down. This would be the case when the straight line transform of $f_j(t)$ approaches a constant. This point of constant slope may be approximated by requiring that the relative rate of change of the slope be minimal on the way down—that is,

$$\frac{y_j''(t)}{y_j'(t)} \longrightarrow \underset{t_j < t \leqslant t_E}{\text{Min!}} \quad \text{and } y_j'(t) < 0, \text{ where } y_j(t) = \ell n \left[\frac{f_j(t)}{1 - f_j(t)}\right]$$

where t_j is the time that the jth technology entered the residual phase and t_E is the end of the period.

Once this condition is satisfied, say at time t_{j+1}, $t_j \leqslant t_{j+1} < t_E$, new coefficients for technology j are determined as follows:

$$\alpha_j = y_j'(t_{j+1}) \text{ and } \beta_j = y_j(t_{j+1}) - y_j'(t_{j+1})\, t_{j+1}$$

Technology $j + 1$ now enters its residual phase, and the process is repeated until the last technology, n, becomes residual or the end of the time period, t_E, is encountered.

Only time t and the estimated coefficients α_i and β_i extracted from historical data, ordered in the sequence of the appearance of the technologies on the market, are treated as independent variables.

Figure 8–4. Global primary energy consumption, major energy sources. (A) linear scale; (b) logarithmic scale. Appearance of straight line trends on B shows exponential growth of consumption.

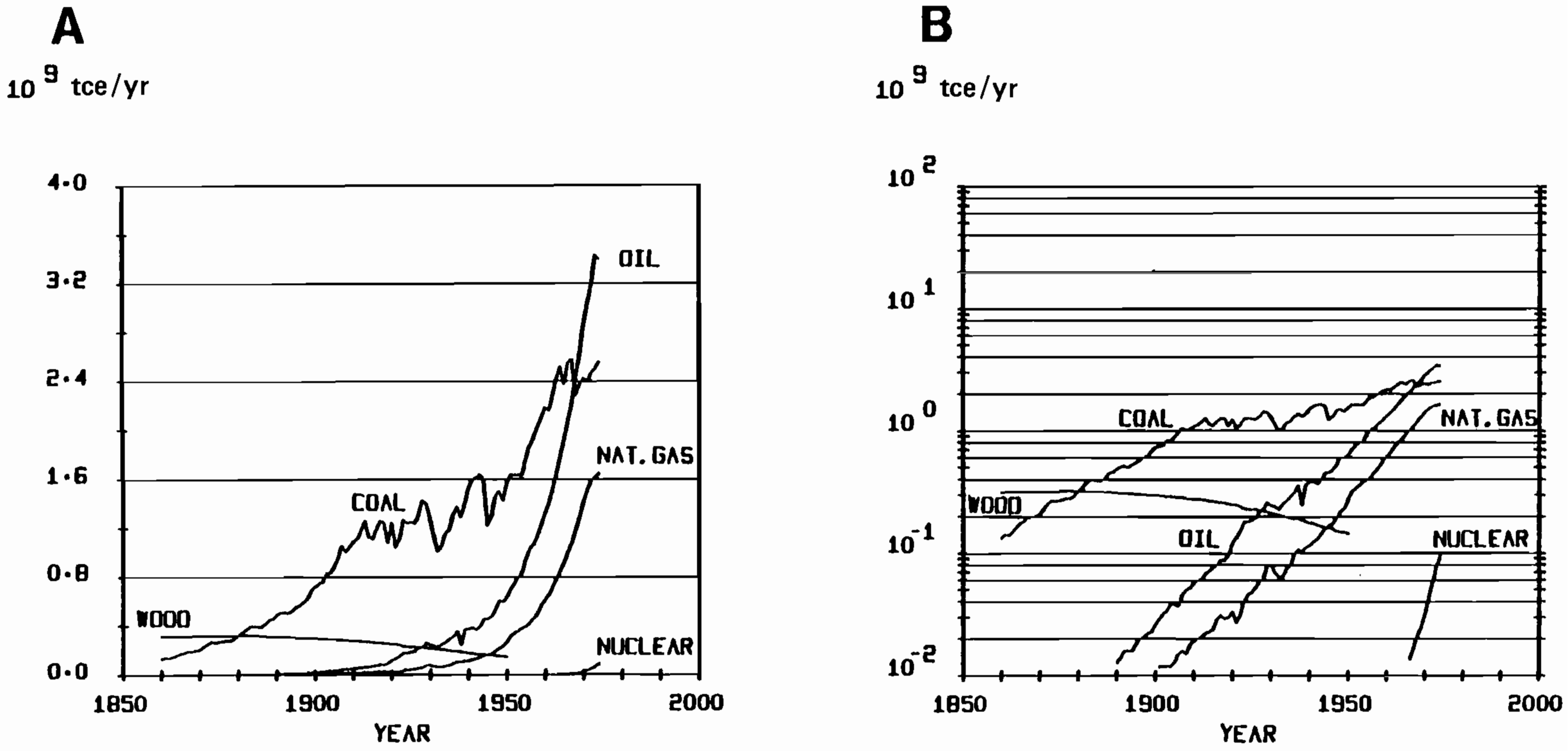
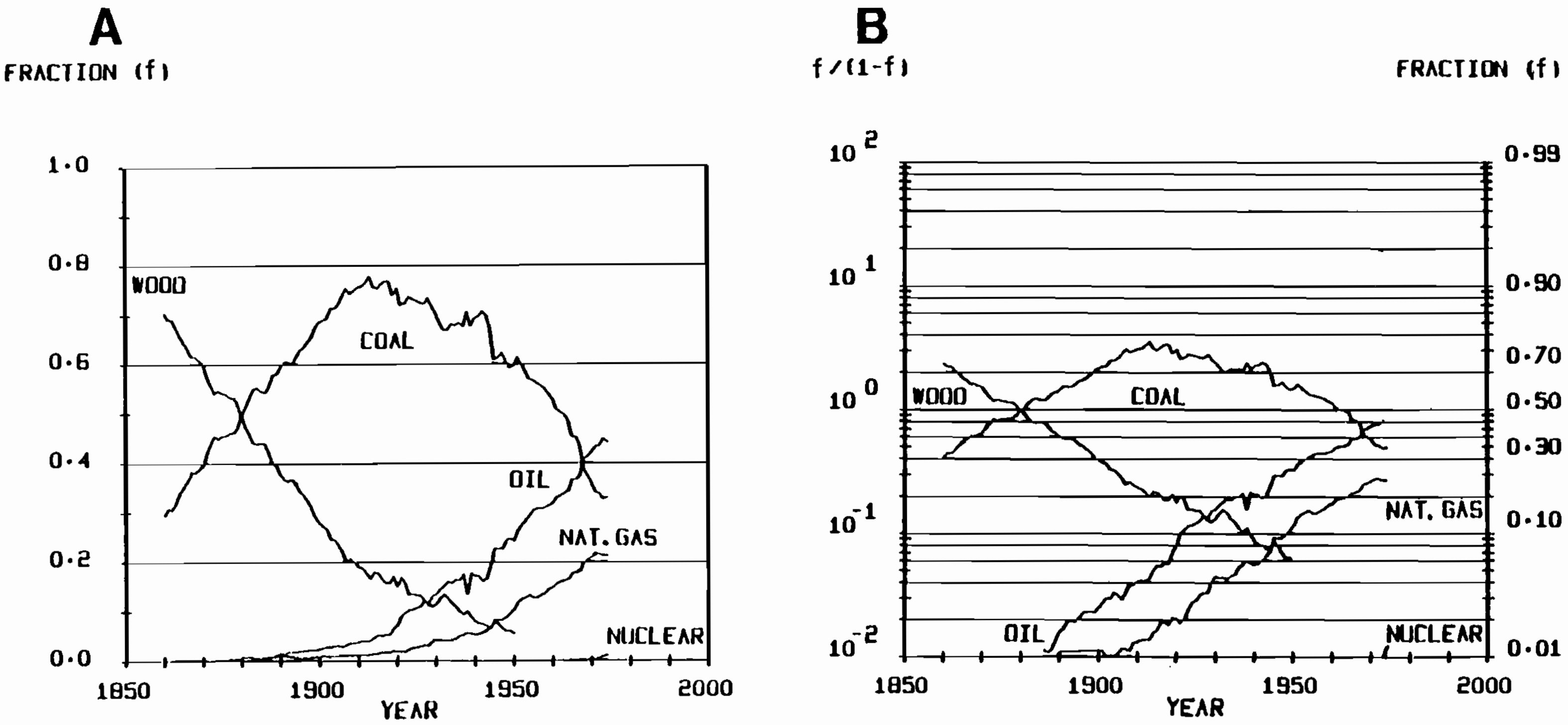


Figure 8-5. Global primary energy consumption expressed as fractional market shares. (A) linear scale; (B) logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share.

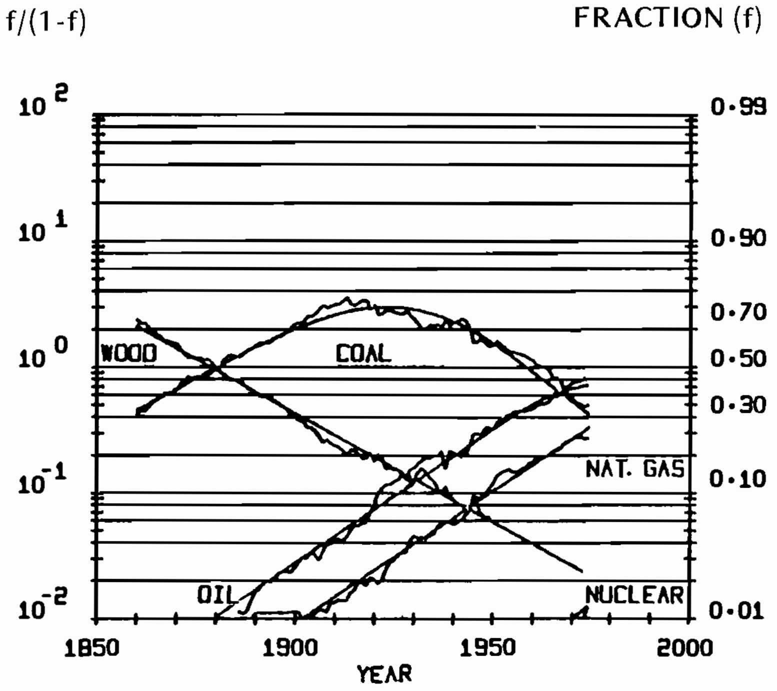


In order to indicate the potential and limits of this energy substitution approach, Marchetti and Nakicenovic applied their empirical model to examples from three different levels of energy systems—global primary energy consumption, primary energy consumption in single countries, and different energy subsystems (e.g., electric utilities and final consumers). Altogether they used sixty different data bases to examine 300 examples for thirty different countries and energy subsystems. These examples cover most of the representative world regions and countries, and in all but a few cases, the quality of prediction of the historical energy substitution process was consistently very good.

HISTORICAL ANALYSIS OF ENERGY SUBSTITUTION

Figure 8-6 reproduces the global substitution of the five primary energy sources plotted on a logarithmic scale as the linear transform of the logistic function. The smooth lines on the plot are model estimates of the historical

Figure 8-6. Global primary energy substitution. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data from Figure 8-5; straight lines show the logistic model substitution paths.



data; the straight lines show where energy sources follow logistic substitution paths. This result is encouraging, since it indicates that this kind of model is capable of reproducing the evolution of fractional shares of energy substitution with very high accuracy. The scatter of the historical data is in good agreement with smooth lines generated by the model. Significant deviations from the trend lines can be observed only during short time periods. Note that the penetration trends have almost the same slope for all energy sources except nuclear energy, which controlled slightly more than a 1 percent share of the market in the early 1970s and is hardly visible on the graph. Note also that during the initial phases of the market penetration, the market shares do not immediately stabilize to long-term substitution trends. Oil penetrated somewhat faster until it reached a 2 percent market share, while natural gas controlled almost a constant 1 percent of the market for over a decade, before both sources stabilized to their long-term substitution trends.

These results show that the market penetration of primary energy systems appears in regular substitution patterns that can be observed from historical data for long periods of time. One of the problems in analyzing periods of one hundred or more years lies in the underlying inconsistencies and gaps in the recorded data. Nevertheless, the logistic substitution model discussed above is very robust in that it produces stable estimates of historical market shares on the basis of very limited input of information.

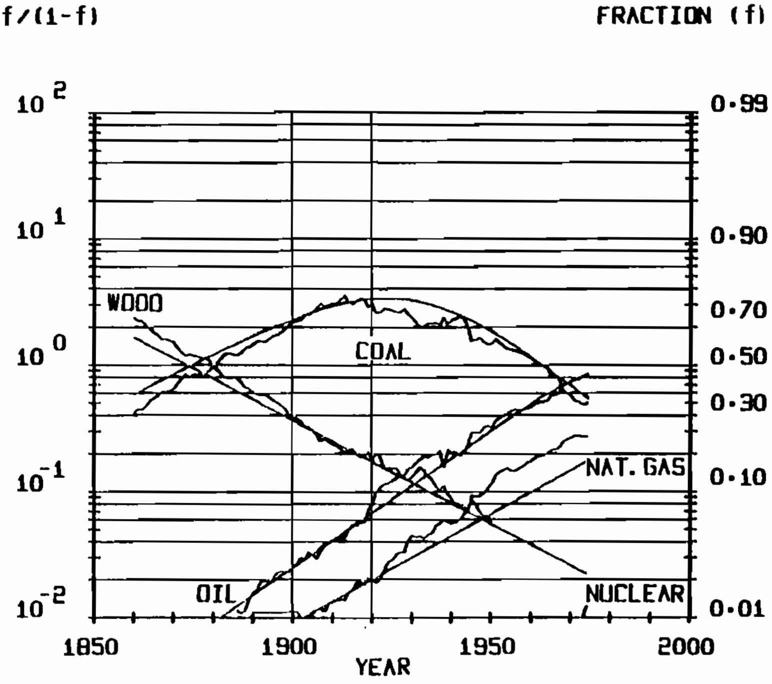
For example, from Figure 8-5 one may take the period from 1900 to 1920 to estimate coefficients of the model. With the data base of only those twenty years, by means of the model it is possible to draw the global pattern of primary energy substitution for the entire period 1860–1974, as shown in Figure 8-7.

The smooth lines in Figure 8-7 give the model's "backward" and "forward" extrapolations of energy use from the data of the twenty-year segment. One possible disadvantage of selecting those twenty years as a data base is that at the beginning of this period natural gas had just penetrated the market with a 2 percent share and consequently its substitution path then was still conjectural. However, the model's forecast from the limited base period to the 1970s is remarkable in that it shows extraordinary agreement with the data from the later years.

By means of these plots and stepping backward in time, it can be seen that even before the First World War, and in spite of the intervening economic depression and the Second World War, one could have predicted the current energy supply situation. Moreover, the oil embargo of 1973–1974 does not appear to affect the long-term substitution trends. The fact that oil has now reached its maximum market share is, reading from the model, a manifestation of the trend that was initiated in the 1920s when natural gas first entered the market as a competitor.

The outline in Figure 8-8 of the primary energy substitution pattern for the United States also brings order to the welter of statistical data for the period 1860 to 1974. Here one sees that the substitution process is very smooth and rather fast until 1920: coal peaks around that date, and oil about forty years later. In this application as well, if the projection were

Figure 8-7. Global primary energy substitution, short data base. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are "backward and forward" extrapolations of energy use from twenty-year historical data segment, although data for entire historical period are plotted; straight lines show the logistic model substitution paths.

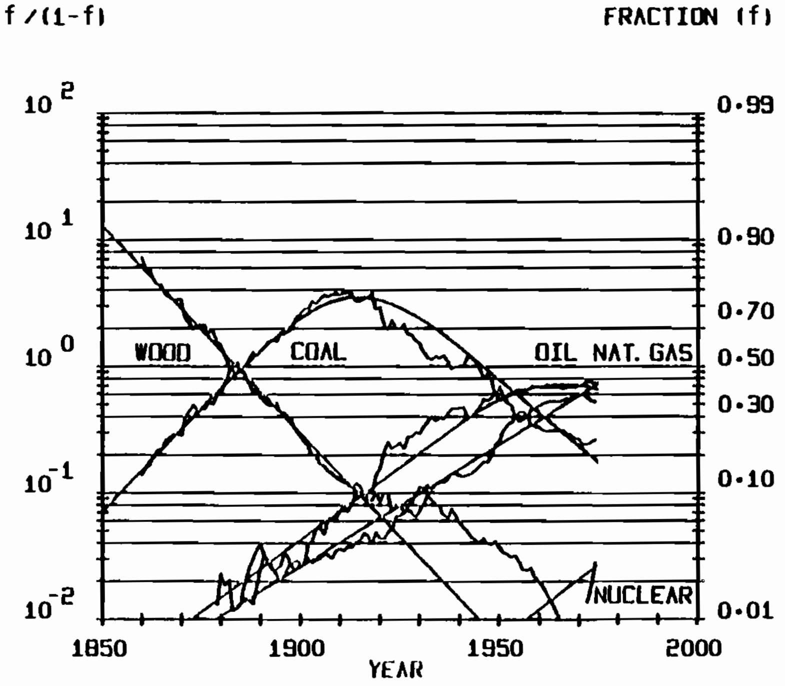


based on data covering a few decades around the year 1900, both of these peaks could have been anticipated much in advance. Thus, the peaks should not be associated solely with events such as wars, economic depression, or the recent oil embargo; as in most of the other cases examined, these events produced only disproportionately small deviations from the long-term substitution paths.

What is unexplained is the drop, during the Depression years, in the relative consumption of coal below the long-term substitution path; nor can we explain the corresponding increase in the use of oil while natural gas consumption remained essentially unaffected. Interestingly, by the 1940s these irregularities are "absorbed," and the overall system retains the long-term substitution patterns established at the beginning of the century in spite of a perturbation lasting for twenty years. Again, there is an indication of the strong internal structure of the substitution process and of the rigid timetable that the system follows, largely independent of outside influences.

The next two examples show the dynamics of substitution in two different

Figure 8-8. Primary energy substitution, United States. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



energy subsystems in the United States. The first example, in Figure 8-9, shows that the competition of four different forms of energy for market shares in the household-commercial sector is characterized by the intensive use of more convenient forms of energy supplied by networks that have rather long development times. This substitution behavior is in good agreement with the primary energy substitution pattern presented in Figure 8-8, underscoring the complex substitution interrelationships at the level of the whole energy system.

The second example, in Figure 8-10, shows the primary energy inputs to electricity generation in the United States. Here, nuclear energy already controls more than 10 percent of the market, so one can assume that its historical penetration rate has stabilized.

Another peculiarity of the system is that natural gas was used more extensively than oil for electricity generation even during the years after the Second World War. A possible explanation is that although oil was cheap and well established as an almost equal partner to coal on the level of total primary energy consumption, in the electricity submarket the

Figure 8-9. Household-commercial sector energy substitution, United States. (A) linear scale; (B) logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.

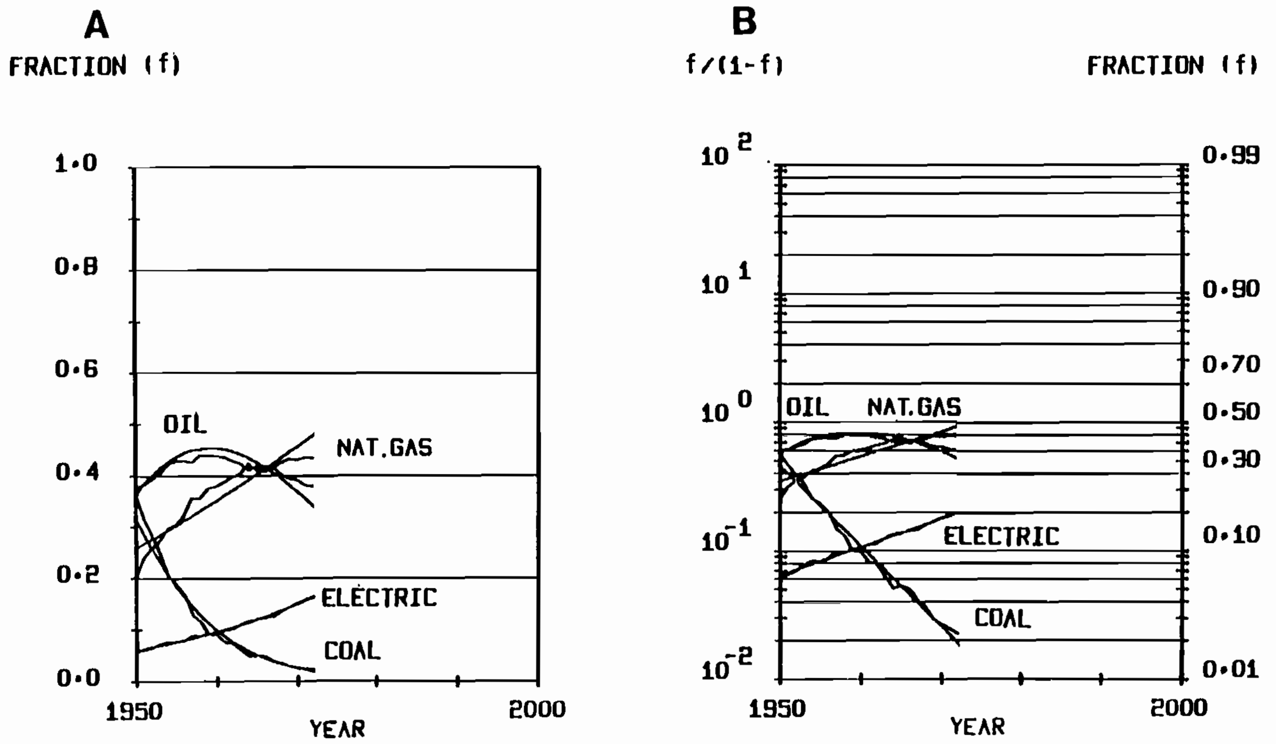
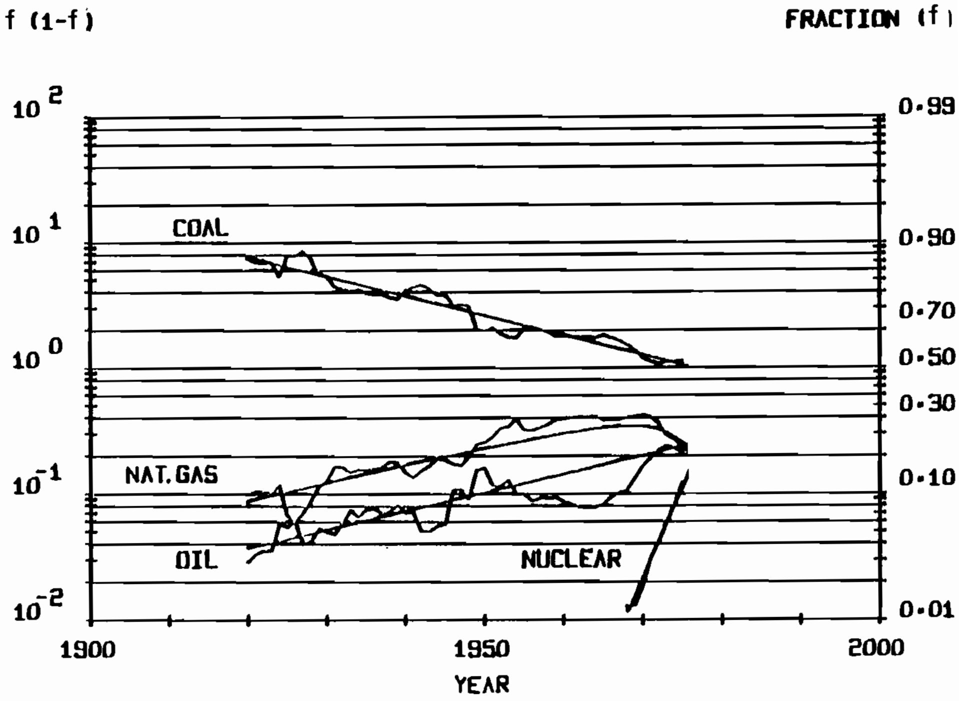


Figure 8-10. Primary inputs to electricity, United States. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



stringent gas price regulation had a decisive effect. However, by 1970 natural gas and oil had about equal shares of 30 percent each. Note that the substitution of energy inputs to electricity generation is consistent with the primary energy substitution for the United States given in Figure 8-8.

Several other examples for different countries or groups of countries were also examined, and the model was almost invariably found to fit the historical data quite well (Marchetti and Nakicenovic 1978, 1979). In general, the larger systems followed the logistic substitution paths much more closely than the smaller ones. We have already seen that the data agreement is extremely good when considering global systems. A plausible explanation is that local perturbations are averaged out in the larger systems.

TAKEOVER TIMES AND BUILDUP RATES

The substitution rates that are so evident with the logistic substitution model can be characterized by the notion of "takeover time"—that is, the hypothetical time it would take a certain energy form to increase its market share from 1 to 50 percent. In fact, the unexpected capacity of this approach to "organize" historical data and to extract the information from very restricted sets of data is related to these very regular takeover times. At the global level it was seen that takeover times are about one hundred years. Similar stable takeover times were observed for all of the other cases studied. However, it was generally noted that the smaller the region or the country, the shorter were the takeover times—for example, in the European member countries of the Organisation for Economic Co-operation and Development (OECD), takeover times were of the order of thirty years. Natural gas penetration is a good example: in most European OECD countries, it took less than ten years before natural gas had 10 percent of the market.

However, in the electricity submarket in the United States, the takeover times of natural gas and oil were more than one hundred years before nuclear energy entered the market, while coal remained unaffected during this period. The electricity submarket is characterized by decreasing takeover times and should be contrasted with the opposite trend observed for the household-commercial sector. In primary energy substitution patterns in the United States, takeover times have been long and stable, on the order of seventy to eighty years.

Related to takeover times is the concept of "buildup rates." As already noted in the discussion of the dynamics of how new technologies replace old ones, the new technology generally requires a very long time in order to capture a sizeable part of the total energy supply. It would be worthwhile to examine the buildup rates of the "new" technologies of the past in order to obtain a benchmark for orientation on the buildup rates of projected new technologies.

The buildup rate may be defined as the exponential growth rate of the new technology in absolute terms as it grows from 1 to 10 percent of the market it serves. Table 8-1 gives the market penetration rates as well as the build-

Table 8-1. New technology buildup rates.

	Technology	*Penetration[a] Rate (%/yr)*	*Buildup[b] Rate (%/yr)*
World primary energy supply	Oil	4.9	6.8
	Natural gas	4.8	6.8
U.S. primary energy supply	Oil	5.3	7.7
	Natural gas	4.5	7.0
OECD-Europe primary energy supply	Oil	10.0	13.3
	Natural gas	15.7	20.7
	Nuclear	6.9	10.4
U.S. inputs to electricity supply	Nuclear	31.0	36.0

[a] Penetration rate is the annual growth rate of the market shares $f(t)$ expressed as $\ell n\ [f(t)/(1-f(t))]$ —i.e., the coefficient α in our model. (See explanation in text on page 260.)

[b] Buildup rate is the exponential growth rate of the new technology in absolute terms as it grows from 1 to 10 percent of the market it serves.

up rates of the various energy supply technologies from the examples already discussed. The buildup rates listed in this table have been estimated from model parameters rather than from historical data, because of the often erratic behavior of the actual data when new technologies are just beginning to satisfy a share of supply. It may be seen that these rates are faster for smaller geographic regions or smaller markets. The buildup rate for nuclear power in the United States, for example, is especially fast.

A SECULAR RULE OF ENERGY SUBSTITUTION: LONG-TERM PROJECTIONS OF MARKET SHARES

The preceding discussions have shown that energy substitution is a very complex process, rich in variation as one ranges from different primary energy markets to respective submarkets. One invariant is the regularity of the substitution process within the system, overshadowing all short-term perturbations and deviations from the long-term trends. The examples taken from global primary energy consumption have shown that the internal structure of the logistic substitution model is robust in that it operates even with limited inputs of information. It thus lends itself to making projections not only "backward" into the past but also into the future.

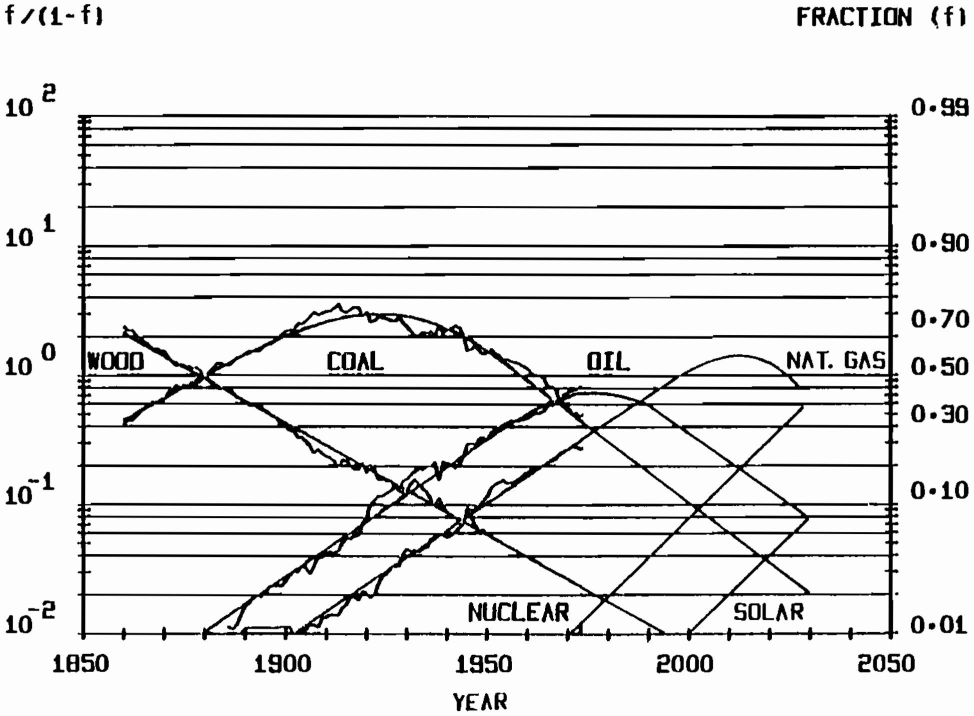
In presenting our approach as described here, we have sometimes encountered an a priori reservation, if not objection, to it. This reservation maintains that the model appears to be deterministic and to lack certain logical links to the generally accepted theories usually applied in forecasting and modeling and should therefore be rejected even if it is successfully applied to the past. In this context we observe the following:

- One should not simply disregard a body of evidence even if it does not fit a certain perception of reality.
- A projection with this substitution model cannot be a complete one. The starting dates and rates of growth of new technologies successfully conquering the market are not endogenous to the model. Also, the model deals with market shares and not with absolute quantities. One must know the absolute level of energy production before the full picture can emerge.

We therefore explore the market penetration constraints affecting the evolution of new technologies (nuclear and solar) in the future energy system by applying the logistic substitution model in what we now consider an appropriate way. The results are shown in Figure 8-11, where the time scale extends to the year 2030. Three observations are in order here.

1. We assume exogenously that nuclear power starts penetrating on a commercially significant scale—that is, 2 to 3 percent of the market—by the year 1970 and that the penetration rate for nuclear power is at the upper end of penetration rates for other forms of energy experienced so far. Such values are nevertheless still somewhat below the rates

Figure 8-11. Global primary energy substitution, 1860-2030. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



experienced for nuclear over the previous decade. The resulting share for nuclear energy in 2030 is 40 percent (see Figure 8–11).

2. We again assume exogenously that solar power starts penetrating on a commercially significant scale by the year 2000 and that the penetration rate for solar power is the same as that explained above for nuclear power. For solar power we thus arrive at 7 percent of the primary energy market by the year 2030.
3. Natural gas seems to take on an ever-increasing share, at least until 2020, leading to values beyond 50 percent (see Figure 8–11).

The first two observations seem to tell us that the transitions take time. A 40 percent nuclear share by the year 2030 is significant, but at the same time, it indicates clearly that an energy supply based mostly on nuclear is not realistic. And a 7 percent solar share is less than what many people hope for today. Note that a 7 percent solar contribution to, for instance, 22.4 TWyr/yr (the IIASA Low scenario projection for global primary energy consumption in 2030) would be the equivalent of 22 million barrels of oil per day (mbd) or 1.6 TWyr/yr. This is a large undertaking when seen in absolute terms.

Regarding the third observation, the potential of natural gas is large, and many energy strategies have not taken this fully into account yet. In Chapter 2, we examine the potential of natural gas; Chapter 17 describes the contribution of natural gas to the IIASA High and Low scenarios, while in Chapter 18 we present an alternative case of nuclear moratorium based on the exploration of the potential of natural gas.

We do not regard these observations as predictions based on ironclad laws of reality. As noted, only a part of the market penetration phenomenon is covered by the model endogenously; assumptions that are exogenous to the model must be made in order to apply it to the future. For instance, we had to assume (in observation 2 above) that solar power would start penetrating on a commercial scale by the year 2000.

Some additional comments on the nature of these observations are in order here. The logistic substitution model has as its object the energy system as a whole. This includes not only the development and production of related hardware and software, but equally, the sociopolitical institutional framework in which the system operates. Often, it is argued, explicit government support could straightforwardly enhance the use of a particular technology. This is true for the prototype and demonstration stage of such a technology. But once such a technology has conquered a few percent of the market, it is the system that controls the further market penetration of that technology. It is only then that the logistic substitution model becomes relevant. Again, the larger the system, the greater the applicability of this model. As illustrated in Figure 8-11, the object is the *global* energy system. Regional or local systems might more easily be made to behave differently. Indeed, the logistic substitution model reveals the "ponderousness" of the energy system—that is, the stunning regularity of the system evolution. Large efforts are needed to avoid these regularities. This is not an impossible task. In fact, the supply effort as defined in the two IIASA scenarios (see Part IV of this book) is a way of doing just that: the projected buildup of new energy supplies exceeds the penetrations suggested by the logistic substitution model (see Figure 17-19).

THE THEORY OF LOGISTIC SUBSTITUTION

Recently, two theoretical developments of the logistic substitution model were proposed at IIASA. The first approach, by Peterka (see Peterka 1977; Peterka and Fleck 1978), follows the work of Mansfield (1961) in that it treats economics as the driving force in the substitution process. In this approach, a simplified investment policy for competing products is assumed, and costs are compared with expected profits. This work confirms that the substitution process can be explained by the application of existing knowledge about the economic incentives affecting producers' decisions.

Basically, Peterka eliminates prices from this initial formulation of the

MACRODYNAMIC SUBSTITUTION MODEL (PETERKA 1977)

Peterka assumes that an industry has to generate profits in order to expand, according to

$$\alpha_i P'(t) = P_i(t)[p(t) - c_i] + Q_i(t)$$

where α_i is the capital needed to increase the production of product $i = 1,2, \ldots ,n$ by the differential amount of total production, $P_i(t)$; $p(t)$ is the price that a unit of each product i brings on the market; c_i is the cost of producing a unit of product i; and $Q_i(t)$ is the external capital extended to the producer of product i. $Q_i(t)$, however, can be neglected in the long run, because it is required only by nonprofitable technologies, and such technologies are rarely supported for very long time periods.

Omitting $Q_i(t)$, the basic equation can be rewritten as

$$\alpha_i \frac{d}{dt} [\ell n P_i(t)] = p(t) - c_i$$

or by taking any two technologies, i and j, subtracting the two equations, and assuming all α_i to be equal—that is, $\alpha_i = \alpha$ for $i = 1,2, \ldots ,n$:

$$\frac{d}{dt} \left[\ell n \frac{P_i(t)}{P_j(t)} \right] = \frac{c_i - c_j}{\alpha} \quad , i \neq j$$

Because all terms on the right-hand side of this differential equation are constants, we can rename them α_{ij}; we can also eliminate the total production by introducing fractional market shares, $f_i(t) = P_i(t)/[\Sigma_j P_j(t)]$; finally, by integration we have

$$\frac{f_i(t)}{f_j(t)} = e^{\alpha_{ij} t + \beta_{ij}}$$

This solution is also the final form of the Fisher-Pry model when we assume $n = 2$. It implies that the fractional substitution of any two technologies, out of many competing, is logistic.

A general solution of this model can be obtained in a number of ways; we use here the simplest, starting from an identity

$$f_j(t) = \frac{f_j(t)}{\sum_i f_i(t)} = \frac{1}{1 + \sum_{i \neq j} \frac{f_i(t)}{f_j(t)}} = \frac{1}{1 + \sum_{i \neq j} e^{\alpha_{ij} t + \beta_{ij}}}$$

Given the n–1 sets of coefficients α_{ij} and β_{ij}, which are determined from historical data, the substitution process of all n technologies is determined. Peterka also shows that the fluctuations of the parameters are smoothed over time so that only the mean values are significant.

model by introducing fractional shares in place of the total production levels. The competition between any two energy sources can also be described in this model by logistic functions. Following this approach, Peterka was able to obtain a general formulation of the model, incorporating all possible pairwise substitutions. In general, this formulation of multiple substitution produces estimates of historical substitution encountered in energy systems that are indistinguishable from those obtained by the phenomenological model illustrated in Figure 8-6.

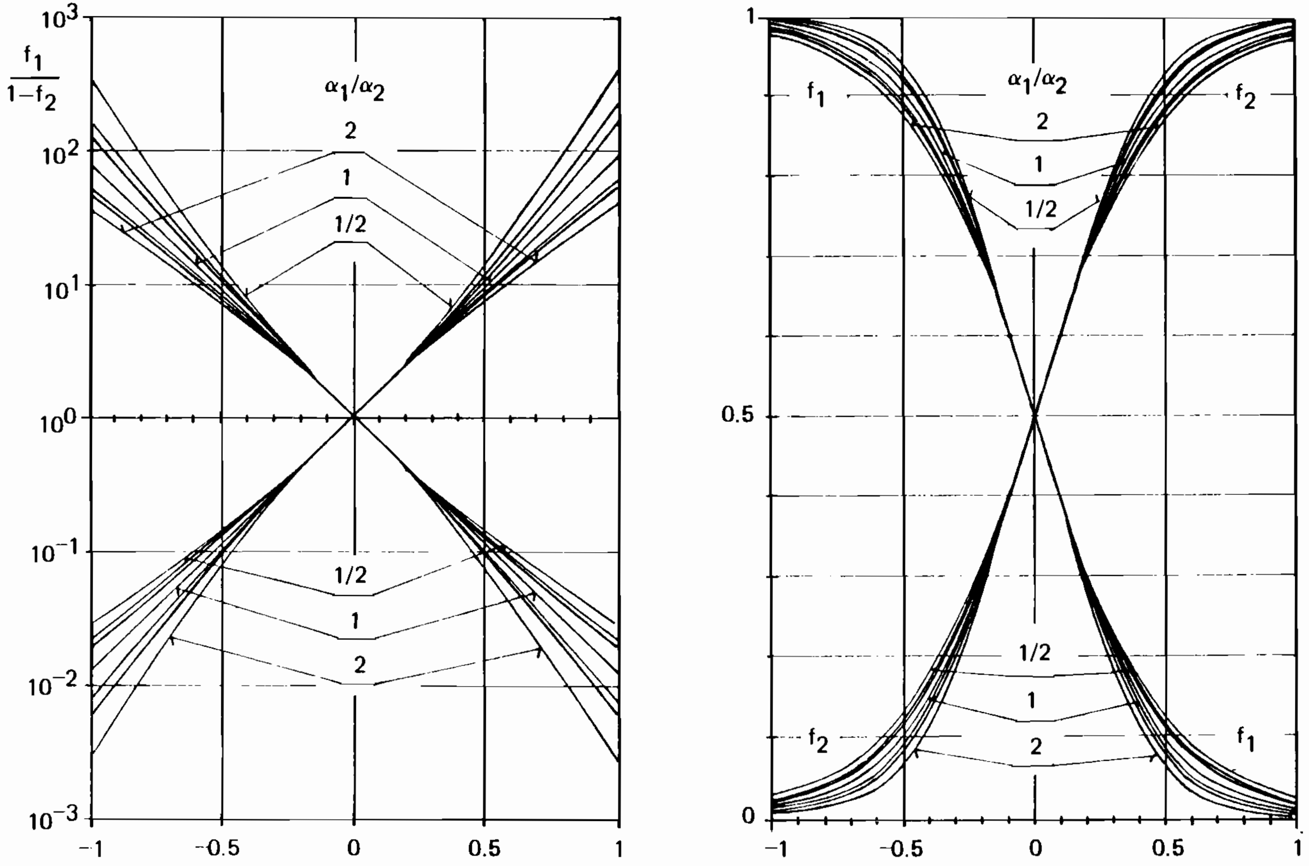
A positive feature of this approach is that market price and absolute production levels—both of which are subject to great variation over time—are eliminated. Remaining, then, are only fractional shares, relative costs of production, and investments embedded in the model coefficients.

As a result, if specific investments for different energy sources (α_i) are all equal, then the substitution process follows the logistic model. Peterka also showed that this simplifying assumption can be relaxed and that long-term substitution paths do not change much when the specific investments are slightly different. While it is true that different specific investments lead to nonlogistic substitution rates, it can be seen from Figure 8-12 that substitution processes can still be approximated by logistic functions for a large range of ratios of different specific investments (α_1/α_2)—in this case for only two competitors (n=2). This confirms the empirical observation that, in practical cases, the logistic model adequately describes the substitution process even when the specific investments are different. More importantly, this result supports the assumption that historical penetration trends can be used to estimate the long-term substitution path of a new technology once it controls a few percent of the market.

The second model, proposed by Fleck (see Peterka and Fleck 1978), uses basic assumptions about the adoption of an innovation by a single individual. Fleck considers only those innovations that proved successful, so that the old established product is fully replaced eventually by the innovation. The individual's decision whether to adopt an innovation once it is proved successful depends on his imitation behavior. In the model, the rate of imitation of all individuals lumped together is proportional to the market share achieved by the innovation. This expresses, in Fleck's terms, the learning aspect of the imitation—the higher the level of adoption, the larger is the flow of information about the innovation, which generates additional stimuli to adopt.

This formulation led Fleck to use the nonstationary, absorbing Markovian chain for describing the substitution process of two competitors, where the transition probabilities can be interpreted as the rate of limitation. In this way, the individual decisions to adopt are aggregated, assuming homogeneity and causal independence of individual decisions. The model takes on a stochastic character. When aggregated, the individual decisions—although linked to complex social and psychological processes—result in an envelope of individual decisions representing the rate of penetration of an innovation. The causality of individual decisions disappears on the level of a whole market; thus, the process is described stochastically.

Figure 8-12. Sensitivity analysis of different specific investments. Investments α_i lead to nonlogistic substitution rates; nevertheless the logistic function can be used as an approximation for a large range of ratios of different specific investments—in this case for only two competitors where: $\alpha_1/\alpha_2 = 1/2, 2/3, 3/4, 1, 4/3, 3/2, 2$, and f_1 and f_2 are fractional market shares (i.e., $f_1 + f_2 = 1$).



Not surprisingly, two theoretical explanations, differing radically in nature, can be given. In the preceding section we explained that the object of the model is the global energy system as a whole, which includes hardware and software and sociopolitical institutional frameworks. Given this complexity, the two theoretical explanations represent two approaches to this complexity, and it is not unlikely that even more explanations could be found. They then mutually shed light on each other. Indeed, for instance, prices and costs in the Peterka model have something to do with the individual's behavior when faced with innovations in the system under consideration and vice versa.

CONCLUDING REMARKS

Our initial objective was to provide a self-consistent, objective, and yet simple method for describing the past behavior of energy systems. The approach adopted showed that regular patterns can be distilled from historical data, that the internal structure of the substitution process is robust, and that it can also be related to traditional economic theory. The logistic substitution model based on this approach reproduces the historical evolution of a large number of energy systems and subsystems (about 300 examples were investigated) so well that its applications to the future should provide useful guidelines to systems analysts.

The substitution process is remarkably regular. This has important implications. When we consider the takeover time as the measure of the time it takes the substitution process to go from 1 to 50 percent of the market share, it turns out that these times are of the order of one hundred years for the global system as a whole and somewhat shorter—of the order of about thirty years—for smaller systems. The takeover time extends over several decades and is fairly constant for any given system, so that we must also consider time as a constraint similar to natural resource and environment constraints. Because of both the long lead times for introducing innovations and the long response time of the energy system, decisions taken today would have their full effect only in the decades to come.

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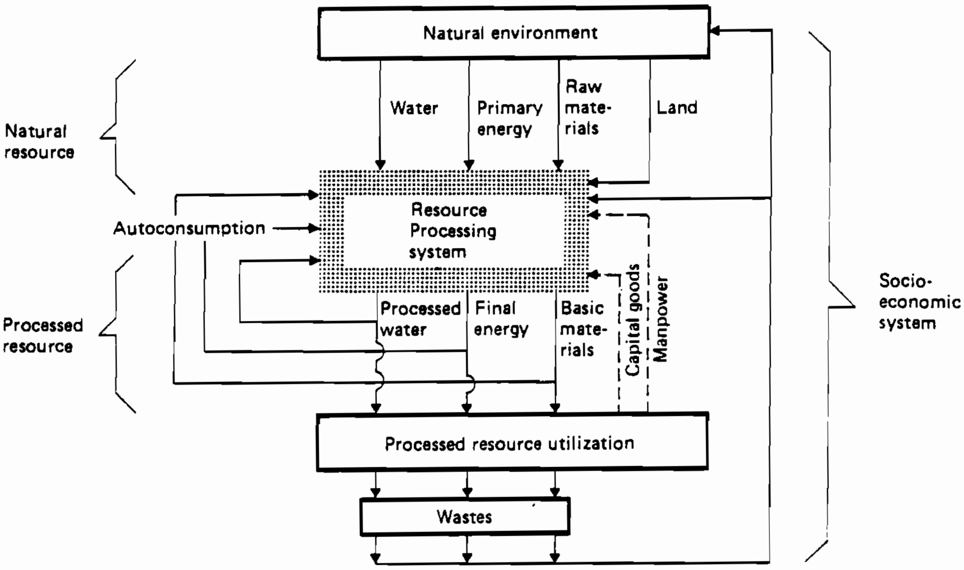
9 THE WELMM APPROACH TO ENERGY AND NATURAL RESOURCES

INTRODUCTION

Natural resources, and especially energy resources, are not generally used in the primary state: they must be processed in order to be available to the final consumer. A resource processing system is schematically shown in Figure 9-1.

Most of the activities within this system are becoming more costly for several reasons. First, there is a need to exploit less easily obtainable resources—for example, offshore oil and mineral ores located in remote areas. Up to now, generally, natural resources at hand have been utilized; hereafter, both extraction and transportation costs will probably increase, although this may be counterbalanced in part by technological progress. Second, because lower grade resources are being used, there are more processing requirements—for example, upgrading lower grade mineral ores, water treatment, and possibly sea water desalination for some uses. Third, increased ecological constraints (e.g., reclamation of land disturbed by open mines; construction of wet and later dry cooling towers for large power plants) are also contributing to these increased processing costs. In general, such costs are expressed as increases in the consumption of economic resources (processed resources, manpower, land, capital) and eventually also of natural resources. Thus, if the objective of the resource-processing system is to convert natural resources into processed resources, then the primary resource

Figure 9-1. Resource processing system.



efficiency or the net primary resource balance of the system would decrease, since it would consume larger amounts of natural resources for its own operation.

Although most natural resources seem to be in relatively large abundance globally, the situation appears different when one considers their availability at specific locations, in specific forms, or in economic terms. For example, globally there are about 7500 m^3 of clean water available per capita (excluding sea water). Nevertheless, the availability of clean water is a problem in many large cities and in some regions—for example, in Colorado for meeting the requirements of oil shale processing and in Wyoming for coal conversion plants. Similarly, globally there are about 37,000 m^2 of land per capita, of which 10 percent is arable. But it is becoming increasingly difficult in industrialized countries to open new surface mines or to find suitable and acceptable sites for new energy facilities such as power plants or refineries.

Global energy resources are also enormous if considered in their own right. However, periodically there are fears of resource scarcity—the current "energy crisis" being one example.

The problem of resource scarcity cannot be solved by considering each resource separately. In fact, proper resource management calls for a global analysis that considers all the qualitative and quantitative interrelations of the natural resources. These interrelations lie largely in the technologies used both to extract primary resources and to convert them into useful resources, each process defining a certain combination of resources and manpower. These interrelationships are summarized in Table 9–1 for mineral fuels.

The mining of coal, for example, can interfere with surface or underground water resources. For example, at Garsdorf, in the FRG, it is necessary to handle on the average more than twelve tons of water for each ton of coal that is extracted. Water is also required, at a later stage, for reclaiming the land that has been disturbed. The mining of coal also requires energy (e.g., electricity, motor fuel) for such operations as blasting and removing the overburden and/or the coal and transporting the coal. Whether coal extraction is underground or, still more so, open cast, a severe burden is imposed on the land used and on the landscape, although such disturbances are becoming more temporary. Materials handling is another problem that is encountered in coal mining for the handling of not only the coal (or mineral) being gained but also the overburden, the sterile rocks, and so forth. The deeper the deposits exploited by surface mining, the greater the amount of materials to be handled (in addition to the water already mentioned). For Garsdorf, the overburden material to be handled varies from a few tons to about fifteen to twenty tons per ton of lignite extracted. And, of course, all such operations—coal extraction and moving, overburden and water handling, land reclamation—call for skilled manpower.

What has been briefly shown here for one operation—mining—and for one energy resource—coal—is applicable, at different levels, to other operations of all energy chains (transportation, conversion, distribution, utilization) or to other energy resources, be they nonrenewable resources such as oil, gas, or uranium or renewable resources such as solar, tides, and wind. Thus, to be able to use a processed energy resource (i.e., final energy), man has to interfere with and use other natural (and human) resources.

A systems analytic method called WELMM has been developed at IIASA and applied to the problem of determining energy strategies. WELMM stands for an assessment of the requirements and the availability of Water, Energy, Land, Materials, and Manpower resources. The basic tools of the WELMM approach are described in the appendix to this chapter.

APPLICATIONS OF THE WELMM APPROACH

The WELMM data can be combined either statically or dynamically, in order to compare various energy strategies on a local, national, regional, or global basis. The studies carried out so far include WELMM comparisons of several electricity supply chains (Grübler and Cellerier 1979), and of different production processes for synthetic liquid fuels (Grenon, Merzeau, and Grübler 1979), as well as assessments of WELMM requirements/impacts of different energy supply strategies at a national/local level (Groupe Ressources de l'HASA, 1979; Grenon and Gourmelon, 1980). The first two studies are of interest globally and are therefore discussed below in more detail.

Table 9-1. Systems aspects of an energy chain (mineral fuels).

Activity / *Resource*	*Harvesting Fuels*	*Upgrading Fuels*	*Transporting Fuels*	*Conversion to Electricity*	*Reprocessing and Management of Final Waste*
Water	Interaction with ground water resources Land reclamation Wastes and water pollution	Water for cooling Process water Liquid wastes	Waterways Coal slurry pipelines	Water for cooling (once through or wet towers)	Water for cooling Process water Liquid wastes Possible interaction with runoff and/or ground water
Energy	Energy is used at all steps; it is deduced from the raw energy content of the fuel being harvested and used for obtaining the final primary energy efficiency of the whole chain				
Land	Surface mining Deep mining (subsidence) Infrastructure: roads, related facilities Waste storage	Facilities	Roads Rights of way: railways, high voltage lines Underground pipelines	Facilities (siting problem) Wood, lumber for construction	Facilities (siting problem) Waste storage
Materials	In equipment and facilities, materials investments at all steps (problems of future recycling)				
	Consumed materials Materials handling and control Waste	Materials control and balance Chemicals Waste	Pipes, cars, tankers, etc. Materials handling	Consumed materials Problem of recycling	Consumed materials Chemicals Materials accounting (possible safeguard)

The WELMM Comparison of Electricity-Generating Chains

One of the first applications chosen was a study of electricity-generating chains, each chain being defined as a set of energy facilities needed to extract, upgrade, transport, and convert the primary energy so as to obtain electricity (see Figure 9-2). Nine chains were compared for producing the same amount of electricity—6.1 TWh—each with a thirty year life span: four chains produce electricity from coal, three from nuclear power, and two from solar power. The major characteristics of these chains are given in Table 9-2 and are summarized below.

Coal 1 and Coal 3 reflect the present status of the technology, whereas Coal 2 and Coal 4 represent an advanced technology and meet the environmental constraints. Coal 1 and Coal 2 have an underground coal mine, and Coal 3 and Coal 4 have a surface mine with a stripping ratio of 2 : 1. The power plant in each case is a 1000 MW(e) unit.

The nuclear chains comprise 1000 MW(e) power plants. The light water reactor (LWR) chain is an extreme case because of the low uranium ore content (0.007 percent U_3O_8), but it can be considered the maximum limit for the amount of uranium to be extracted (which is bigger than the amount of coal to be mined for the same electricity production). As far as the fast breeder reactor (FBR) is concerned, it was assumed that only a small amount of uranium would be extracted, while most of the fuel supply would come from ^{238}U (depleted uranium in enrichment plants) and from

Figure 9-2. Three types of electricity-generating chains.

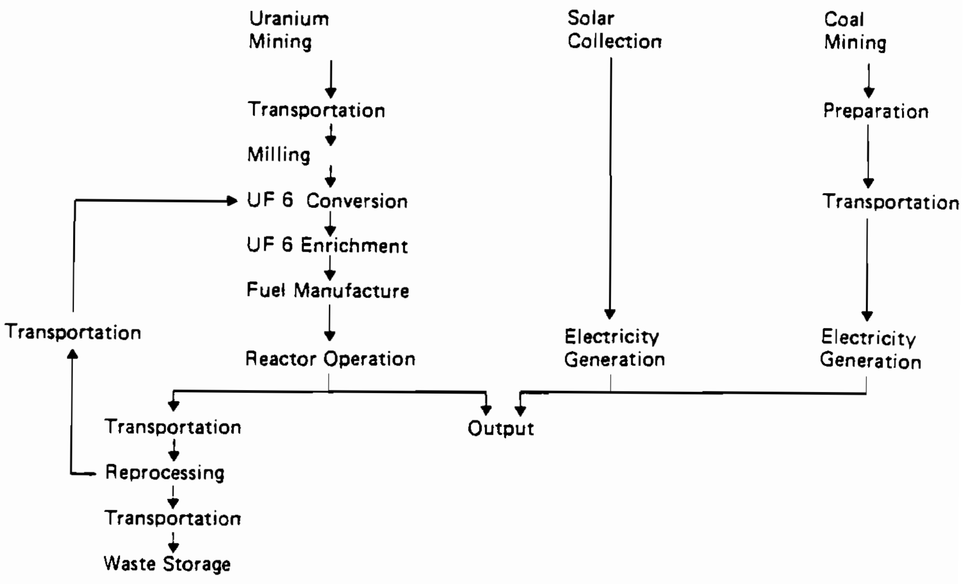


Table 9-2. Characteristics of the electricity-generating chains (6.1 TWh, thirty-year life span).

	Coal 1	*Coal 2*	*Coal 3*	*Coal 4*	*LWR 1*	*LWR 2*	*LMFBR*	*Solar 1*	*Solar 2*
Mining	U.S. western underground coal mine, seam thickness: 1.5 m		U.S. western surface coal mine, seam thickness: 9.2 m		60% surface, 40% underground, 0.203% U_3O_8	Underground shale mine,	Chattanooga 0.007% U_3O_8	–	–
Preparation	Coal preparation plant				Uranium mill, enrichment, fuel fabrication		Uranium mill, fuel fabrication	–	–
Transport	Rail, 900 km	Slurry pipeline, 900 km	Rail, 900 km	Slurry pipeline, 900 km	Negligible	Negligible	Negligible	–	–
Power plant	1000 MW(e), load factor 70%, conventional	1000 MW(e), load factor 70%, fluidized bed, environmentally controlled	1000 MW(e), load factor 70% conventional	1000 MW(e), load factor 70%, fluidized bed, environmentally controlled	1000 MW(e), load factor 70%, thermal efficiency: 33%, 3.2% ^{235}U fuel		1000 MW(e), load factor 70%, thermal efficiency: 40%, UF_6 tails and natural Uranium fuel	28 × 100 MW(e), STEC, direct radiation, 1500 hrs/yr, 1500 kWh/m^2/yr	14 × 100 MW(e) STEC, direct radiation, 2700 hrs/yr, 3000 kWh/m^2/yr
Electricity storage	–	–	–	–	–	–	–	6 hours on site thermal	
Reprocessing	–	–	–	–	Uranium reprocessing		Uranium and plutonium reprocessing	–	–
Waste storage	Negligible	Negligible	Negligible	Negligible	Low level waste storage, temporary (maximum 100 years), high level waste storage			–	–

the plutonium produced in other LWRs. The transportation of uranium has been omitted.

The solar chains comprise 100 MW(e) solar thermal electric conversion (STEC) plants. The two chains differ in terms of solar radiation (the Southern France type or the Californian type).

Examples of results obtained by a WELMM analysis are shown in Table 9-3 and Figure 9-3, the latter presenting the cumulative land and materials (nonenergy plus energy) required to build and operate these nine chains for thirty years. These cumulative requirements were obtained by aggregating the data collected and studied for each facility of each chain. They offer insight into possible constraints for developing future electricity supply strategies.

The largest land-consuming chains by far are the solar chains, especially Solar 1, with a southern European direct solar radiation of 1500 kWh per m^2 per year. The smallest land consumer is the LMFBR chain. The land requirements for the solar chains are large mainly because of the heliostat fields of the STEC modules. The land impacts are also considerable in the LWR 2 chain and in the four coal chains.

If one compares the various chains with respect to the requirements for construction materials, the two solar chains have requirements about one order of magnitude higher than any of the other chains. These requirements correspond to the high quantities of steel, concrete, sand and rocks, and other materials required for constructing the heliostat fields and towers. On the other hand, the solar chains require practically no materials for their operation. The light metal fast breeder reactor (LMFBR) and the LWR 1 chains show the best results if one compares the total material requirements (for construction plus thirty years of operation) for various chains. But,

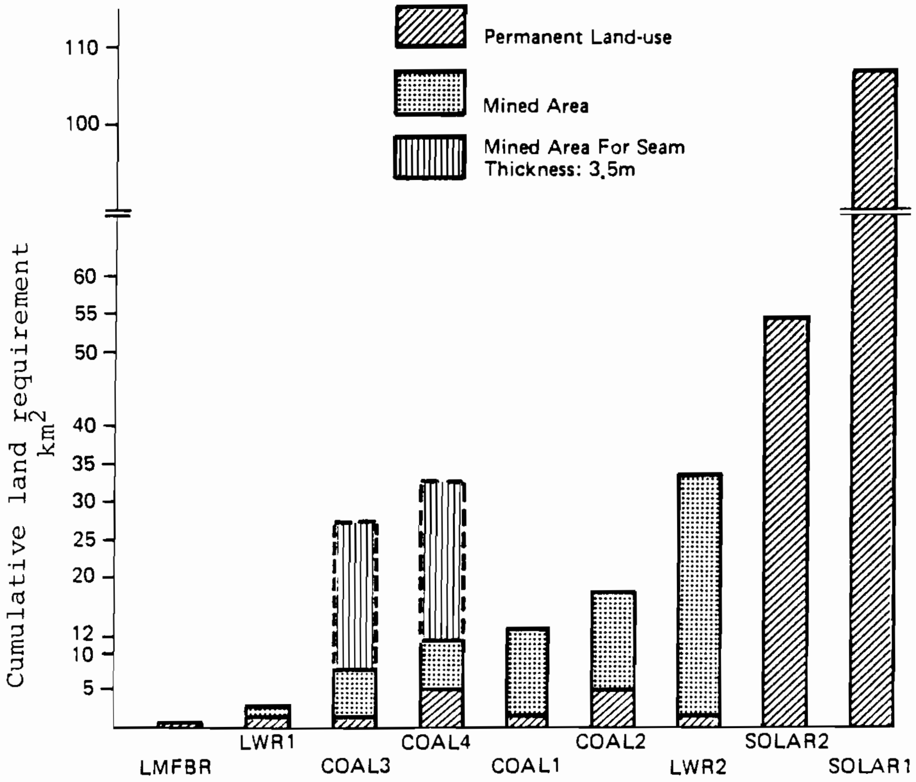
Table 9-3. Material requirements for construction and operation of electricity chains (10^3 tons).

	Metals for Construction	*Other Materials for Construction*	*Nonenergy Materials Operation (cumulative 30 years)*	*Energy Materials Operation (cumulative 30 years)*	*Total*
Coal 1	43	151	8287	79,000	87,480
Coal 2	65	140	23,566	84,000	107,770
Coal 3	44	142	4000^+	79,000	83,186
Coal 4	67	130	23,230	84,000	107,430
LWR 1	41.8-56.6	192.7	132	2700	3066-3080
LWR 2	43.4-58.2	192.7^+	132	119,300	119,668-119,683
LMFBR	33	276.3	NA	800	1103
Solar 1	844.3-1930.4	3298-6778	NA	0	4142-8708
Solar 2	666.4-965.7	2005-3390	NA	0	2671-4355

NA—Not available.

+ = more than or additional.

Figure 9-3. Cumulative land requirements (km^2) for energy chains producing 6.1 TWh electricity. The importance of the seam thickness of opencast mining is indicated as an example for Coal 3 and 4. For explanation see Table 9-2.



the LWR 1 chain should be approached with care, because of the high grade uranium ore considered (0.203 percent U_3O_8), which reflects the current situation of uranium ores. These high grade ores could be fully extracted over the next decades, and one would have to examine preferably the LWR 2 chain or an intermediate chain in order to reflect the long-term perspectives of a LWR chain. Therefore, only the LMFBR seems to be practically independent of such resource constraints, because of the need for very small quantities of natural uranium (about two tons per year) from low grade ores in addition to that of the UF_6 tails recovered from LWR chains.

From the above comparison, it is obvious that the LMFBR would be the least demanding in terms of land and materials requirements. This would be followed closely by the LWR, provided that its fuel requirements could be met by high grade ores. The land and materials handling requirements for the operation of LWRs with poor quality ore (e.g., with 0.007 percent U_3O_8) may even surpass those of equivalent coal-based systems. The STEC system would be the most demanding in terms of its requirements of land construction materials but not for its operation. These general features would not change significantly with changes in the location of various facilities. Nevertheless, for a more detailed and complete assessment, precise geographical location would have to be taken into account.

The WELMM Constraints on New Synthetic Liquid Fuels

Liquid fuels are, and will remain for a long time, essential for both developed and developing economies. Nevertheless, it is now becoming quite clear that the supply of conventional oil is finite, including the largest deposits and those still untapped. Thus, in the not so distant future, there will have to be a shift to the use of synthetic liquid fuels and/or of unconventional oil resources—probably progressively in a few decades at the global level, perhaps sooner (in the 1990s) in some countries for political and/or other reasons. (See Chapter 2 for a discussion of resource supply.)

Among the various possibilities are syncrudes from tar sands or from oil shales and liquid fuels obtained through coal liquefaction. (The production of liquid fuels from coal is discussed in Chapter 3). Economic comparisons of these three alternatives are difficult because of the different technologies and stages of development.

Nevertheless, there are some common characteristics of the sources of synthetic liquid fuels. First, they rely on a large resource, as discussed in Chapter 2. One of the most remarkable characteristics of these unconventional resources—as they are presently known—is the predominance of supergiant accumulations. For example, the Athabasca tar sand deposit, which has an area of 23,300 km^2 with 90 billion tons of bitumen in place, is at least once or twice the size of the largest of all conventional fields, Ghawar in Saudi Arabia. The Piceance Creak Basin in Colorado contains about 80 billion tons of shale oil in high grade oil shale beds. One of many examples of huge coal deposits of similar size is the Kuznesk Basin in the USSR, with total hard coal resources of 850×10^9 tons spread over an area of 33,000 km^2.

Another common characteristic of these unconventional resources is that, to date, the available technologies seem to be economically viable only on a very large scale, which implies a much greater environmental impact than has been experienced for most other natural energy resource exploitation. Thus the problem of their development cannot be analyzed by looking only at the resource. In fact, environmental and WELMM constraints for large-scale extraction processes (e.g., shortage of water, possible restriction on disturbing land, manpower and material shortage) will probably influence the rate of development more than the ultimate recovery of the resource.

For this reason, an evaluation of the WELMM requirements of different approaches to synthetic liquid fuels would be helpful in revealing the possible constraints or bottlenecks that a new technology may have to overcome to be considered viable. However, in making such an evaluation, one encounters the difficulty of the lack of data: as yet, there are only two industrial plants operating for tar sands and only one for coal liquefaction, while the commercial exploitation of oil shales still remains at the project level. Using whatever data are currently available in a published form on the operating of industrial plants, pilot-scale plants, and project and study estimates, a preliminary comparison has been made of the WELMM requirements associated with different synthetic fuel technologies. This provides some useful insights, as discussed below.

Water. Figure 9-4 shows estimates of water requirements for different technologies. In order to compare their relative impact on water resources, the production of 1 cubic meter of synthetic fuel has been chosen as a reference.

It appears that coal liquefaction would require the largest amount of water, especially with the current method—the Fischer-Tropsch synthesis process. The reason is that for this process water is considered a chemical feedstock. For tar sand, the major part of the water consumption occurs at the conversion stage because of the current "hot extraction method." One disadvantage of this process is that most of the water discharged with the tailings in the tailing pond cannot be recycled (because it contains some solid particles), nor can it be discharged into a river because of the presence of bitumen. For oil shale, the critical steps are the waste disposal and oil shale upgrading, during which 60 percent of the water is consumed.

It is important to know whether the water resources in the affected regions are sufficient to support such a development. Water supply does not seem to be a likely problem to inhibit the tar sand industry in Athabasca; on the other hand, in Colorado, the shortage of water will be a serious problem for a large-scale exploitation of its oil shales.

Energy. In order to build and operate a plant, to harvest the primary energy, and to upgrade and transport it, a great deal of additional energy is needed, particularly if the "quality" of the resource is low. For each process, one may give the ratio of energy consumed in resource recovery to energy produced for the market (see Figure 9-5).

Table 9-4 represents some values for the ratio of energy consumed in different processes. The values of the ratio for all synthetic fuel processes, as well as for the enhanced recovery of oil, are very low, especially when compared with those for the production of conventional oil, even in the difficult conditions of the North Sea.

On the basis of the data in Table 9-4, we consider it too early to conclude that there is a real difference between the energy efficiencies of the different processes studied here. The relatively low values for the actual coal liquefaction process (apart from significant energy requirements for steam production) also reflect the fact that the plant is producing a wide variety of products (energy and nonenergy). Second generation coal liquefaction

Figure 9-4. Water requirements for different synthetic liquid fuel processes compared to enhanced recovery of conventional oil. *Sources:* (a) Bechtel Corporation (1975, 1976, 1977); (b) and (c) Crawford et al. (1977); (d) Resources Management Consultants Ltd. (1978); (e) Syncrude Canada Ltd. (1971, 1973); (f) Bechtel Corporation (1975, 1976, 1977); Hittman Associates Incorporated (1974, 1975); (g) Synfuels Interagency Task Force (1975).

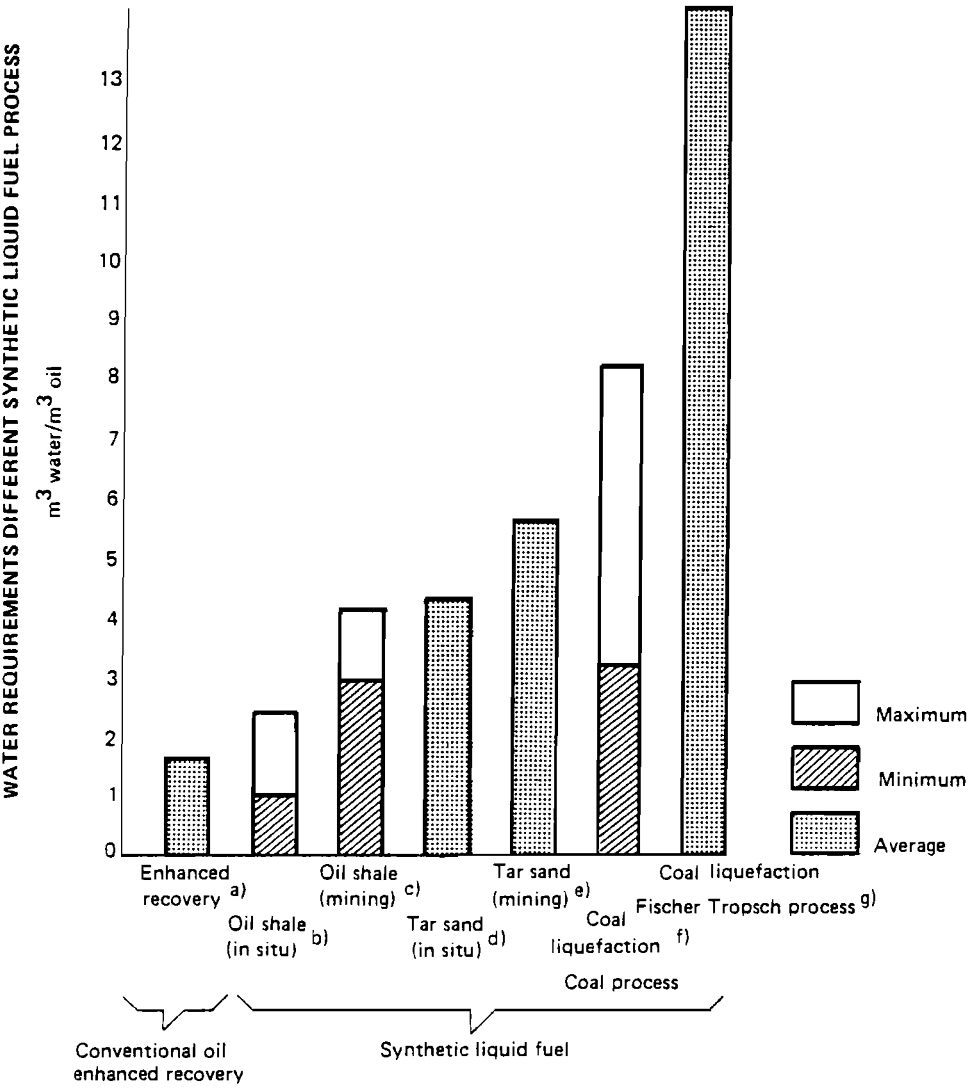


Table 9-4. Ratio of energy consumed in resource recovery to energy produced for the market.

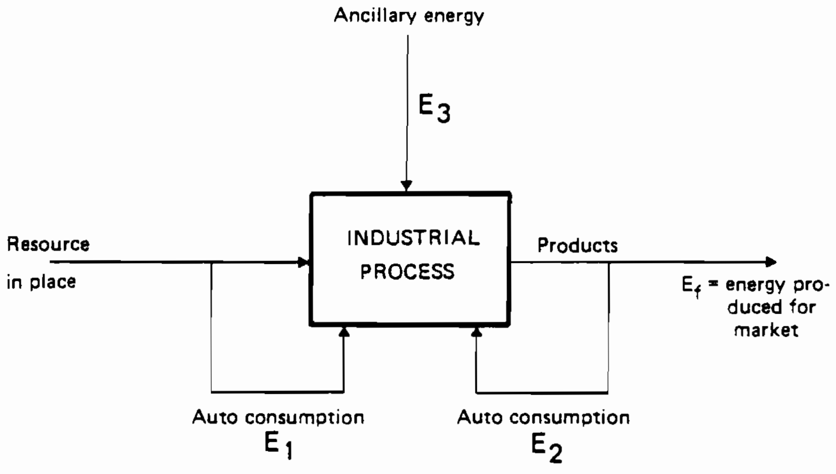
Tar Sand GCOS 45,000 bbl/d[a]	*Tar Sand Imperial 141,000 bbl/d*[b]	*Oil Shale Projects*[c]	*Coal Liquefaction*		*Enhanced In situ Combustion*[f]	*Oil, North Sea*[g]
			Actual[d]	*Advanced*[e]		
3.5-4	1.9-2.2	2.2-10	0.8-1.6	2.2-3	2-8	> 100

Sources: (a) Heming (1976); (b) Resources Management Consultants Ltd. (1978); (c) Marland (1977); (d) Muir (1977); (e) Bechtel Corporation (1976); Oil and Gas Journal (1974); (f) Burger (1979); and (g) Klitz (1980).

processes (more optimized in the synfuel output) achieve higher efficiencies, but values are based on laboratory or pilot plants.

On the other hand, if one considers the rate of recovery of the energy in place, it is higher for tar sand exploitation or enhanced recovery than for conventional oil wells—about 65 percent for the Syncrude (1978) and the Great Canadian Oil Sand (GCOS) plants and 30 to 60 percent for the different methods of enhanced recovery, compared with an average of 25 percent for conventional oil. The recovery rate for coal mining is very dependent on the local geological conditions and usually is of the order of 80 percent. However, in very big opencast exploitations, as are needed for commercial coal liquefaction plants, the recovery rate would decrease to 50 percent (as was experienced, for example, for lignite mines in the FRG [Fettweis 1976]).

Figure 9-5. The ratio of energy consumed in resource recovery to energy produced for the market.



Land. The processes used for exploiting tar sands, oil shale, and coal are all very extensive users of land. They require land for mining development, overburden and waste disposal, construction of facilities, and off site requirements (e.g., roads). The open pit mining method is certainly the most economically attractive for large deposits of low grade, because it permits a high rate of recovery of the resource and allows the use of large and efficient equipment. However, in some instances, because of large overburden thickness, it may be more economical to proceed with underground mining rather than with surface mining operations. Table 9-5 compares the land requirements for different processes based on open pit mining, only. The fixed land requirements for the different synthetic fuel complexes (capacity 25,000 to 125,000 barrels per day) are in the range of 1 to 11 km^2, as against 0.17 km^2 for the Alaska conventional oil fields of capacity 180,000 barrels per day. The land requirements for mining (in m^2 per barrel produced) are similar for the different processes (0.026 to 0.05 m^2 per barrel) if one considers the same favorable geological conditions for coal mines as for oil shale or tar sand (stripping ratio of 0.35). However, the mining conditions most likely to be available for coal projects would mean land requirements of up to ten times those required by equivalent oil shale and tar sand projects.

The figures for the total mined area for different projects, when considered over their lifetimes, are gigantic, as shown in Table 9-5. Such land disturbances may result in considerable local impacts, such as increases in erosion and sedimentation, changes in soil quality, destruction of vegetation. However, owing to the progress in reclamation and rehabilitation or restoration techniques, temporary land disturbance could also be an advantage and, in some cases, the land may be of better quality after the operation than it was before.

Materials. Table 9-6 shows certain characteristics of different raw materials. Because they contain rather low percentages of organic matter, it is necessary

Table 9-5. Land requirements for synthetic fuels (based on open pit mining).

	Tar Sand *125,000* *bbl/d*[a]	*Oil Shale* *50,000* *bbl/d*[b]	*Coal (actual)* *50,000* *bbl/d*[c]	*Coal (advanced)* *25,000* *bbl/d*[d]
Fixed land for surface installations (km^2)	11	1.5-4	4	1.3
Area affected by mining per year (m^2/bbl output)	0.028	0.026-0.029	0.05-0.2	0.04-0.3
Total mined area for project (km^2)	31.5	12.9-14.3	25-100	10-75

Sources: (a) Syncrude Canada Ltd (1978); (b) Project Independence (1974); (c) Synfuels Interagency Task Force (1975); Grübler and Grenon (1979); and (d) Bechtel Corporation (1976); Grübler and Grenon (1979).

Table 9-6. Properties of tar sand, oil shale, and coal.

	Tar Sand (Wt%)	*Oil Shale (Wt%)*	*Coal (Wt%)*
Organic matter	9-13.5	14-20	50-80
Inorganic matter	80-90	78-85	5-25
Moisture	2-10	1-2	1-40
Organic Composition			
Carbon	83.1	79-81	73-83
Hydrogen	10.3	10.2-10.5	5-6
Oxygen	1.4	4.8-6.7	10-20
Nitrogen	0.3	2.1-2.6	1-2
Sulphur	4.9	0.9-1.2	0.5-5

Source: Cameron (1969).

to handle relatively large quantities of these raw materials. All have in common a deficiency of hydrogen and significant quantities of impurities. If one considers the physical state of the organic matter of each material, then tar sand seems to have some advantage because it contains oil as such.

The stripping ratio and the ore grade affect the production considerably. Table 9-7 shows, for example, that for tar sand, in one of the most favorable zones, about one ton of overburden must be removed and two tons of tar sand must be mined in order to produce one barrel of synthetic fuel. Table 9-8 gives information on the problem of waste production. For example, the mining of oil shale results in a volume of processed shale that is about 1.2 times that of the raw shale. Because of the expanded volume, a complete return into the excavated area is impossible. One possible solution is to deposit the spent shale in deep natural canyons, which involves an additional cost for transportation and considerable impact on the scenic quality of the landscape. For tar sands, even if the nature of the waste is different, the

Table 9-7. Materials mined to produce one barrel of synthetic fuel.

Tar Sand Mining[a] *Open Pit*		*Oil Shale Mining*[b]		*Coal Mining*		
					Open Pit[d]	
Overburden (t)	*Tar Sand* (t)	*Underground* (t)	*Open Pit* (t)	*Underground*[c] *Coal* (t)	*Overburden* (t)	*Coal* (t)
1	2-2.2	1.5	2	1	1.7-5.8	0.3-0.4

[a] Values for tar sand correspond to the conditions of the current GCOS and Syncrude complexes—they are among the most favorable.

[b] Values correspond to very high grade oil shale (35 g/st) and to classical retorting and upgrading processes.

[c] Values correspond to an underground mine (long wall, 1 seam about 4 m thick) and to the Fischer-Tropsch process.

[d] Values correspond to surface mining with relatively low oxygen-carbon ratio and to the hydrogen-coal process.

Table 9-8. Waste produced in the production of one barrel of synthetic fuel.

Tar Sand Mining[a]			*Oil Shale Mining*[b]	*Coal Mining Waste*
Sand (t)	*Water* (t)	*Bitumen* (t)	*Spent Shale* (t)	*from Processing* (t)
1.8	1.9	0.03	1.2	0.25-0.3[c] 0.03-0.11[d]

[a] Values for tar sand correspond to the conditions of the current CGOS and SYNCRUDE complexes—they are among the most favorable.

[b] Values correspond to very high grade oil shale (35 g/st) and to classical retorting and upgrading processes.

[c] Values correspond to an underground mine (long wall, 1 seam about 4 m thick) and to the Fischer-Tropsch process.

[d] Values correspond to surface mining with relatively low oxygen-carbon ratio and to the hydrogen-coal process.

question is also serious, and the problem of storage area for tailings is becoming more acute. A similar, though less critical picture is shown for coal liquefaction; huge quantities of ash (about 0.3 tons per barrel of fuel produced through the Fischer-Tropsch process) must be disposed of.

Manpower. For all these processes, manpower requirements for construction and operation are very important. Table 9-9 gives some figures relating to the Syncrude plant (1978), to the Imperial Project (Resources Manage-

Table 9-9. Manpower requirements for different synthetic liquid fuel processes.

Projects	*Design and Construction Manpower Requirements (man-hours)*	*Total Workforce at Peak Construction (number of persons)*	*Workforce for Operation and Maintenance (number of persons)*
Tar sand, SYNCRUDE, open pit mining (125,000 bbl/d)[a]	43 × 10^6	7500	2500
Tar sand, in situ process (141,000 bbl/d), Imperial Project[b]	55 × 10^6	9930	2036
Oil shale, open pit mining (100,000 bbl/d)[c]	8.7 × 10^6	2200	1800
Oil shale, underground mining (100,000 bbl/d)[c]	8.7 × 10^6	2200	2362
Coal liquefaction, underground mining, Fischer/Tropsch process (40,000 bbl/d)[d]	NA	11,000-15,000	7400
Coal liquefaction, open pit mining, hydrogen-coal process (25,000 bbl/d)[e]	7.0 × 10^6	a	820-1000

NA—Not available.

Sources: (a) Syncrude Canada Ltd. (1978); (b) Resources Management Consultants Ltd. (1978); (c) Project Independence (1974); (d) Hoogendoorn (1975, 1978); (e) Bechtel Corporation (1976); Synfuels Interagency Task Force (1975).

ment Consultants Ltd. 1978), and to some oil shale and coal liquefaction projects.

Manpower problems are a serious potential bottleneck in view of the heavy development in exploitation of this kind of resource. There are two major reasons for this. First, the design and construction of tar sand or oil shale plants require the services of a very wide range of qualified workers (boilermakers, carpenters, cement finishers, electricians, insulators, iron workers, millwrights, plumbers and pipefitters, operating engineers and pressure welders) as well as experience in widely different areas, such as solid handling, mining, and upgrading. Very few of the design and engineering companies can cope with this demand. Second, there are high peaks in the workforce requirement. Unless a very tight schedule is established for the different projects, there could be a wide fluctuation in the employment market. One of the main constraints of fast expansion would therefore be the relative scarcity of engineers and skilled workers.

Even in the operational phase, the oil companies will have to face a new situation. Manpower requirements for the production of conventional oil (especially since the discovery of giant fields) have been low. For example, a field in North Alaska, with an output of 180,000 barrels per day requires only twenty three man-years for operation and maintenance (Bechtel Corporation 1975, 1976).

For the coal liquefaction process, the high number of coal miners would be the most crucial point. For example, for the new SASOL project in South Africa (Hoogendoorn 1975, 1978), about 3700 people are required for the newly developed Bosfesspruit colliery that will produce the coal for the synfuel plant.

The influx of large numbers of workers into relatively remote or scarcely populated areas (Colorado, for example) could have a significant social impact on the area and require the construction of new schools, roads, hospitals, and the like. This would also mean the consumption of water, land, energy, and materials for domestic use, and it is therefore also necessary to take into account all these indirect WELMM requirements.

The above assessment of the WELMM requirements of different synthetic fuel processes clearly shows that the magnitude of means used will not be of the same order as for the recovery of conventional oil. From these preliminary results, coal liquefaction seems to be the least favorable process with respect to water, land, and manpower requirements. Possible developments would still take place only in countries with abundant coal resources in favorable geological conditions. On the other hand, the WELMM comparison between tar sand and oil shale does not show a big disadvantage to oil shale, although this would have been true if one had considered only their capital costs.

Again, the current techniques of exploitation of these resources are not utilizable for small deposits that could make useful contributions to the energy supply. It is therefore necessary to develop new methods, better adapted to the smaller size deposits and to the human and material resources available.

CONCLUSION

The solution to one resource crisis should not create a shortage of another resource. For example, one should not opt for an energy option that places too high a constraint on land or water. Once the resources have been considered in specific locations, in specific forms, or in economic terms, their relative scarcity becomes apparent.

From the above study on energy chains for producing electricity, it can be seen that the large-scale use of STEC technology would be possible only in remote areas (implying the choice of energy vectors that can be transported and distributed easily and efficiently), mainly because this technology is a very intensive land consumer. On the other hand, the material requirements for the construction of heliostat fields are enormous and may be a problem if remote areas have to be reached. The study also has shown that the logical continuation of a long-term nuclear strategy lies in the use of the FBR technology, because of the tremendous amount of materials to be handled and of the mining impacts that would result from the use of low grade ores.

As regards the production of synthetic liquid fuels, a prerequisite to the large-scale use of unconventional oil is the mastering of in situ technologies, principally because present technologies require huge amounts of land. Similarly, the discovery of less water-intensive processes—especially for coal liquefaction and oil shales—will be necessary for any large-scale exploitation project.

The type of information that is obtained from a WELMM analysis may provide decisionmakers with additional knowledge of the natural resource aspects correlated to energy strategies. This is especially true since physical data are not likely to fluctuate as widely as monetary data. In fact, when prices or financial data are either lacking or uncertain (which is often the case for long-term strategies and new technologies), it is useful to express the natural (and human) resources in physical terms or, as we say, in "WELMMite" requirements and to emphasize their systems implications and interrelations. This new systems approach to energy—or more broadly speaking to development strategies—supplements classical economic analysis and is a possible building block of multiattribute, multicriteria decisionmaking analysis.

APPENDIX 9A: THE BASIC TOOLS OF THE WELMM APPROACH

In order to assess the WELMM requirements for different energy supply options and the availability of such resources at the national, regional, and global levels, the first step is to collect, analyze, and list all relevant information in a suitable format so as to allow its easy handling and manipulation for desired applications. Two types of data bases have been developed—the facility data base and the resource data base. The composition and development of these bases are discussed below.

The Facility Data Base

The facility data base contains the WELMM resource requirements for constructing and operating various typical energy facilities—namely, coal mines, oil fields, coal unit trains, pipelines, tankers, conversion plants, or power plants. In fact, these "facilities" are industrial units considered at one of the stages of valorization of an energy resource. Each stage can be characterized by a process—for example, gaseous diffusion, centrifugation, and laser for uranium enrichment; or pipeline and tanker for crude oil transportation. An energy facility can be associated with each process. Fortunately, there is a tendency toward size standardization that makes WELMM resource-accounting easier—gaseous diffusion plants of ten million separative work units; crude oil tankers of 250,000 to 300,000 dead weight tons; nuclear reactors of 1000 and 1300 MW(e). Ultimately, it might be possible to have standards for similar facilities, for a given technology, and for a certain industrial development of a given geographical region.

To date, approximately one hundred facilities have been studied at IIASA, of which about fifty have been computerized. Table 9-A1 lists these facilities by primary energy form. For well-known, conventional energy sources, the number of facilities included is of course higher than that for the so-called "new energy sources" or for those that are not much in use worldwide.

Additionally, sixty five coal mines have been studied (the target is to represent one hundred basins), and their data have been entered and managed in the facility data base somewhat differently because of the specificity of the extraction processes by comparison with other facilities. This forms the coal mines data base, as discussed in this chapter.

For each energy facility, the facility data base contains both quantitative and qualitative data as well as descriptions of the construction and operation of that facility. Specifically, the facility construction file contains information on general characteristics—for example, identification, technology

Table 9-A1. Number of facilities included in the facility data base per energy source

Energy Source	*Number of Typical Facilities Studied*
Hydrocarbons	
Conventional (oil, gas)	20
Unconventional (tar sands, oil shale, heavy oil)	5
Solid fossil fuels	20
Nuclear (fission)	30
Solar and biomass	10
Hydroelectric power, geothermal	10

employed, size of the facility, economic data—and on natural and human resource requirements for constructing the facility—that is, the direct WELMM requirements. The facility operation file contains information on general characteristics—identification, energy in- and outflows and other by-products, description of the operation, lifetime, energy efficiency, availability, economic data, environmental impacts (pollution, waste)—and on natural and human resource requirements for operating the facility for one year—the WELMM requirements.

An explanatory footnote and a reference to the data source are given with each of the data. Some detailed explanations are also given, such as data variations depending on the geographical, technical, and time context being considered. Storage of the data at various aggregation levels is possible. For example, manpower requirements are given as a total of man-hours or man-years, but there is also a breakdown of that total into four categories of manpower—manual technical (technicians, qualified workers); manual nontechnical (nonqualified manpower); nonmanual technical (engineers); and nonmanual nontechnical (lawyers, doctors, etc.). A quality judgment associated with each of the values increases the value of the facility data base.

The quality appreciation is, of course, subjective and aims to take into account the reliability of the data source, its viability, its homogeneity with other sources, and the range of uncertainty. Following Hittman's (1974) classification, the quality is described by means of marks within a range of 1 to 5: 1 is very good (± 10 percent), 2 is good (± 25 percent), 3 is fair (± 50 percent), 4 is poor (± 100 percent), and 5 is expressed as an unknown validity. Table 9-A2 gives an example of a coal gasification facility, illustrating the type of data contained in the facility data base.

The value of a data base is dependent upon the value (i.e., the accuracy) of the data collected. Thus, four methods have been used for obtaining accurate information. First, there has been close cooperation with a number of industrial companies or organizations concerned with the energy sector in various countries. Second, existing data bases have been used, although they are generally more restricted in their scope and content. Third, questionnaires have been distributed to companies, research institutions, and public organizations, and the responses have been studied. Finally, an extensive literature search has been conducted. Once the data have been collected, they are analyzed and synthesized either at IIASA or within collaborating organizations.

The management system used for the facility data base is called INGRES and was developed at the University of California at Berkeley and adapted at IIASA. Supplementing INGRES is a system called ENERTREE that was developed at IIASA; ENERTREE links the data base and the application programs, thereby permitting a hierarchical access and simplifying the task of the end user.

A Substructure of the Facility Data Base: The Coal Mines Data Base: It is relatively easy to define standard types of facilities at the top end of the coal

Table 9-A2. Example of a printout for a coal gasification facility.

Facility code:	COALGAS1
Facility name:	El Paso coal gasification complex
Country:	United States
Primary capacity:	SNG $0.2703 \times 10^{10}\ m^3$
Secondary capacity:	Not applicable 0.0000
Direct efficiency:	0.572000
Planning duration:	NA
Construct duration	3.00000 years
Load factor:	0.910000
Life time:	30 years

Primary Inputs		
ip	Low sulfur < 1% bituminous coal	0.851×10^7 t
ipe	Clean coal	0.585×10^7 tce_7000 kcal/kg
Primary Outputs		
op	SNG	$0.2703 \times 10^{10}\ m^3$
ope	SNG	0.334×10^7 tce_7000 kcal/kg
Secondary Outputs		
os1	Tar	300814. m^3
os2	Tar oil	197865. m^3
os3	Naphta	63350.4 t
os4	Crude phenols	40825.2 m^3
os5	Ammonia	78327.6 t
os6	Sulfur	56412.0 t

WELMM Requirements for Construction

Resource	*Quantity*	*Unit*	*Quality*	*Footnote*
Aluminum	4535.000	t	3	CGO105
Copper	363.000	t	3	CGO105
Electricity	100.000	10^6 kWh	4	CGO102
Land temporary exclusive	3.885	km^2	1	CGO103
Land temporary total	3.885	km^2	1	CGO103
Manpower total	6118.400	man-years	1	CGO104
Motor fuel total	NA	10^9 kcal	NA	CGO102
Process heat fuel total	0.000	10^9 kcal	2	CGO102
Steel pipes and tubes	10884.000	t	3	CGO105
Steel plates	21770.000	t	3	CGO105
Steel reinforcing bar	2177.000	t	3	CGO105
Steel structural	6530.000	t	3	CGO105
Total steel (sum of all kinds)	41359.000	t	3	CGO105
Water intake total	0.227	$10^6\ m^3$	3	CGO101

WELMM Requirements for Operation

Resource	*Quantity*	*Unit*	*Quality*	*Footnote*
Chemical and allied products	NA	t	NA	CGO111
Electricity	0.000	10^6 kWh	1	CGO108
Land temporary exclusive	3.885	km^2	1	CGO109
Land temporary total	3.885	km^2	1	CGO109
Manpower total	985.000	man-years	1	CGO110
Materials	NA	t	NA	CGO111
Motor fuel total	0.000	10^9 kcal	2	CGO108
Process heat fuel total	0.000	10^9 kcal	1	CGO108
Water consumption cooling	5.078	$10^6\ m^3$	1	CGO107

Table 9-A2 continued.

	WELMM Requirements for Operation			
Resource	*Quantity*	*Unit*	*Quality*	*Footnote*
Water consumption process	5.131	10^6 m^3	1	CGO107
Water consumption total	10.209	10^6 m^3	1	CGO107
Water discharge total	2.805	10^6 m^3	1	CGO107
Water intake cooling	5.965	10^6 m^3	1	CGO107
Water intake process	6.720	10^6 m^3	1	CGO107
Water intake total	12.775	10^6 m^3	1	CGO107

NA—Not available.

chain (conversion and transportation)—for example, coal unit trains of 10,000 tons, gasification complexes of 2300 million m^3 per year—especially when one considers the increasing trend of standardization of the size of energy installations. On the other hand, it is practically impossible to reduce the large number of coal mines, opencast or underground, to a few representative examples.

Many factors influence coal-mining activities—for example, the geology of the deposit, the degree of mechanization, manpower costs, the extraction technology used. We are presently conducting a study of some one hundred representative large-scale coal mines, with the aim of collecting and analyzing the WELMM data. In particualr, we are focusing on those basins that can contribute significantly to a potential global coal market. For each basin, representative mines from the point of view of technology and geology (depth, number and thickness of seams, coal quality, etc.) are being studied, in order to obtain a sufficient number of mines so as to be able to classify them according to size, technology used, WELMM requirements, and the conditions of each basin. Mines in the following countries are being studied—Australia, Austria, Canada, France, the Federal Republic of Germany, the German Democratic Republic, Hungary, India, Poland, the Republic of South Africa, the Soviet Union, the United Kingdom, and the United States.

Data are obtained from the review of the literature (environmental impact statements are of particular interest) and from responses to a questionnaire developed at IIASA in cooperation with coal experts. The status of the coal mines data base as of mid-1979 is as follows: some 162 questions were asked about general characteristics of the mines and the WELMM construction and operation requirements. On the average, 60 percent of the questions have been answered to date. Table 9-A3 shows an example of the data for general characteristics of coal mines and geological conditions of a mine in Austria.

Our present approach, based on a few representative mines per basin, represents considerable progress over the methodology developed in the U.S. For example, in the energy supply planning model of the Bechtel Corporation (1975; 1976) the modeling effort for the coal mining activities is based on only four U.S. mines. Nevertheless, even with our approach it

Table 9-A3. Example of data printout for a coal mine in Austria.

General Characteristics of the Mine		
Process	m+p	Mining and preparation
Type of technology	surf	Surface
Data origin	projkf	Projected for a certain field
Reference year of data	1984	Year
Total number of coal seams	2	Number of seams
Including seams to be mined out	2	Number of seams
Seams supposed to be mined out in reference year	1	Number of seams
Lower thickness of coal seams	2.000	Meters
Average upper ash content of seams mined out	30.000	Percent
Average thickness of coal seams in reference year	7.000	Meters
Total mining seams thickness	25.000	Meters
Overburden to coal ratio	4.450	m^3 per metric ton
Dip of coal seams in degrees	flat	Flat coal seams
Maximum depth of mining in reference year	60	Meters
Marginal depth of mining	180	Meters
Methane emanation	0.000	m^3 per metric ton daily output
Tectonic distortion description	regbedd	Regular bedding
Coal density in situ	1.275	Metric tons per m^3
Rock (overburden) density	1.950	Metric tons per m^3
Necessity of rock explosion (only surface)	no	No
Necessity of coal explosion (only surface)	no	No
Surface landscape	hmfoga	Hilly mountain forest grazing agriculture
Average January temperature	NA	Degree celsius
Average July temperature	15	Degree celsius
Range of annual precipitation, minimum	NA	Millimeters
Range of annual precipitation, maximum	NA	Millimeters
Range of ground freezing, minimum	0.000	Meters
Range of ground freezing, maximum	0.000	Meters
Average depth of ground freezing	0.000	Meters
Degree of industrial development of the region	devdp	Developed industry great population density
Long distance transportation possibilities	exloc	Existing transportation facilities
Total remaining geological resources in reference year	33.000	10^6 metric tons
Economic and technical recoverable reserves in reference year	30.000	10^6 metric tons
Recovery rate	0.900	Ratio resources in ground/reserves
Grade of coal	brown	Brown coal
Range of moisture content of coal, minimum	26.000	Percent
Range of moisture content of coal, maximum	38.000	Percent
Average moisture content of coal	32.245	Percent
Range of ash content of coal, minimum	20.000	Percent
Range of ash content of coal, maximum	47.000	Percent
Average ash content of dry coal	33.430	Percent
Minimum caloric content of coal	1985	kcal per kg
Maximum caloric content of coal	2985	kcal per kg
Average caloric content of coal	2505	kcal per kg
Annual capacity	1.250	10^6 metric tons
Construction duration	6.000	Years
Period of initial increasing mine output	3.000	Years
Total lifetime of the mine	27	Years

Table 9-A3 continued.

Year of beginning of exploitation	1988	Year
Coal output in reference year	1.250	10^6 metric tons
Number of operating faces	2.000	Number of operating faces
Average output from a face	2500	Metric tons per day
Number of working days per year: coal winning	250	Number of days per year
Number of working days per year: overburden moving	250	Number of days per year
Number of working shifts per day: coal winning	3	Number per day
Number of working shifts per day for overburden	3	Number per day
System of seam opening (underground mining)	0	This is a surface mine
Position of main shafts	0	This is a surface mine
Number of main shafts	0	Number of main shafts
Method of mining	stripbw	Stripping with bicket wheel excavator

NA—Not available.

is not yet possible to obtain highly accurate information on all aspects of coal exploitation in a particular coal basin since this depends on how many representative mines there are for the basin in the data base and how much conditions vary within the basin. A study of the relations between geological parameters and the consumption of natural resources is therefore being made.

The Resource Data Bases

In addition to the accounting of WELMM requirements as discussed above, another type of accounting is needed and has to be done in parallel. Here the focus is on determining a region's potential to contribute, through its resources, to national or even international economy. These "regional accounting" schemes form what we call resource data bases. Two types of resource data bases are currently being set up, depending on the type of regional accounting desired. Indeed, for WELMM applications there are two different ways of defining a region; two different accounting methods and two types of data have been used. A summary of these methods is given below.

For the first method, we start with a given natural deposit and draw around it the region that would be affected by possible exploitation. This requirement is served by the global resource data base, which collects information on WELMM resources associated with giant or supergiant deposits of fossil and mineral fuels. Data are gathered, as summarized in Figure 9-A1, on the geographical and geometrical parameters of the deposit and its possible status in the McKelvey classification (identified, hypothetical, speculative, subeconomical, etc.) and on the geological parameters of the deposit and its geological environment, as well as on the possible simul-

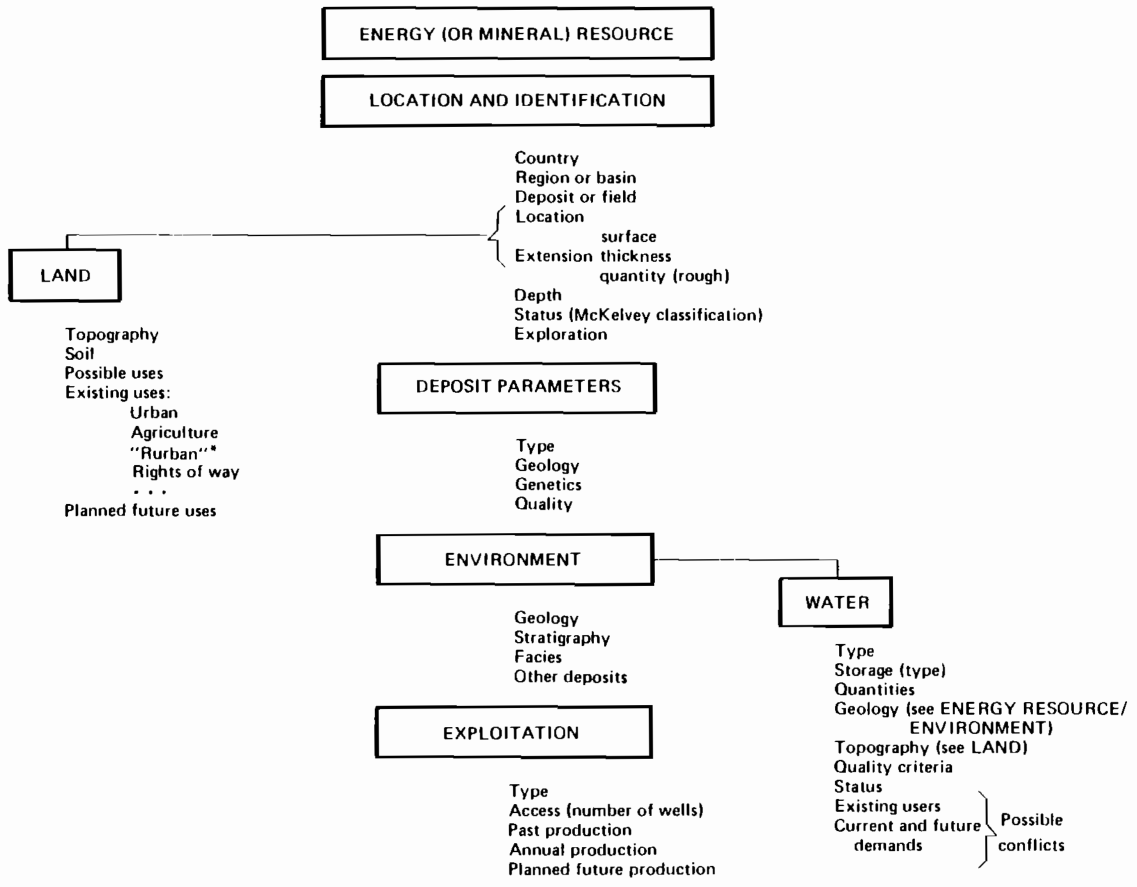


Figure 9-A1. Basic concept of the WELMM global resource data base.

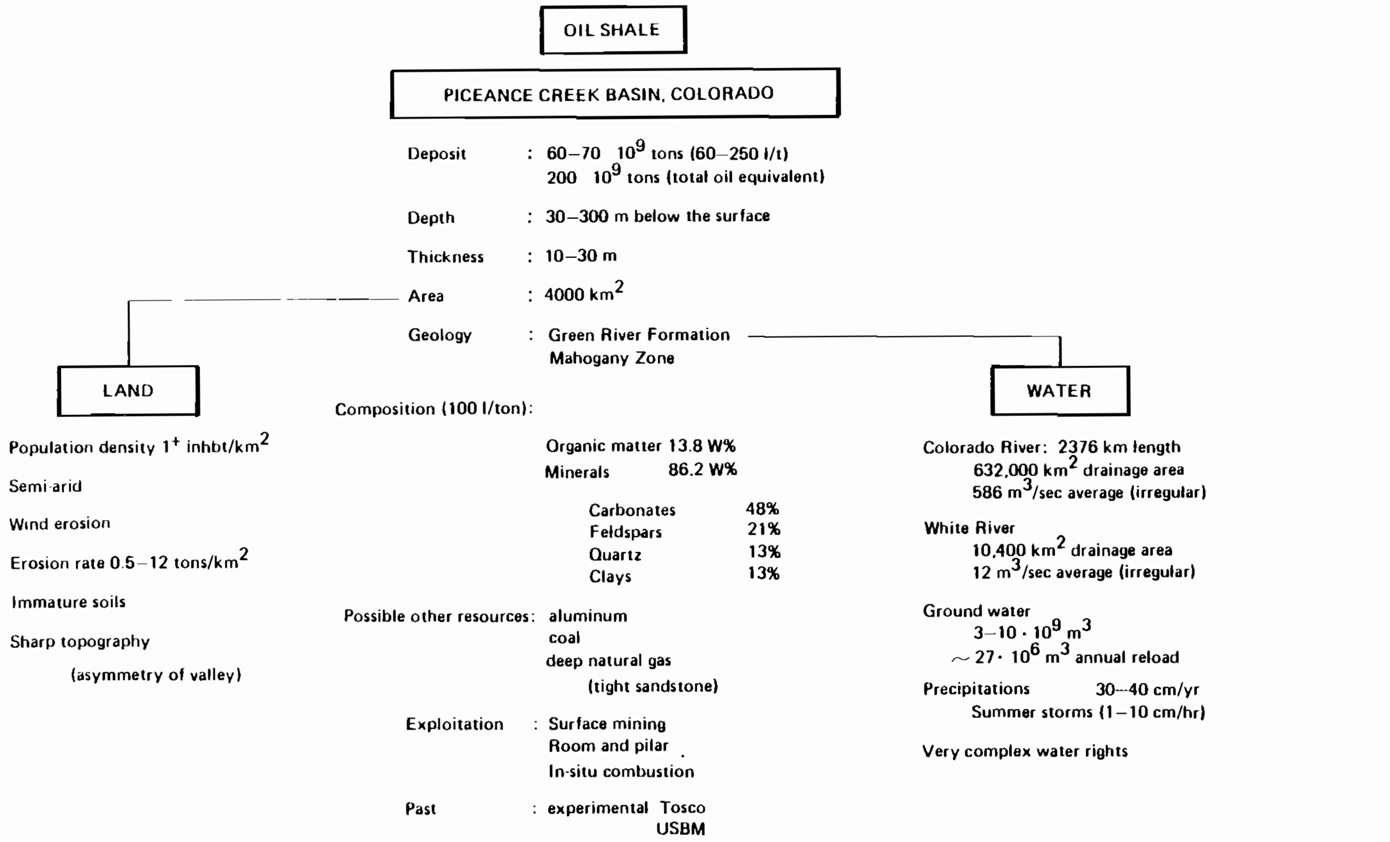
*new types of human settlements in rural areas taneous occurrences of other minerals and/or fuels; on potential, present, or past exploitation; and on historical production. In addition, data on land and water resources associated regionally with the deposit are gathered and filed, especially for the various factors that would be of importance should the exploitation of the resource be planned on a large scale.

An example of highly aggregate data is given in Figure 9-A2 for the oil shale resource of the Piceance Creek Basin in Colorado. The identified resource (60 to 70 billion tons of oil in rocks with an oil content of between 60 and 250 liters per ton; 200 billion tons including rocks of lower oil content) is very large and worth consideration, but land conditions (semi-aridity with noticeable wind erosion) and water resources (irregularity of the Colorado River, large ground water resources, but little annual reload) raise difficult problems and threaten to have large impacts on the environment.

This data base has so far been developed only for unconventional oil resources, which seem to be of particualr importance for future energy strategies. The source of data is, apart from the literature, the replies to detailed questionnaires on tar sands, heavy crude oils, and oil shales that was distributed to many private and public institutions in about twenty countries.

The second method for defining a region is to take into account the social, geographical, political, or administrative determinants. One is then able to estimate all the potentials of that particular area–energy and mineral deposits, solar resources, biomass, availability of territory and water, and so forth. The main concern of this data base is then no longer a giant resource (an energy deposit in a certain area), but a collection of "small potentials" that are of particular importance for selecting an optimum local regional energy strategy. This data base is called the regional resource data base and includes information from different fields, dividing the WELMM parameters as follows: water–permanent water, underground water, rain gauge; resources–fossil and fissile resources, geothermal resources, wind, solar; land–land use and land cover, topography, geology, geophysics; and population–density of habitation. The regional resource data base is being developed and tested over an area of 10,000 km^2 in Southern France.

Figure 9-A2. Data file for an oil shale deposit, Piceance Creek Basin, Colorado.



OIL SHALE

PICEANCE CREEK BASIN, COLORADO

Deposit : 60–70 10^9 tons (60–250 l/t)
200 10^9 tons (total oil equivalent)

Depth : 30–300 m below the surface

Thickness : 10–30 m

Area : 4000 km^2

Geology : Green River Formation
Mahogany Zone

Composition (100 l/ton):

Organic matter 13.8 W%
Minerals 86.2 W%

Carbonates	48%
Feldspars	21%
Quartz	13%
Clays	13%

Possible other resources: aluminum
coal
deep natural gas
(tight sandstone)

Exploitation : Surface mining
Room and pilar .
In-situ combustion

Past : experimental Tosco
USBM

LAND

Population density 1^+ inhbt/km^2

Semi-arid

Wind erosion

Erosion rate 0.5–12 tons/km^2

Immature soils

Sharp topography
(asymmetry of valley)

WATER

Colorado River: 2376 km length
632,000 km^2 drainage area
586 m^3/sec average (irregular)

White River
10,400 km^2 drainage area
12 m^3/sec average (irregular)

Ground water
$3-10 \cdot 10^9\ m^3$
$\sim 27 \cdot 10^6\ m^3$ annual reload

Precipitations 30–40 cm/yr
Summer storms (1–10 cm/hr)

Very complex water rights

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10 ENERGY AND CLIMATE

INTRODUCTION

This chapter considers interactions between energy and climate. The relationship is two way. On the one hand, the by-products of energy conversion—such as waste heat and carbon dioxide—can influence climate. In the other direction, climate influences the demand for energy—for example, changes in temperature affect requirements for heating and cooling. Also, climate can influence the supply of energy, especially with respect to solar and wind energy conversion and to hydroelectric power.

The impact of energy systems on climate has received increasing attention recently as awareness of man's potential to alter the earth's climate has developed, as knowledge of the complexity and sensitivity of the climate system has increased, and as local and regional changes have been observed because of pollution. Currently no observed global climatic changes can be attributed to man's energy use, but possible future changes on this scale, perhaps of an undesirable and irreversible nature, are of concern.

As noted in Part I, in 1975 global commercial primary energy consumption was some 8.2 TWyr/yr,[a] 90 percent of this from fossil fuels. Over the

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[a] Throughout the book we have distinguished between installed power capacity (TW) and annual production of energy (TWyr/yr). However, in this chapter we refer to TW throughout because of the physical properties of the climate system; here, it is more accurate to consider the power unit W and TW.

next fifty years, global energy consumption could increase by a factor of three to six. Although the resulting waste heat release to the environment would be three orders of magnitude lower than the solar energy absorbed at the earth's surface, it could have an impact on global climate because of its uneven distribution and high concentration at certain places.

There could also be a climate problem associated with increased levels of carbon dioxide concentration in the atmosphere if fossil fuels continue to play a dominant role in future energy systems. It has been observed that the amount of carbon dioxide in the atmosphere is increasing and that through the so-called greenhouse effect,[b] carbon dioxide may affect the climate system. These potential effects have been discussed in the literature for more than one hundred years, but recent studies (e.g., Flohn 1979; Kellogg 1978) suggest that the buildup of carbon dioxide in the atmosphere because of fossil fuel combustion could, by the year 2000, cause climatic changes larger than the natural climatic variability. Others (e.g., NAS 1977) suggest that the global mean temperature could increase by more then 6 K by 2150–2200 because of carbon dioxide increases in the atmosphere, indicating that the climatic effects of this gas may be a major factor limiting future energy production from fossil fuels.

The resources, the production potentials, and the physical and technological constraints of various energy sources are discussed in detail in Part II of this book. Here, we observe that only three primary sources have the potential for meeting a large fraction of the global primary energy demand over the long run—namely, fossil fuels (mainly coal), nuclear power, and hard solar energy. Thus, future energy supply systems will rely heavily on the use of one or more of these supply sources. An understanding of the possible climatic implications of the large-scale deployment of each of these energy sources is therefore important because of the built-in inertia of energy systems. The reason for this inertia is that typical energy installations (e.g., mines, refineries, power plants) are expensive, require from five to ten years for their development or construction, and have working lives of from fifteen to fifty years. We therefore examined the global climatic implications of the large-scale use of these three energy sources. Specifically, we consider the potential climatic impacts of the following:

- Large-scale waste heat release, particularly when concentrated in certain areas;
- Substantial increases in the atmospheric concentration of carbon dioxide and of other gases and particles; and
- Major changes in the earth's surface characteristics.

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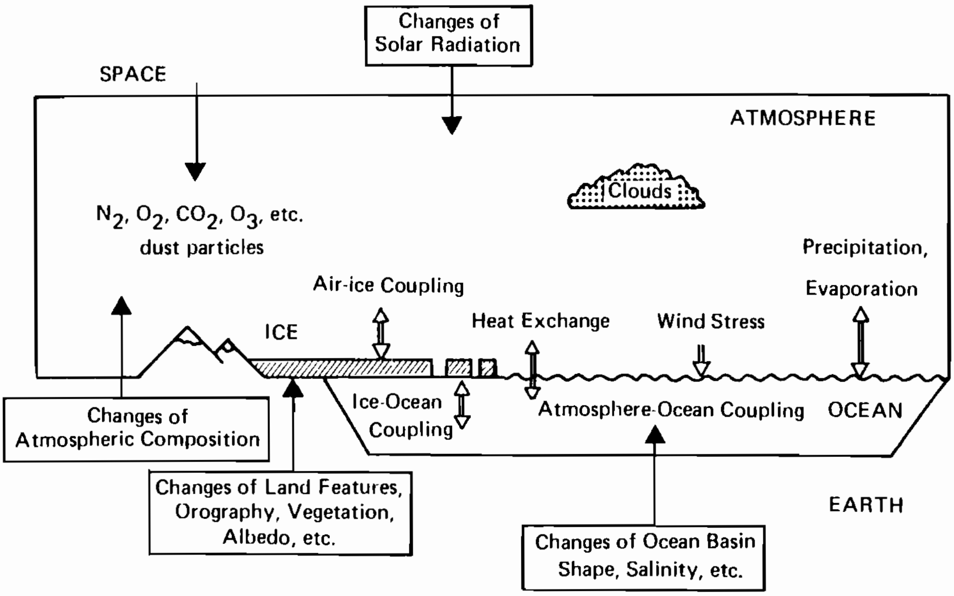
[b] Carbon dioxide is virtually transparent to incoming solar radiation but absorbs longwave radiation coming from the earth surface and reradiates some of it back to the surface. This is referred to as the greenhouse effect, although the analogy is not perfect—it is more like a "blanket effect." An increase in the concentration of the gas in the atmosphere would give an increased earth surface temperature with all other factors remaining constant.

The first of these issues is more or less independent of the energy supply mix and may be considered common to all supply strategies. The remaining two problems are specific in nature and relate mostly to the effects of using fossil fuels and hard solar systems, respectively. In the following paragraphs we survey the state of knowledge about these interactions and describe the methods and results of IIASA's studies of possible climatic impacts of future energy strategies.

CLIMATIC IMPACTS OF ENERGY SYSTEMS

In order to describe the interactions between energy and climate, we define "the climate system" and indicate why it appears to be sensitive to changes introduced by human activities. As can be seen in Figure 10-1, the climate system consists of not only the atmosphere but also four subsystems—the ocean, the cryosphere (ice and snow), land, and the biosphere. The arrows in the figure indicate how these components interact through a wide variety of processes (e.g., evaporation from land and ocean surfaces into the atmosphere; wind stress on the oceans). Thus the climate system is highly complex and nonlinear. Historical data indicate that climate has varied and continues to vary on time scales ranging from short periods (season to season, year to year) to geologic time (millions of years).

Figure 10-1. The climate system. *Source:* National Academy of Sciences (1975).



Energy conversion systems can influence the climate system in three ways. First, all energy, after passing through various conversion processes, is ultimately released to the environment as waste heat. Second, the burning of fossil fuels adds certain gases and particles to the atmosphere: either these can alter the amount of solar radiation absorbed, scattered, or emitted by the atmosphere or by the earth's surface, or they can alter the amount of other gases in the atmosphere. Third, large-scale changes in the characteristics of the earth's surface, such as its reflectivity, roughness, moistness, or the temperature of the ocean surface, could cause climatic changes.

The extent to which the climate system can be influenced varies. Locally, energy systems can be seen to influence climate: the fact that urban areas are often warmer than the surrounding countryside has often been noted (see, e.g., Landsberg 1975). Regionally—say over a distance of tens to thousands of kilometers—man's activities are seen to influence climate. For instance, increases of precipitation in areas up to 1000 km downstream of several U.S. cities have been traced to the effects of urban industrial pollution on the airflow (Hosler and Landsberg 1977). The potential impact of energy systems on this scale is large.

Globally, there is no evidence that man's activities are influencing climate presently. But such an influence is possible in two ways. First, global climate could be affected by a change in the amount of a gas (e.g., carbon dioxide) in the atmosphere. Even though this gas might be added at scattered locations, the atmosphere distributes gases very quickly and evenly, so that the increase would occur globally. This does not mean that the resulting climatic variations would be the same over all global regions: a doubling of the amounts of carbon dioxide in the atmosphere would not, for example, lead to the same surface temperature change or rainfall change in all regions. Second, global climatic variations could be caused by a large anthropogenic change in just one area, resulting in a change in the atmospheric (or oceanic) circulation such that other changes occur upstream and downstream of the perturbed area. It is not the possibility of a globally averaged climatic change that is the central issue here, but rather, the inevitable regional climatic shifts that could result from man's disturbances of the climate system.

Present understanding of the climate system is not sufficient to be able to predict reliably the potential climatic changes due to different energy strategies. However, it is possible to make some preliminary estimates of the impacts of energy conversion. First, one can look at how the climate system has responded to natural anomalies and "predict" the impact of manmade perturbations by analogy. For example, the response of the climate system to large-scale anomalies in sea surface temperature could be taken as an analogy for the response to a widespread area of waste heat release. Or on a smaller scale, the local meteorological effects of an ocean island heated by the sun could be taken as an analogy for the local effects of a power station. A second approach is to use information on climate history. For example, climatic eras in the past when the world was warmer than at present could provide the basis for scenarios of future climates due to manmade warming.

Unfortunately, both of these approaches suffer from lack of data and from questions about interpretation.

A third approach is to use models of the climate system to examine the sensitivity to manmade perturbations. A hierarchy of climate models exists, ranging from very simplified models that essentially describe the energy balance of the system to very complicated models that numerically describe the three dimensional atmospheric circulation. Since our understanding of the climate system is incomplete and the existing models contain many simplifications and do not describe all components and interactions of the entire climate system, the interpretation of the results of model studies must be made with care. The most common kind of climate model study, examples of which are given later in this chapter, are model sensitivity studies, in which the model is used first to simulate present climate and then to simulate climate with an imposed perturbation such as an addition of waste heat. The difference between the two simulation experiments represents the sensitivity of the simulated climate to a perturbation. Whether the real climate system would respond the same way as shown by the simulation experiments is not known. Thus, the results of such model studies should be interpreted as indicating the direction or the order of magnitude of response of the climate system.

CLIMATIC IMPACTS OF WASTE HEAT RELEASE

Although the problem of regional climatic shifts deserves emphasis, the use of global averages can be taken as a starting point for discussing the impact of waste heat. On a global basis, the total amount of heat released by man's present activities is only about one-ten-thousandth of the amount of solar energy absorbed by the earth's surface. (For a discussion of energy flows through the environment see Chapter 6.) An extreme global projection of 20 billion (10^9) people with an average per capita energy demand of 20 kWyr/yr would lead to a total heat release of 400 TW, which is about one-two-hundredth of the solar energy absorbed. This could give rise to a surface temperature increase of 1 K if one considers the energy balance of the global system (Kellogg 1978). However, by considering the average global system, we are ignoring the fact that energy consumption is not and will not be distributed evenly over the earth's surface. Already man's release of heat over 1 to 100 km^2 areas is sometimes found to be of about the same magnitude as, or greater than, the absorption of solar energy over the same area. It is this uneven distribution of waste heat with concentration of release in certain areas that has a much greater potential to alter global climate patterns. This potential could be realized with a total waste heat release of less than that in the extreme projection above. Flohn (1975) estimates that the amount of energy involved in natural climatic changes is of the order of 100 to 300 TW, suggesting that manmade perturbations of this magnitude could also produce global-scale climatic changes.

The maximum amount of electric power generated currently at a single thermal power station is about 3000 MW(e), and the atmospheric effects of related heat dissipation rates are not considered serious problems (Hanna and Gifford 1975). However, proposals to build power parks to generate 10,000 to 50,000 MW(e) on a land area of 5 to 100 km^2 in the United States stimulated investigation of the meteorological effects of such large heat releases. These effects must be estimated on the basis of comparable sources of heat and moisture, such as islands heated by solar radiation, urban-industrial complexes, forest fires, and volcanic eruptions. It has been suggested that waste heat release from such power parks would increase cloudiness and precipitation in the area and possibly act as a trigger for severe weather (see e.g., Hanna and Gifford 1975).

The impact of waste heat on global climate has been studied using numerical models of the atmospheric circulation. General circulation models (GCMs) are recognized as the best tools currently available for investigating the global impacts of perturbations such as waste heat. However, as noted earlier, the GCMs do have shortcomings that must be taken into account in interpreting the results of experiments. In particular, the absence of a coupled ocean circulation, the poor treatment of clouds, and hydrological and subgrid scale processes are seen as shortcomings (Williams 1978a). There are also methodological problems in determining the significance of results of experiments.

Washington (1971) used the GCM developed at the (U.S.) National Center for Atmospheric Research (NCAR) to investigate the response of the model atmosphere to an addition of 24 W/m^2 over all continental and ice regions. Results showed a 1 to 2 K increase in global average surface temperature with an 8 K increase over Siberia and northern Canada. A more realistic input of heat was used in further studies (Washington 1972) that assumed a per capita energy usage of 15 kWyr/yr and a population of twenty billion, with the energy released according to present population density distribution. It was concluded that the thermal pollution effects were no greater than the inherent variability (noise level) of the model, illustrating the methodological problems of distinguishing "signal" from "noise" in model experiments.

In a further experiment with the NCAR GCM, waste heat was added to an area extending from the Atlantic seaboard of the United States to the Great Lakes and to Florida (Llewellyn and Washington 1977), assuming that energy consumption in that area was equal to that presently consumed in Manhattan Island (90 W/m^2). In this case, temperature differences of as much as 12 K were observed in the vicinity of the anomalous heating, but the authors concluded that the heating had little effect above the surface layer and downwind from the source region.

Within the IIASA Energy Systems Program and in cooperation with the Meteorological Office, United Kingdom, a series of simulations was made (with the GCM developed by the Meteorological Office) to investigate the sensitivity of the atmospheric circulation to 150 to 300 TW of waste heat release from small areas (4.4×10^5 km^2) located in the ocean in the northern hemisphere. The principal reason for considering such effectively point sources was that with a waste heat input of 150 to 300 TW, a significant response of the simulated atmospheric circulation was considered likely if the input was concentrated in a small area. Earlier model experiments (Washington 1972) indicated that when 300 TW were equally distributed over all continental and ice areas, no significant effects could be detected. In addition, one might give some technological meaning to such point sources, with reference to the energy island concept, as discussed by Marchetti (1976). Figure 10-2 shows the locations of the heat input and Table 10-1 lists the combinations of point sources and heat inputs used in five simulations.

In four of the GCM simulations, only sensible heat was added to the lowest layer of the atmosphere. In the fifth simulation, the heat was added to a 10 m deep ocean box modeled beneath each area of waste heat input; when equilibrium was reached, some of this heat had caused an increase in the ocean temperature, and both sensible and latent heat were released to the atmosphere.

Figure 10-3 shows the differences of sea level pressure between the first simulation and the average of three model control runs that had no waste heat input. The areas where the signal-to-noise ratio is greater than 5 have been shaded. There are large coherent areas of sea level pressure change not only over the areas of heat input but elsewhere in the hemisphere. Other simulations showed a similar response in the vicinity of the Atlantic heat input, as can be seen in Figure 10-3 for the first simulation; this gives confidence in interpreting this response as a significant one.

The details of the various simulation runs and their results are described by Murphy et al. (1976) and by Williams, Krömer, and Gilchrist (1977a, 1977b, 1979). In short, the results of the five waste heat model runs indicate that the response of the simulated atmospheric circulation to the input of waste heat at point sources is not just in the area of input. Moreover, the response varies according to the location, amount, and method of heat input.

Another waste heat scenario, the so-called Megalopolis Scenario, was analyzed at IIASA with the same atmospheric model to study further the response of the atmosphere to variations in the method of heat input (Krömer,

Table 10-1. Areas and amounts of heat input in five GCM sensitivity experiments.

Experiment	*Area*	*Heat Input (W)*	*Remarks: Total heat input (W)*
01	A & C	1.5×10^{14} at each	3×10^{14}
02	B & C	1.5×10^{14} at each	3×10^{14}
03	A only	1.5×10^{14} at each	1.5×10^{14}
04	A & C	0.75×10^{14} at each	1.5×10^{14}
05	A & C	1.5×10^{14} at each	3×10^{14}; heat was added to ocean box beneath each area rather than directly to atmosphere

Sources: Experiments 01 to 05 are discussed in detail by Murphy et al. (1976) and by Williams, Krömer, and Gilchrist (1977a, 1977b).

Figure 10-2. Point sources of waste heat input used in five IIASA GCM experiments. *Sources:* Murphy et al. (1976); Williams, Krömer, and Gilchrist (1977a, 1977b, 1979).

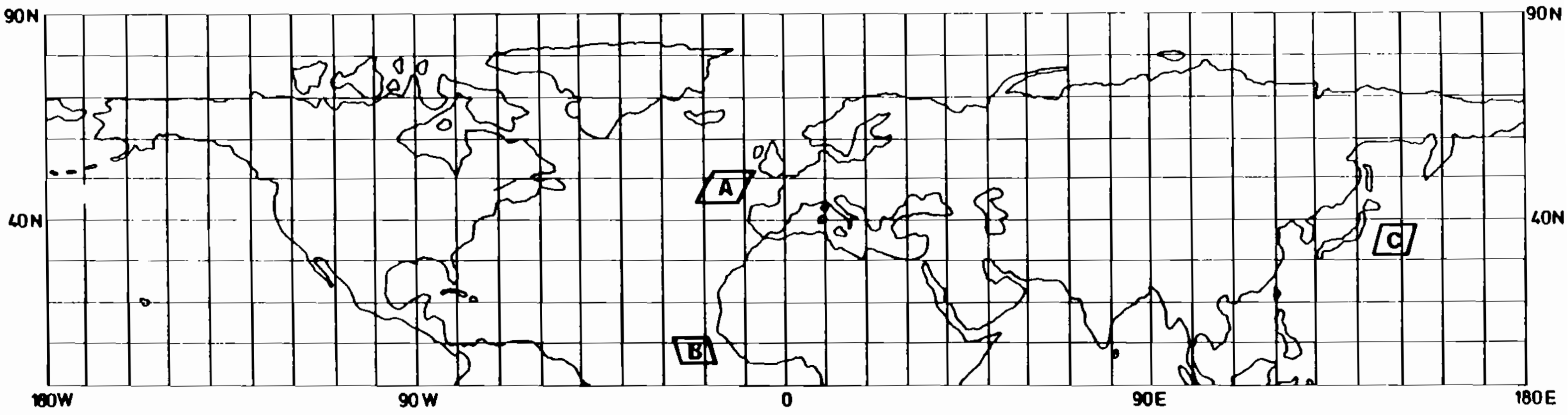
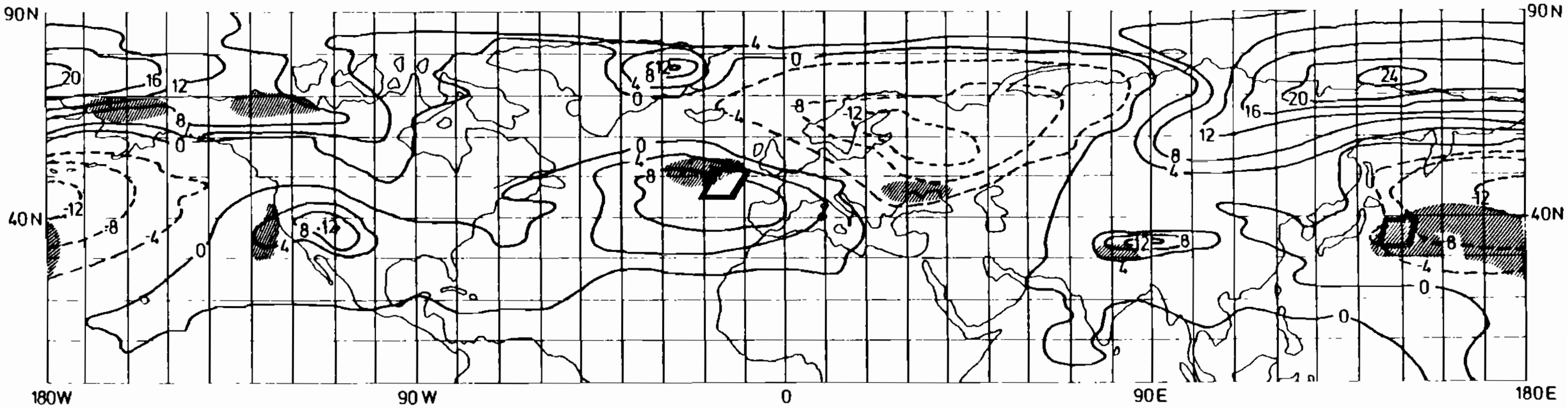


Figure 10-3. Difference in forty-day mean sea level pressure between experiment 01 and the average of the three control integrations. Shaded areas indicate where signal-to-noise ratio is greater than 5. Units are millibars. *Source:* Williams, Krömer, and Gilchrist (1979).



Williams, and Gilchrist 1979). In this scenario the heat was released from six different regions in the northern hemisphere. The selected areas represent locations where large population and/or large energy consumption densities could be expected in the future. The assumption that the waste heat release areas are distributed in a more realistic way over continental areas, rather than over the oceans as in the earlier simulations, makes the Megalopolis Scenario results more open to interpretation with respect to the two IIASA energy demand and supply scenarios discussed in Part IV of this book.

Figure 10–4 shows the geographical distribution of the chosen energy consumption areas in the Megalopolis Scenario. The selected areas were in the range 4–14 × 10^5 km^2, and their heat inputs were chosen in such a way that the heat released per square meter was the same for each area. Three simulation runs were made for this scenario with total heat inputs of 300 TW (60 W/m^2), 50 TW (10 W/m^2), and 30 TW (6 W/m^2), respectively. This is indicated in Table 10-2.

It was found that when the heat input of 300 TW is spread over six areas, the hemispheric response is comparable to that when the heat input is concentrated at only two energy parks. There is still a large number of areas over which the signal-to-noise ratio is greater than 5, suggesting that there is a significant model response to the megalopolis heat input. A further result is the strong regional-scale response of some of the megalopolis areas. As in the earlier model experiments, there are large coherent areas of change in the meteorological fields such as sea level pressure, not only over the area of heat input but elsewhere in the hemisphere.

If the heat input is reduced to 50 TW, the impact decreases only to a small extent, emphasizing again the strong nonlinear behavior of the model atmosphere. There are also strong similarities in the responses to 50 TW and to 300 TW. A further reduction of the waste heat release to 30 TW seems to bring the response of the model atmosphere closer to the model variability or noise level as described by the average of three control simulations.

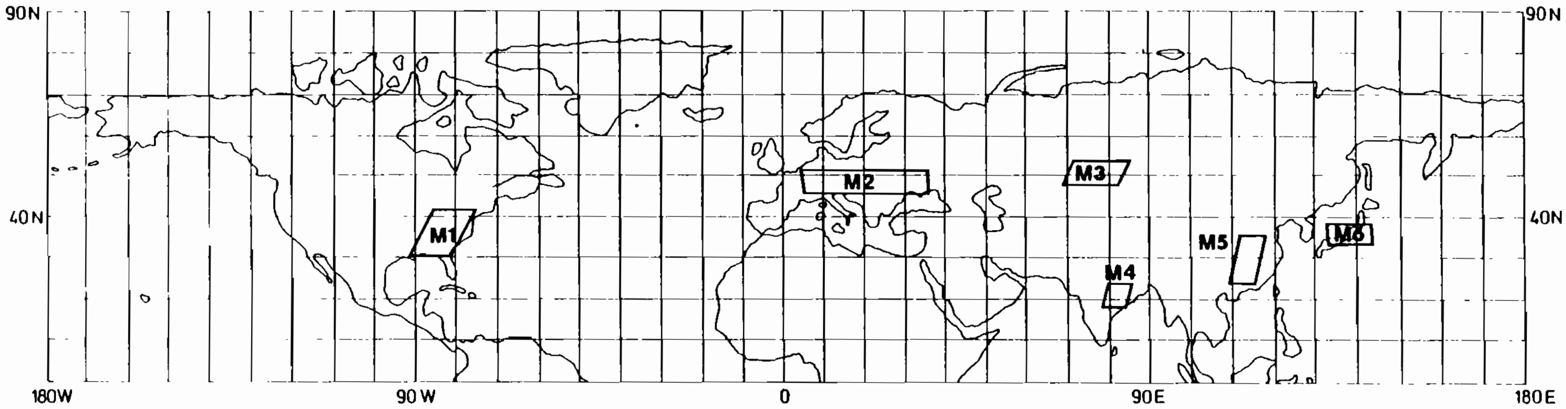
The results of various NCAR and IIASA atmospheric model studies sug-

Table 10-2. Area size and heat releases in three simulations with megalopolis scenario.

Area	*Area Size (km^2)*	*Heat Released (TW)* *MX01*	*MX02*	*MX03*
M1 (U.S.)	12 × 10^5	72	12	7.2
M2 (Europe)	14 × 10^5	84	14	8.4
M3 (USSR)	6 × 10^5	36	6	3.6
M4 (India)	4 × 10^5	24	4	2.4
M5 (China)	8 × 10^5	48	8	4.8
M6 (Japan)	6 × 10^5	36	6	3.6
Total	50 × 10^5	300	50	30

Source: Based on data from Krömer, Williams, and Gilchrist (1979).

Figure 10-4. Energy consumption areas in the IIASA Megalopolis Scenario. *Source:* Krömer, Williams, and Gilchrist (1979).



gest that waste heat is not a problem on the global scale, in that it is unlikely to perturb the global average climate state in the foreseeable future. We have seen that only when extremely large amounts of heat (on the order of several hundred terawatts) were released in small areas could any significant changes in the model atmospheric circulation be determined. With an energy consumption level of 30 to 50 TW, there appears to be little or no ground for global concerns regarding the climatic impact of waste heat release.

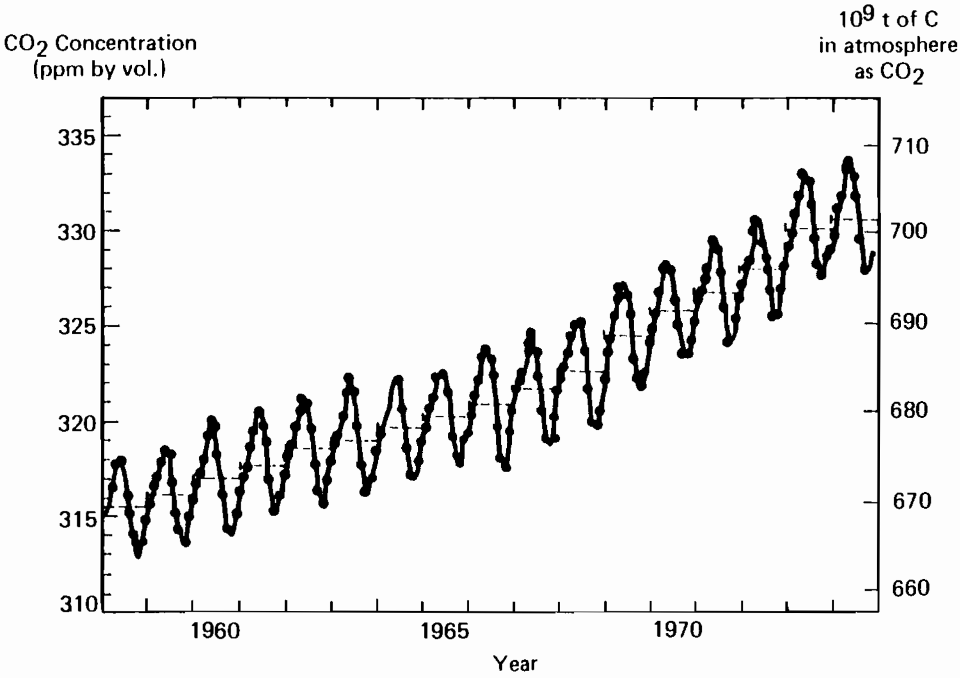
CLIMATIC IMPACTS OF GASEOUS AND PARTICULATE RELEASE INTO THE ATMOSPHERE

Whereas the impact of waste heat release on climate is common to the use of fossil fuels, nuclear energy, and hard solar energy, there are two other significant climatic effects associated with the large-scale use of specific energy sources. These are the impacts likely to result from a large release of carbon dioxide and other gases and particles in the atmosphere and from major changes in the surface characteristics of the earth. The first of these impacts is dealt with in the next two sections, while the second impact is considered in the section thereafter.

In addition to waste heat, fossil fuel usage produces certain gaseous and particulate substances that could interact significantly with the climate system. The release of carbon dioxide by fossil fuel consumption has received special attention recently in view of the physical properties of the gas and its observed buildup in the atmosphere. Figure 10-5 shows the trend in the concentration of atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii, for the period 1958-1974. Since this gas is mixed rapidly through the atmosphere, this can be taken to represent the global trend. Superimposed upon a seasonal oscillation of about 6 parts per million by volume (ppmv), there is a secular increase in the concentration from about 315 ppmv at the beginning of the period to about 332 ppmv at the end. It is accepted that part of the observed increase is due to the addition of carbon dioxide to the atmosphere by the combustion of fossil fuels; it is also argued that some of the increase is due to the destruction of forest (in particular tropical) vegetation. Estimates suggest that the preindustrial atmospheric carbon dioxide concentration was about 290 ppmv. The ultimate sink for the carbon dioxide added by man's activities is the ocean, but the transfer to the deep ocean occurs much more slowly than the present rate of addition to the atmosphere. A continuation of increasing fossil fuel usage and tropical deforestation would, as far as our knowledge of the complex carbon cycle (sources and sinks of carbon and transfers between them) is concerned, lead to a further increase in the atmospheric concentration of carbon dioxide.

A doubling of the atmospheric concentration of carbon dioxide, according to state of the art climate models, would lead to an increase of the global average surface temperature of 1.5 to 3K. These numbers could be high or low because of feedbacks being either not accounted for or incorrectly in-

Figure 10-5. Atmospheric CO_2 concentration at Mauna Loa Observatory. *Sources:* 1958-1971 data from Keeling et al. (1976); 1972-1974 from Baes et al. (1976).



corporated in present models. In any case, regional changes in climate, in particular those related to precipitation, are of much more significance than global average surface temperature changes. Both model and observational studies suggest that polar areas could be more sensitive to a global temperature increase than areas at other latitudes.

Although the climatic impacts of increasing levels of carbon dioxide have received considerable attention, Flohn (1978a, 1979) emphasizes that other gases released by man's activities also have a significant greenhouse effect. In particular, the impacts of N_2O, CH_4, NH_3, and freons should not be neglected. The model study of Wang et al. (1976) has shown that a doubling of the atmospheric concentrations of N_2O, CH_4, and NH_3 would give surface temperature increases of 0.7 K, 0.3 K, and 0.1 K, respectively.

Flohn has considered the possible time scale of a global warming due to the combined greenhouse effects of carbon dioxide and other manmade trace gases. Starting with an initial carbon dioxide content of 320 ppmv in the atmosphere, Table 10-3 shows the temperature increase corresponding to different values of a so-called virtual carbon dioxide content, which is the actual carbon dioxide content plus an equivalent due to the other trace gases. Using some recent projections of growth of carbon dioxide (Zimen, Offermann, and Hartmann 1977), Flohn (1978b) derived the curves illus-

Table 10-3. Combined greenhouse effect (CGE) and CO_2 increase.

Temperature Increase (K)	Virtual CO_2 Content (ppmv)[a]	Real CO_2 Content (ppmv)[a] Contribution of Real CO_2 to CGE 33%	50%	67%
0.5	400	(346)	360	374
1.0	490	(376)	405	432
1.5	580	(406)	450	492
2.0	670	(435)	495	555
2.5	760	(465)	540	615
4.0	1150	(560)	740	878

[a] Parts per million by volume.

Note: Temperature increase was computed using the fixed cloud top attitude version of the model proposed by Augustsson and Ramanathan (1977). The values in parenthesis refer to a case where trace gases contribute twice as much to the greenhouse effect as does carbon dioxide, which is considered unrealistic.

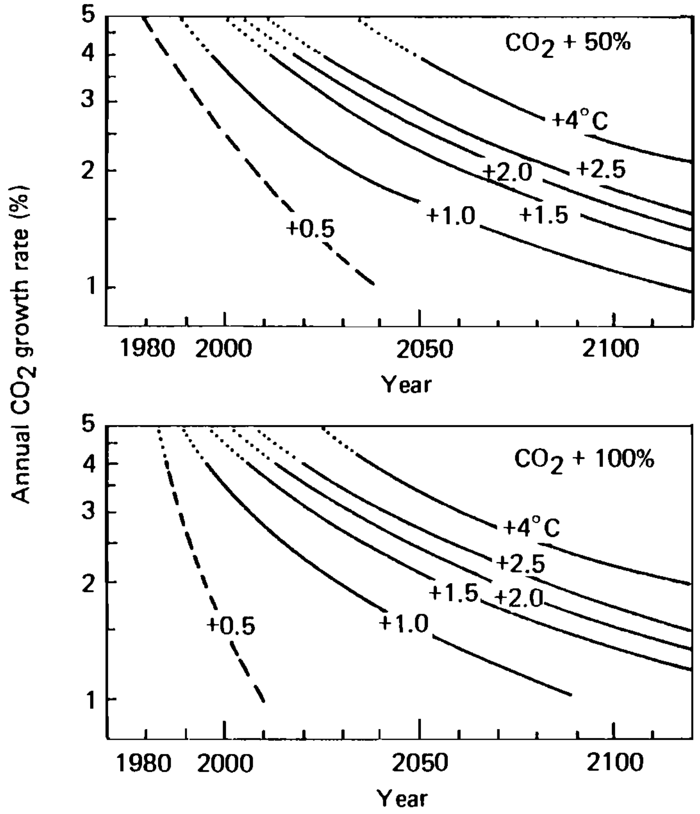
Source: Based on data from Flohn (1978b).

trated in Figure 10-6, which give a time scale for expected temperature levels at different carbon dioxide growth rates. With a carbon dioxide growth rate of 3.5 to 4 percent per year, and assuming that carbon dioxide contributes 67 percent to the greenhouse effect, a warming of 0.5 K due to the combined greenhouse effect would occur between 1990 and 2000. Even when the carbon dioxide growth rate is reduced to 2 percent per year, this temperature level is reached around the year 2010.

Since there are many uncertainties in the results of model studies of the impact of increasing atmospheric carbon dioxide (and other trace gases) concentration, and since it is of interest to "predict" the regional climatic changes, particularly the precipitation changes that could result from such a potential increase, approaches other than modeling have also been taken recently. Kellogg (1978) suggests that one way to find out what a warmer earth might be like is to study a time when the earth itself was warmer than it is now. As Kellogg points out, such a time existed 4000 to 8000 years ago, a period referred to as the Altithermal. Evidence for climatic conditions at that time can be derived, among other things, from data on the distribution of fossil organisms in ocean sediments and pollens in lake sediments, from historical data of lake levels, and from data on the extent of mountain glaciers.

An extension of this approach is made by Flohn (1978b), who suggests that the "level of perception" for a quasi-global warming would correspond to a global average surface temperature increase of about 0.5 K. A warming of 1 K would be equivalent to the early Middle Age period warming (~900 to 1100 A.D.). A warming of 1.5 K would be equivalent to the postglacial warm period (the Altithermal), which Flohn dates as 5500 to 6500 years before the present. A warming of 2 to 2.5 K would be equivalent to the last interglacial period, about 125,000 years before the present. And finally, a warming of 4 K could lead to a situation in which the Arctic Ocean would be

Figure 10-6. Temperature thresholds plotted as a function of time and initial CO_2 growth rate for two values of the combined greenhouse effect. Temperature thresholds are derived from a fixed cloud top altitude version of the model proposed by Augustsson and Ramanathan (1977). *Source:* Flohn (1978b).



free of ice; an analogous situation is not known to have occurred during the previous two million years.

Flohn made a detailed analysis of the climatic conditions during each of these periods, considering them as scenarios for possible future climates due to manmade warming. He asks, Can climatic history repeat itself? This is important because of many recent manmade changes in boundary conditions—e.g., in vegetation, albedo, soil moisture, and atmospheric composition. These changes might make it impossible to reestablish climate patterns experienced during earlier warmer periods.

The release of particulate material has also been considered with some interest, focusing on the release of sulfur and nitrogen compounds that would probably not have as large a climatic impact as would the above substances. Particulates are produced both directly as smoke or soot and indirectly from gases and sulfates and hydrocarbons. Observational evidence for changes in particle loading of the atmosphere shows an increase in loading over the previous century, but it is not clear whether this increase is a regional- or a global-scale phenomenon. The interaction of particles with radiation and thus their impact on climate depends on complicated absorption and backscatter characteristics of the particles and on surface and cloud conditions. It seems that most anthropogenic particles exist over land where they are formed and are sufficiently absorbing to cause a warming of the earth/atmosphere system (Kellogg 1978). However, there is no quantitative evaluation of the role of particles at the present time, owing to a lack of observed data on the nature and distribution of the particles and of appropriate models. Particles can have further impacts on the condensation/precipitation process and on the albedo of clouds (Kellogg 1978), but the climatic consequences of these have not been considered in detail.

THE CARBON DIOXIDE PROBLEM AND FUTURE ENERGY STRATEGIES

Models and input information are required in order to assess the future atmospheric carbon dioxide concentrations resulting from different energy strategies and their climatic implications. Estimates of the rates of future use of fossil fuels can be used to describe the input of carbon dioxide into the atmosphere as a function of time. In order to predict the proportion of fossil fuel carbon dioxide remaining in the atmosphere, a model of the carbon cycle must be used, in which the reservoirs of carbon (atmosphere, ocean, biosphere) and the transfers between them are considered. The effects of the increased atmospheric carbon dioxide concentration can then be assessed using a climate model.

Currently, uncertainties must be attached to the results of each of these models. For example, in the use of carbon models, much uncertainty has arisen regarding the role of the biosphere. While it is accepted that part of the observed increase of atmospheric carbon dioxide content is due to the combustion of fossil fuels, it has been argued recently that the destruction of the biosphere has also been adding carbon dioxide to the atmosphere (e.g., Bolin 1977; Woodwell 1978). Whether the biosphere has indeed been a source of carbon dioxide and, if so, to what extent is not presently known. Previously, it had always been assumed that the biosphere was a sink for atmospheric carbon dioxide, as are the oceans. If it were proved that the biosphere has, at least within the last century, been a source of carbon dioxide, then revision of the estimates of future atmospheric carbon dioxide concentrations based on fossil fuel combustion rates would be required. Similarly, in the case of climate models, the roles of feedback mechanisms, such as the cloudiness-temperature interaction, are still uncertain. Because of these uncertainties, we are unable to predict accurately the future buildup of carbon dioxide resulting from a given energy strategy and its likely climatic consequences. Nevertheless, the models do give us an idea of the magnitude of the problem.

An example involving the use of a carbon cycle model and the results of a climate model is given by the study of Niehaus and Williams (1979). The model of the carbon cycle (Niehaus 1976) used in this study simulates the exchange of carbon and radiocarbon among eight reservoirs. The global average surface temperature response to the increasing atmospheric carbon dioxide concentration was assumed from the study of Manabe and Wetherald (1967).

Figures 10-7 and 10-8 show two of the several hypothetical energy strategies for the period up to the year 2050, analyzed by Niehaus and Williams (1979). In Figure 10-7, the energy consumption reaches a level of 30 TW by the year 2050, the use of fossil fuels peaks around the year 2000, and energy is supplied after that date largely by solar and nuclear sources. In the second strategy (Figure 10-8), the energy consumption reaches 50 TW, with the entire demand being satisfied by fossil fuels. Figures 10-9 and 10-10 illustrate the atmospheric carbon dioxide concentrations given by the carbon model for these strategies, together with carbon dioxide emissions resulting from the strategies and estimates of the resulting global average surface temperature change. For the hypothetical 30 TW solar and nuclear strategy of Figure 10-7, the emissions of carbon dioxide peak around the year 2000, as shown in Figure 10-9. In this case, the atmospheric carbon dioxide concentration reaches a maximum of 400 ppmv in about the year 2020, and the resulting

Figure 10-7. Hypothetical 30 TW solar and nuclear strategy. *Source:* Based on data from Niehaus and Williams (1979).

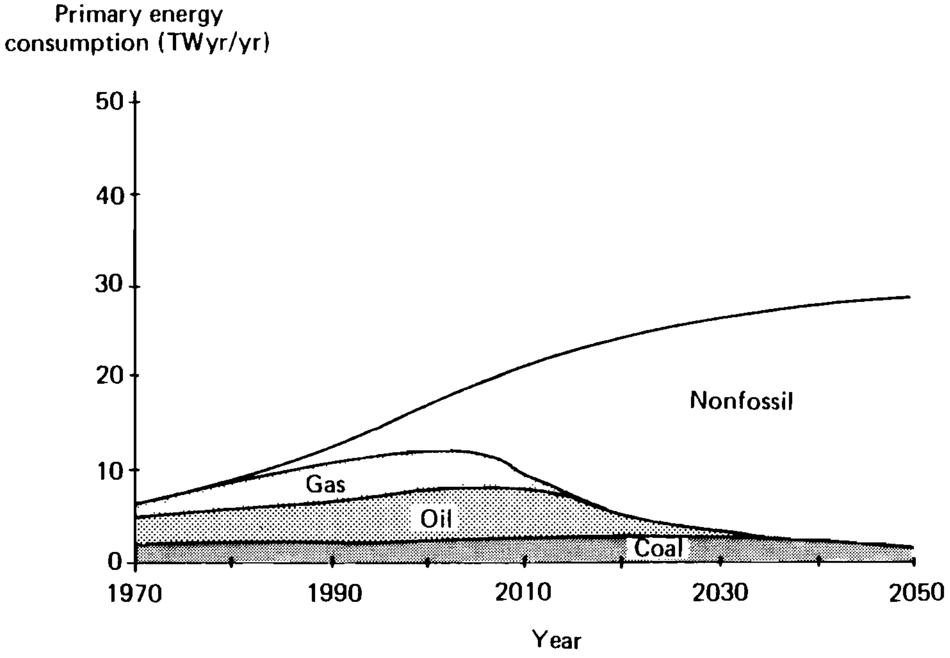


Figure 10-8. Hypothetical 50 TW fossil fuel strategy. *Source:* Based on data from Niehaus and Williams (1979).

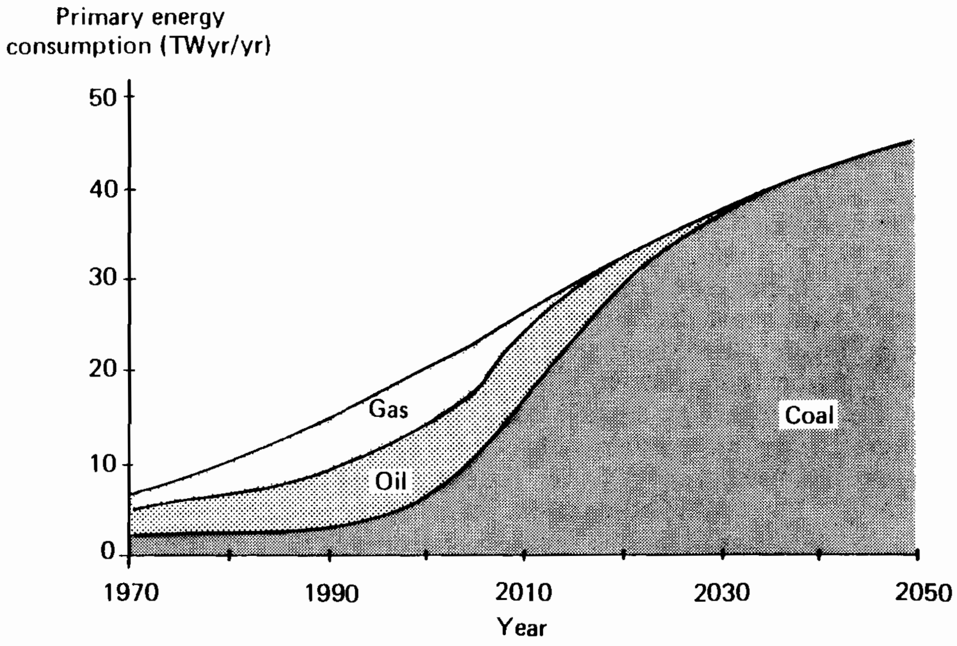


Figure 10-9. CO_2 emissions, atmospheric CO_2 concentration, and temperature change for 30 TW solar and nuclear strategy. *Source:* Niehaus and Williams (1979).

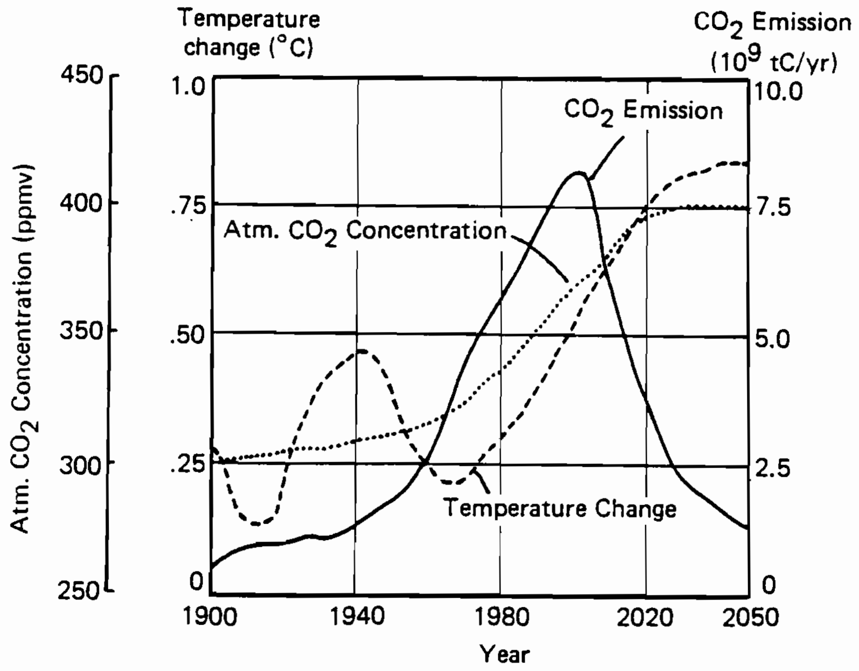
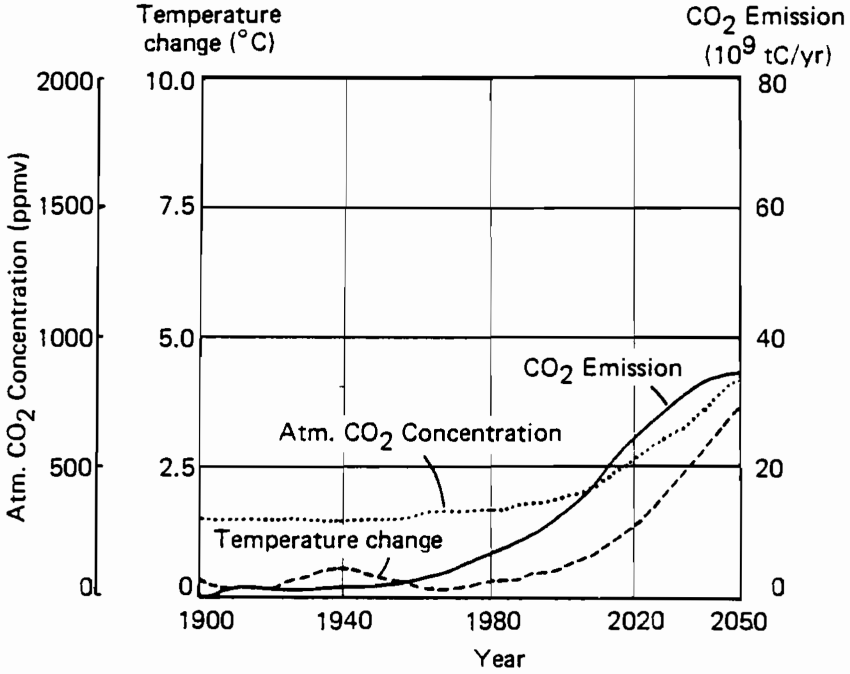


Figure 10-10. CO_2 emissions, atmospheric CO_2 concentration, and temperature change for 50 TW fossil fuel strategy. *Source:* Niehaus and Williams (1979).



change in mean surface temperature is less than 1 K. On the other hand, if energy consumption reaches 50 TW by the year 2050 and only fossil fuels are used to supply this energy, then the emissions of carbon dioxide would keep increasing all along, giving an atmospheric carbon dioxide concentration of 800 ppmv in 2050 and a mean surface temperature increase of about 4 K (Figure 10-10).

Although the results of the above model studies are subject to many uncertainties and cannot be taken as reliable predictions, still they illustrate the magnitude of the carbon dioxide problem. Within the limitations of our present knowledge, it is seen that depending on the energy strategy followed, the climate impact due to carbon dioxide buildup over the period of the next fifty to seventy years could remain small—that is, much less than 1 K—or it could become as large as 4 K.

POSSIBLE CLIMATIC IMPACTS OF LARGE-SCALE SOLAR ENERGY DEPLOYMENT

If solar energy is called upon at some time in the future to meet a large fraction of man's energy needs, it would be able to do so mostly through the deployment of hard solar systems such as those based on solar thermal electric conversion (STEC), photovoltaic (PV), and solar satellite power (SSP) applications. Of these, the SSP systems are considered a remote possibility, and their climatic impacts have not yet been evaluated. Other solar energy conversion systems (e.g., wind, wave power, hydroelectric power, biomass, OTEC) can be used locally in favorable situations, but are not expected to contribute greatly to the global energy requirement and therefore cannot be expected to have a global climate impact. (See Chapter 5 for a discussion of the hard solar option for meeting future global energy requirements.)

The possible climatic impact of the large-scale deployment of solar energy systems has received little attention in the literature. A IIASA workshop held in 1976 examined the physical characteristics of the conversion systems, assessed their impact on boundary conditions of the climate system, and discussed the climatic implications of such impacts. The workshop findings are described by Williams, Krömer, and Weingart (1977).

STEC and PV Systems

Large-scale deployment of STEC and PV systems would lead to regional changes in the surface heat balance, surface roughness, and hydrological characteristics. The climatic impacts of such changes in the earth's surface characteristics have not been investigated in detail, but a few relevant studies are available that at least indicate the kinds of impacts that could be expected. For example, in a series of model simulations, Charney, Stone, and Quirk (1975) used the GCM developed at the Goddard Institute for Space Studies to compare the simulated atmospheric circulation occurring with albedo values of 0.14 and 0.35 in the Sahel area of West Africa. They noted a decrease in precipitation and convective cloud cover as a response to an increase in albedo. Similar experiments made by Ellsaesser et al. (1976) with a zonally averaged model further supported Charney's hypothesis. In their later, more refined experiments with the GCM, Charney et al. (1977) observed that in an area where appreciable evaporation from the surface occurs, an increase of albedo reduces the absorption of solar radiation by the ground and, consequently, the transfer of sensible and latent heat to the atmosphere. The resulting reduction in convective cloud cover tends to compensate for the increase of albedo by allowing more solar radiation to reach the ground, but it reduces the downward flux of longwave radiation even more, so that the net absorption of radiation by the ground is decreased. Without evaporation, the increase of albedo causes a decrease of radiative flux to the ground and thus a decrease of convective cloud and precipitation. Two further results of the work of Charney et al. (1977) are of significance. First, changes in evaporation rate are as important as albedo changes. Second, observable effects can be expected when the characteristic time for a change in the surface flux of moist static energy to penetrate to cloud base is smaller than the time required for new properties to be advected into the region. This suggests a minimum dimension of the albedo change area of 40 to 80 km for observable effects.

A local atmospheric circulation mode developed by Berkofsky (1976) also showed that the vertical circulation and thus cloudiness and precipitation responded to surface albedo changes in desert areas. In particular, this model showed that a lowering of the surface albedo in a desert region could lead to increased vertical velocity and possibly to increased rainfall.

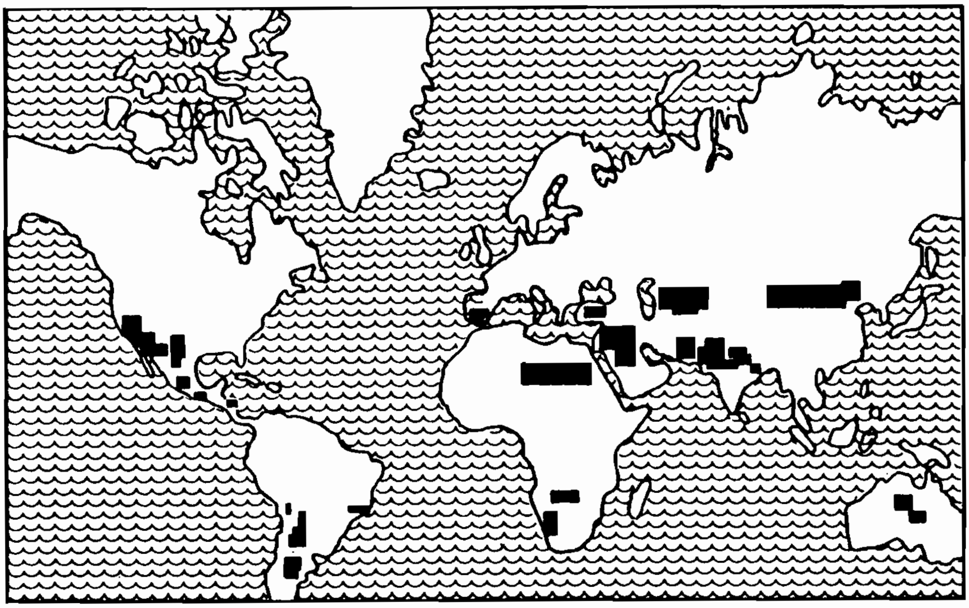
Jäger, Chebotarev, and Williams (1978) have discussed the surface energy balance changes due to STEC systems. Their analysis shows that STEC systems do not really change the magnitude of the net heat flow from the surface to the atmosphere, but the mechanism of transfer is changed; the significantly lower heat release from the surface is compensated by a release of waste heat from cooling towers upon energy conversion. In this context some impacts of STEC systems on climate can be evaluated in the same way as the potential impact of waste heat from fossil fuel combustion or nuclear power plants.

One preliminary experiment to evaluate the impact on global climate of STEC systems was made by Potter and MacCracken (1977). The model used is a zonally averaged model—that is, it considers a two dimensional (latitude-height) climate system. A scenario for albedo modification due to intensive solar energy production, derived by Grether, Davidson, and Weingart (1977), was used as input to the model. This scenario considered a world population of ten billion with a per capita energy requirement of 10 kWyr/yr and assumed that the generation of 100 MW(e) would require a reflector area of 3 km^2 (this is an overestimate in order to account for the effects of access roads, population increases, etc., in the collector region) and a total land area of 9 km^2. It was suggested that a rough estimate of the albedo change due to STEC facilities could be obtained by assuming that an area equal to the total reflector area has become completely black. Thus the new albedo is approximately two-thirds of the natural albedo in a region of intensive solar energy conversion. Figure 10-11 shows the land area assumed by Grether, Davidson, and Weingart (1977) to be devoted to STEC facilities.

Using this scenario, Potter and MacCracken (1977) modified the zonally averaged albedo in the model within the zone 50^0N to 40^0S correspondingly. No other surface boundary conditions were altered (e.g., runoff, evaporation, and surface roughness), even though these could also be influenced by the large-scale deployment of STEC systems. Figure 10-12 shows the latitude-height distribution of change in atmospheric temperature between the case with STEC-related albedo changes and the control case of the model. As might be expected, the troposphere warmed because of the increased absorption of solar radiation. The maximum warming occurred over the latitudes of largest coverage of solar facilities in the given scenario. Potter and MacCracken also analyzed the latitudinal distribution of precipitation change for the land area in each zone and found that the maximum increase in precipitation occurred in the subtropics of the Northern Hemisphere.

The results of the above experiment should be considered preliminary because of the rather simple assumption made in the scenario of Grether, Davidson, and Weingart (1977) regarding the effective change in boundary conditions. As was pointed out by Jäger, Chebotarev, and Williams (1978)

Figure 10-11. Land area assumed by Grether, Davidson, and Weingart (1977) to be devoted to STEC facilities in a 100 TW solar scenario.

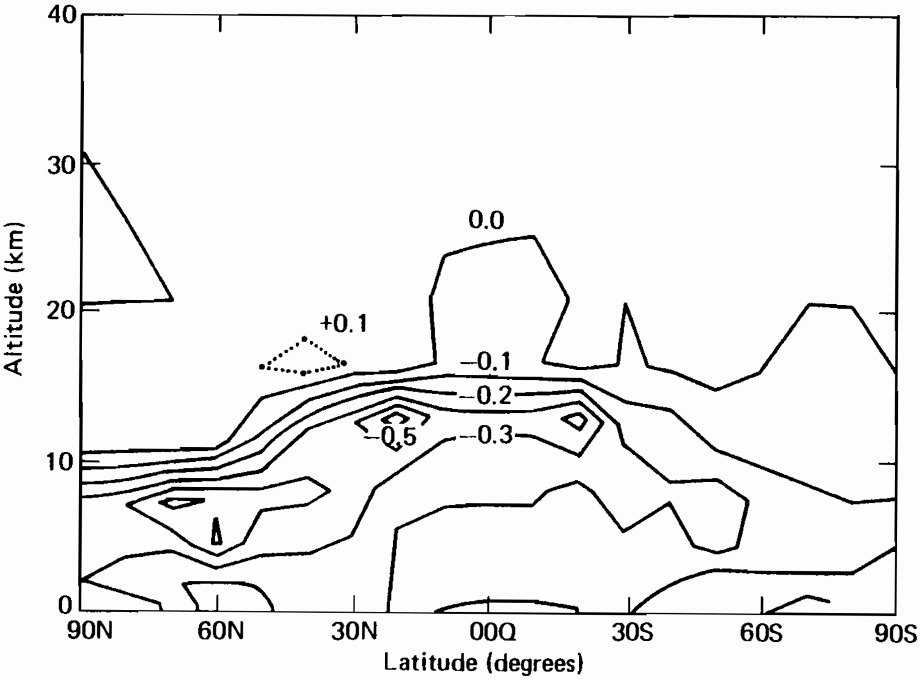


and discussed earlier in this section, the large-scale deployment of STEC facilities is likely to change the local energy balance rather than the albedo, in particular because of the release of waste heat. Also, the effects of a zonally averaged albedo change were investigated within a zonally averaged model; it is difficult to extrapolate the results in order to evaluate the impacts of regional energy balance changes on the general atmospheric circulation. Nevertheless, the results show that impacts are possible on the scale of the scenario illustrated in Figure 10-11.

Very little is known about the potential impact of changes in surface roughness over large areas. In atmospheric GCMs a drag coefficient, which takes into account surface roughness, is used for computing horizontal stress components and the vertical fluxes of sensible heat and water vapor in the surface boundary. A limited number of experiments have been made with GCMs to investigate the impact of changes in the drag coefficient. The results of these experiments were briefly reviewed by Williams (1977) and suggest that the changes can have an impact on climate patterns. Similarly, the potential impact of large-scale changes in surface hydrological characteristics also deserves attention, as the results of model studies (e.g., Walker and Rowntree 1977; Barry and Williams 1975) have recently confirmed the importance of large anomalies in surface wetness in influencing the atmospheric circulation. However, as yet no scenarios of changes in surface roughness and surface hydrological characteristics relevant to large-scale deployment of STEC facilities have been studied.

A series of simulations has been made jointly by the Stanford Research

Figure 10-12. Latitude-height distribution of difference in temperature (degrees K) between model case considering 100 TW solar energy conversion and control case. *Source:* Potter and MacCracken (1977).

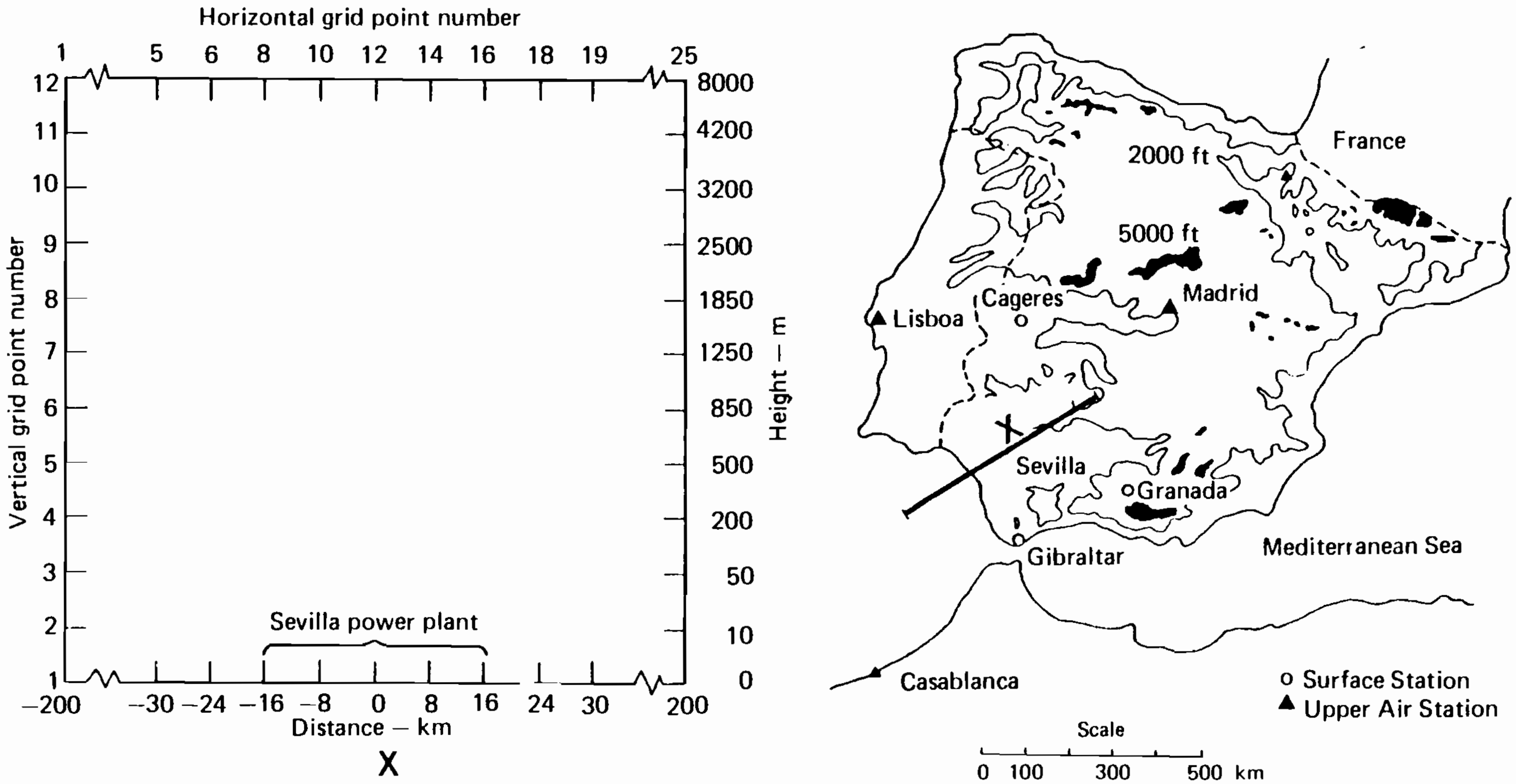


Institute of IIASA, using a "mesoscale" model of the atmosphere developed by Bhumralkar (1977) to investigate the regional impact of a STEC facility (~30 GW(e)) on the meteorological conditions in southern Spain. The model is two dimensional and considers a horizontal plane 400 km long and a vertical plane 8 km high. The model solves equations for the atmospheric processes within this domain and predicts the changes in such meteorological variables as cloudiness, precipitation, and atmospheric temperatures due to a change in the surface energy balance.

For this project, the changes in surface energy balance were assumed to be due to the installation of a STEC facility. The changes are attributed to optical losses and absorption of solar radiation by mirrors, energy losses at the central receiver, piping and storage losses within the STEC facility and, finally, to waste heat release at cooling towers during energy conversion.

Figure 10-13 shows the location of the hypothetical STEC facility that has been considered in the experiments. As indicated in the inset to this figure, the STEC plant is assumed to have a horizontal dimension of 32 km, which implies an area of 1024 km^2. In order to investigate the changes upstream and downstream of the STEC plant, a grid 400 km long is considered with the STEC plant in the center. As also indicated in the figure, it is as-

Figure 10-13. Location of STEC plant and a schematic representation of the model grid used in the study of the regional meteorological effects of a large-scale STEC installation.



sumed that the STEC plant is aligned SW-NE, which is the direction of the prevailing wind. The temperature, humidity, and wind data required for initial conditions of the model run were compiled from a number of meteorological observing stations whose locations are also indicated.

Two sets of model runs were investigated. In the first set, a perturbed run (with STEC) and a control run were started with initial conditions for a July day, while in the second similar set, the two runs were started with initial conditions for a January day. After several hours of simulation time for each run, the regional climatic conditions in the perturbed and control runs belonging to the same set were compared. It was concluded from the results of these simulation experiments that the installation of the STEC plant caused in the summer case an earlier and more persistent cloud formation than in the unperturbed case. The unperturbed control case indicated a sea breeze situation in which clouds form later in the day and move quickly oceanward rather than remaining over one area. A small increase in humidity resulting from the installation of the STEC plant was also observed in the winter case, although the prevailing wind in this case was strong enough to prevent any development of cloud cover over the land.

Although these experiments have been of a preliminary nature and confined to one region only, they do suggest the possibility of regional-scale meteorological impacts of STEC installations of a few tens of gigawatts. (The potential impact of PV systems is generally considered to be similar to that of STEC systems.) Such investigations need to be expanded considerably to cover different regions with different climatic conditions and a range of STEC capacities. The global-scale climatic impact of STEC (and of other solar systems) is of concern for a more distant future since, as discussed in Chapter 5, the hard solar systems will probably not reach a high level of deployment (tens of terawatt level) until sometime in the later half of the next century in view of various economic, technological, and market penetration constraints.

IMPLICATIONS FOR ENERGY POLICY OF THE CLIMATE CONSTRAINT

Currently, there are many uncertainties about the specific climatic impacts of the large-scale deployment of any of the major energy supply sources. It seems likely, however, that the global impacts of waste heat and changes in surface conditions will be felt in the more distant future than those from changes in concentration of carbon dioxide and certain other infrared-absorbing gases. In recent years, most concern has centered on the carbon dioxide question. The question is whether present knowledge of the carbon cycle and the climate system justifies changes of existing energy policies. The IIASA Workshop on Carbon Dioxide, Climate and Society (Williams 1978b) concluded that mankind needs—and can afford—a period of between five and ten years for vigorous research and planning to narrow uncertainties sufficiently to be able to decide whether a major shift away from fossil fuels is called for because of the climatic implications.

Participants at the IIASA workshop formulated a number of policy statements that can, to a large extent, be taken as a general statement on the interaction between energy policy and climate research at the present. The main points of these policy statements are as follows:

- Quantitative estimates on the rates of increase of carbon dioxide (and other infrared-radiation-absorbing molecules) in the atmosphere, and resulting global and regional climate changes are uncertain and are likely to remain so for most of the next decade. Thus, it is premature to implement at this time policy measures requiring the reduction of the use of coal and other fossil fuels. Present knowledge justifies comprehensive study of many alternative energy supply systems, but does not yet warrant a policy of curtailment of fossil fuel use.
- Policies emphasizing the use of coal (because of its great abundance) in preference to nonfossil (non-carbon-dioxide-producing) energy supply systems are at present equally unjustified. Since such policy decisions can become difficult and very costly to reverse, it is most important to maintain flexibility in energy supply policies at this time.
- Climatological impact assessments of escalating energy use must be performed in greater depth than in the past.
- Systems that allow ready environmental amelioration must be considered. Such systems would have to be either nonpolluting (or very nearly so) or lead to environmental effects that can be easily mitigated. There are several possible systems that can satisfy these conditions, including a solar-hydrogen or a hydroelectric-hydrogen system, an energy supply fueled largely by synthetic methanol manufactured at energy islands using nuclear (breeder) or hard solar energy supply, or very highly decentralized solar energy supply systems.
- Systems employing a short-time recycling of carbon through the atmosphere can also be considered. For example, the use of biomass as a fuel is a possibility. Stripping carbon dioxide from exhaust stack systems and even from the atmosphere itself is in principle feasible, and the manufacture of methane or methanol from the carbon thus obtained would be an effective “recycling” system. The carbon could also be stored in the living biomass or in the deep ocean.

THE IMPACT OF CLIMATE ON ENERGY SUPPLY AND DEMAND

In terms of the impact of climate on energy supply, climate can influence the research and/or the exploration for energy sources. For example, exploratory drilling for oil in the Gulf of Mexico entails climatic problems quite different from those on the North Slope of Alaska (Critchfield 1978). Selection of sites for power stations also requires climatic considerations. The roles of different climatic variables are of particular significance for solar, wind, and hydroelectric power sources. For this reason, programs such as the U.S. National Insolation Resource Assessment Program have been established in order to collect, record, and archive climate data useful to the forecaster and researcher. Local climate also influences the method, materials, timing, and costs of both constructing energy supply facilities and transporting energy (e.g., routing of colliers and tankers; highway and railway maintenance).

The impact of climate variation on supply is mainly through the impact on such renewable resources as wind, biomass, and solar systems, although transport of other energy sources can be affected by anomalous climate conditions. Droughts have been noted to influence hydroelectric power supply. For example, the drought in the northeast United States during the period 1961–1966 reduced flow rates of rivers and reservoir levels; New York City reservoir levels were reduced to 40 percent of their capacity in 1965 (Critchfield 1978).

As far as the impact of climate variability on energy demand is concerned, it has been shown, for the United States at least, that the increasing use of air conditioning and electric heating in homes has increased the sensitivity of energy demand to temperature changes. Mitchell et al. (1973) computed the seasonal total heating degree-days for each state of the United States and for each of the forty-two heating seasons from 1931–32 to 1972–73. The study allowed an estimate of climate influences on heating fuel demand. Results showed that in one year out of one-hundred years one should expect a national total demand for heating fuel to exceed the long-term average demand (for constant economy) by as much as 10 percent. Similarly, the demand can be expected to exceed its average demand by at least 3.6 percent on an average of one heating season in five. Of course, when one part of the continent is colder than average, it is not unusual for other sections to be warmer than average. The probable extreme deviations are larger when regions are considered, especially in the southern and Pacific states. For example, for the South Atlantic states, in one year out of one-hundred years one should expect a total demand for heating fuel to exceed its long-term average demand by 20.4 percent. To the extent that fuels are not readily distributed from one part of the country to another, the study was significant.

An examination of the record of winter accumulations of heating degree-days revealed that the greatest accumulation occurred over the northern United States and Canada during the winter of 1935–36 (Beltzner et al. 1976). It was estimated that large areas of the northern United States and Canada would have had an increased fuel consumption of 50 percent or more in February 1936.

One further interaction between climate and energy demand and supply is in the field of forecasting. Here it is difficult to draw the line between weather and climate. In a discussion of the sensitivity of energy demand to weather influences, the value of a forecast of an extreme event, based on climatological data, was pointed out (see Critchfield 1978). Similarly, it was shown that small temperature forecast errors cause extra millions of cubic feet of natural gas to be required by moderate-sized cities to protect against optimistic but false forecasts during cold weather. The above two examples serve to illustrate the need for the use of climatological data for developing statistics to aid in forecasting energy demand.

There are a large number of interactions between climate and energy systems. Many correlations between the two systems have been observed, but much work is still required. In particular, an adequate theory of existing climate and the ability to predict future climatic variability are required.

CONCLUDING REMARKS

In order to supply energy to satisfy a medium- to long-term demand of several tens of terawatts, three primary energy sources are available—fossil fuels, nuclear, and solar. Each of these sources can influence the climate system—by the emission of waste heat, by changing concentrations of atmospheric constitutents, or by changing surface conditions.

Model experiments suggest that waste heat releases would have to be extremely large—of the order of 100 TW—in order to perturb global average climatic state. This is not to say, however, that regional changes would not occur with waste heat emissions from an energy supply of 20 to 50 TW. Likewise, changes in surface characteristics, such as albedo, roughness, or wetness, would have to be on a large scale in order to affect climate on the global scale, but could have impacts on local or regional climate even when such changes are relatively small.

As for the carbon dioxide problem, because of the large uncertainties in the present knowledge of the carbon cycle, it is not possible to quantify with a high degree of certainty the possible buildup of carbon dioxide in the atmosphere due to continued large-scale reliance on fossil fuels over the next fifty years. If the generally held "views" on the magnitudes of sources and sinks and transfer rates of carbon dioxide are accepted, it appears that the atmospheric concentration of carbon dioxide may increase by 20 to 100 percent over the next fifty years, depending on the global level of energy consumption and the extent of reliance on fossil fuels.

The corresponding increase in global average surface temperature would be in the range 0.5 to 2 K. However, one should not expect the same temperature changes in all parts of the globe—some areas would experience greater and some smaller changes. Additionally, there would be regional changes in other climatic variables—of particular significance is rainfall.

Nevertheless, in view of the present uncertainties in quantifying the effects of carbon dioxide, it seems premature to recommend only those energy strategies that actively discourage the use of fossil fuels. At the same time, in view of the probable climatic implications of increased concentration of carbon dioxide in the atmosphere, it would be unwise to build future energy strategies that continue to rely greatly on the use of fossil fuels. A prudent policy, in our opinion, would be to have sufficient nonfossil options incorporated in the energy supply system over the next few decades so as to allow expansion from that base, if necessary, as the effects of carbon dioxide become better quantifiable through further research.

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11 RISKS AND STANDARDS IN ENERGY SYSTEMS

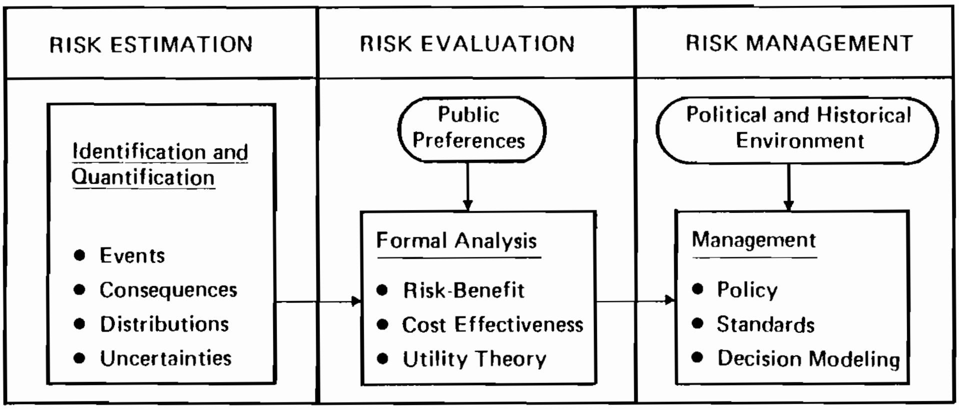
INTRODUCTION

All known energy options, and thus any energy supply mix, have associated with them risks to human health and safety and to the environment. Such risks arise both because of the possibility of accidents in the energy facilities (e.g., dam failures, sinking of underground mines, explosions in various plants) and because of the gradual environmental degradation that goes along with even the normal operation of such facilities (e.g., emission of carbon dioxide, sulphur dioxide, and other hazardous gases into the atmosphere; increase in radiation level; spillage of oil either at sea or on land).

The assessment of such health and environmental risks is an extremely important part of formulating future energy strategies. Therefore, this chapter discusses a variety of techniques for, first, understanding more precisely the nature of such risks and, second, understanding how, in formulating energy strategies, the scientific analysis of risks might be incorporated along with economic analyses, analyses of public preference, and other relevant analyses.

In 1974, a Risk Assessment Project was established jointly by the International Atomic Energy Agency (IAEA) and IIASA to increase understanding of the risks of energy systems. A risk assessment framework was developed that distinguished three elements of the assessment process—risk estimation, risk evaluation, and risk management—as shown in Figure 11-1.

Figure 11-1. Risk assessment framework.



The estimation process deals with the identification and the quantification of the risks that might be associated with operating a technological system. The main outputs of the risk estimation studies are quantified consequences (e.g., increase in illness and deaths) and their probability distributions as applicable to different groups of the affected population.

Risk estimation is by far the most studied aspect of risk assessment. As such, the IIASA effort did not concentrate on research in this particular field.

Once the risks associated with different energy options have been estimated, the problem becomes one of comparing the risks, first, with each other and, second, with other important energy system attributes (e.g., capital and operating costs; reliability of supply). Such comparisons are complex because the risks and attributes of concern differ in so many ways. They may be fundamentally different in nature (e.g., nuclear proliferation risks versus the risk of more frequent power blackouts); they may have very different probability distributions (e.g., the relatively low probability associated with a serious nuclear accident verus certain carbon dioxide increase associated with burning fossil fuels); or they may affect different populations (e.g., occupational risks versus public risks, risks to current generations versus those to future generations, or the global risks of carbon dioxide increase versus the local risks near liquified natural gas [LNG] terminals). In order to decide whether one particular energy mix is preferable to another, a process for comparing such a varied collection of risks and attributes is needed. It is this process that we refer to as risk evaluation.

Ultimately, how one evaluates different risks, how one compares cancer incidence to the incidence of black lung disease or a near-term increase in power blackouts to a long-term increase in global carbon dioxide, will depend on one's personal values or preferences. Thus, there can be no single, objectively correct procedure for evaluating risks. However, there exist a variety of techniques that can aid in understanding, first, how to systematically apply one's own values to a complex, multidimensional choice among energy systems and, second, how to better analyze the values held by others and possibly incorporate such values in energy policy decisions. It is these techniques that are addressed in this chapter. They include risk-benefit analysis, cost-effectiveness analysis, a procedure for measuring and analyzing public attitudes toward energy systems, and an examination of preference-based evaluation procedures known variously as decision analysis, risk-benefit analysis, and multiattribute utility measurement.

Risk management refers to the organizational and political aspects of the environmental management of energy systems. It involves the pragmatic problems that arise when competing groups, which most likely disagree on both the estimation and the evaluation of risks, actually try to negotiate and implement an energy strategy. Note that since risk evaluation techniques often also involve the political decisionmaking process, the line between risk evaluation and risk management is not always as sharp as suggested by Figure 11-1. At IIASA, standard setting was studied as one important part of risk management. This research focused on the dynamics of regulatory agencies setting standards for energy systems. In the following sections we discuss separately the three components of the risk assessment process as related to energy systems.

RISK ESTIMATION: IDENTIFICATION AND QUANTIFICATION

Four categories of information are needed to describe the risks from the use of a technology, both for planned operations and for unplanned occurrences —events (e.g., emissions, accident sequences, wind direction) and the probability of their occurrence; the consequences of these events (e.g., health effects, property damage); the distribution of consequences within the population affected; and the uncertainties in these estimates. The data base for these four categories establishes the objective portion of any risk assessment study, although there is often a certain degree of subjectivity introduced by the judgments of technical experts. Also, since there is no natural law specifying how these data are to be aggregated, there can be no really objective unified measure of risk. This problem of aggregation will be dealt with more fully in the risk evaluation section. Here we concentrate on approaches to estimating risks.

There are two types of methods for obtaining data in each of the four categories. In the first of these one examines frequent events of well-established technologies, using statistical means to analyze historical data. An example of such an event is the continuous release of pollutants from a normal technological operation: here the reliability of the data source is a crucial issue. Problems may arise in the definition of test population versus control population, the sampling procedure, background noise, correlation versus causal relation, and competing risks. Nevertheless, statistical methods, based on actual data, are often judged to lead to the most reliable results. In reality, however, many of these problems are often insurmountable.

As will be discussed later in the chapter, the greatest uncertainties in estimating energy systems risks arise in the case of coal, which has the longest documented history of all commercial primary energy carriers.

However, when the events of concern are very infrequent or have associated with them major consequences, it is neither possible nor desirable to estimate risks by just waiting for sufficient historical data to accumulate. Put another way, we can no longer base the development of a technology on trial and error, which is equivalent to hypothesis and experiment in science. With the implementation of technical systems on a global scale, man has entered the domain of "hypotheticality" (Häfele 1975) where it is no longer acceptable, at the level of the complete system, to correct a hypothesis by the outcome of an experiment. This applies both to accidents in large, modern technical installations such as LNG terminals or nuclear power plants and to routine emissions from well-established technologies such as carbon dioxide emissions from fossil-fueled power plants.

For these sorts of risks a second approach to risk estimation is needed. The second type of method estimates low frequency risks (see e.g., Gumbel 1938)–risks that, in principle, can be predicted usually on the basis of an extrapolation from statistical data. Examples of such methods are fault- and event-free analyses as well as computer simulation models for determining failure rates of various facility components (e.g., pumps, automatic control systems, pipes, valves, vessels). Information on the reliability of the system elements is usually available, and from this one can estimate the performance rate of special equipment composed of such elements. The behavior of the total system is then synthesized. Since so many different event paths are possible, those paths contributing significantly to the risk are identified, and both their probability of occurrence and consequence distribution are estimated. Generally, such results follow smooth curves with decreasing probabilities of occurrence for increasing serious consequences. As suggested in studies by the U.S. Nuclear Regulatory Commission (1975a) and by Farmer (1967), the total density function is important for a complete estimation of risks.

However, methods falling in this second category have certain shortcomings. First, only those failures and event sequences that can be envisaged by experts can be included. In this context, common-mode failures pose particularly severe problems. Another limitation is that human failures, especially under stress, are difficult to quantify (USNRC 1975a). Most studies of this sort are therefore based essentially on extrapolation techniques requiring expert judgment. Since the probability of many event sequences is as low as 10^{-6} per year, there are no historical data with which to verify the analytical results.

RISK EVALUATION

The risks associated with energy systems include direct and indirect effects on human health; damage to property; impacts on social institutions and social relations; and environmental impacts on the biosphere, the atmosphere, the oceans, and the land. Moreover, different risks will vary in terms of their probability distributions (e.g., high frequency versus low frequency), their geographic distributions (e.g., global versus regional), and their demographic distributions (e.g., occupational versus public). Comparing alternative energy systems therefore requires some set of procedures for comparing different risks in all their different dimensions. It is these procedures that we address here under the heading of risk evaluation.

In Chapter 10, the research that has been done on large-scale risks associated with climatic change was discussed. However, past research has more often focused on human health risks, particularly fatality risks, and it is principally these risk categories that are discussed here.

Average Fatality Risks of Various Human Activities

Starr, Greenfield, and Hausknecht (1972) suggest the average risk of acquiring a fatal disease as a yardstick for determining acceptable risk levels, since it has been demonstrated that the risks of many accepted technologies have been gradually reduced to this level (Starr, 1969). This risk Starr found to be 10^{-6}/person per hour. Pochin (1977) has compared the individual risks of various human activities by normalizing them to a fatal risk value of 10^{-6}. For example, three weeks of factory work in the clothing industry or only three hours of work in the mining industry each result in the probability of one fatality in one million; likewise, traveling either by automobile for 100 km or by airplane for 500 km has an associated fatal risk of 10^{-6}.

Of course, average expected values will vary greatly among people and circumstances. Also, such averages may mask important differences in the probability distributions of the accidents from which they were derived.

Quantified Health Risks of Energy Systems

We now consider the human health risks associated with energy systems. The order of magnitude of these risks may be seen from estimates of the human health impacts due to electricity production in the United States in 1975. In that year, for the total population there were between 2000 and 19,000 deaths and between 29,000 and 48,000 diseases (Hamilton and Manne 1977).

In Table 11-1 we give quantitative estimates of human health risks associated with 1 GWyr of electricity production for five primary energy sources—coal, oil, natural gas, nuclear (light water reactor), and solar thermal. These estimates are based largely on statistics published by the U.S. Department of Labor and on various assessments reported in the literature.

However, in some cases (e.g., the public health effects of sulphur dioxide, particulates, and radiation exposure) the data are based on a linear, nonthreshold extrapolation from high level, acute exposures. For each energy system, estimates are also made of the relative impacts of the various stages in the fuel cycle. Because of a lack of quantitative or even good qualitative

Table 11-1. Estimated human health effects from 1 GWyr (8.76×10^9 kWh) of electricity generation.

	Accidental Injuries (in man-days lost)		*Accidental Deaths*		*Fatal Diseases*	
Power Plant Type	*Occupational*	*Public*	*Occupational*	*Public*	*Occupational*	*Public*
Coal						
Fuel supply	1920-3100		1.2-1.8		5.6-8.4	
Transport fuel and materials	640-880	1500-1800	0.63-0.73	2.7-3.8		
Normal operation	790		0.05			3.2-22
Construction	590		0.17			0.006-0.04[a]
Total	3940-5360	1500-1800	2.0-2.8	2.7-3.8	5.6-8.4	3-22
Oil						
Fuel supply	3850		0.38			
Transport fuel and materials	750	2-3	0.071	0.0048		
Normal operation	110		0.027			1-7
Construction	440		0.12			0.004-0.03[a]
Total	5140	2-3	0.6	0.0048		1-7
Gas						
Fuel supply	2200	2200	0.23	0.16		
Transport fuel and materials	190	2	0.027	0.003		
Normal operation	110		0.027			0.003-0.02
Construction	200		0.054			0.002-0.014[a]
Total	2700	2200	0.34	0.163		0.005-0.034

Table 11-1 (continued)

Light water reactor						
Fuel and reprocessing	300–400		0.12		0.05	
Transport fuel and materials	5	6	0.0025	0.011		
Normal operation	10		0.03		0.032	0.03
Construction	310		0.082			0.003–0.21[a]
Total	620–720	6	0.23	0.011	0.082	0.033–0.051
Solar thermal						
Material supply	450		0.071			0.05–0.35[a]
Transport of materials	32–44	75–90	0.032–0.037	0.14–0.19		
Construct plant	3400		0.95			
Construct storage	580–2300		0.28–0.29			
Normal operation	2200–2800		0.8–1.0			
Total	6700–9000	75–90	2.1–2.4	0.14–0.19		0.05–0.35

[a] Resulting from emissions from coal that was used to melt metals, and so forth.

Sources: Estimates based on data from U.S. Department of Labor; and also on assessments of the U.S. Atomic Energy Commission (1974); Inhaber (1978); Bliss et al. (1977); Lave and Freeburg (1973); Caputo (1977); Hildebrandt and Vant-Hall (1977).

One of the references cited for Table 11-1 is the Canadian Atomic Energy Control Board's report by Inhaber (1978), a report that has attracted strong criticism. While the only Inhaber results that are incorporated in Table 11-1 are those having to do with occupational health effects during construction, we feel that we should include here some supplementary data to Table 11-1. Presented below are the results from the Atomic Energy Control Board report along with the results of J.P. Holdren's critique (Holdren et al., 1979) of that report. The numbers attributed below to Holdren are the results of his trying to reproduce Inhaber's numbers using Inhaber's methodology. As is evident, there are some important inconsistencies between Holdren's results and Inhaber's. Unfortunately, we received the Holdren report too late in the editing process to incorporate into this chapter a proper treatment of his work. Still, we feel that the unresolved disagreements are important and that the reader should be aware of them, even if only in the rough form that we have been able to present them here.

	Person-days Lost/GWyr(e)[a]	
Energy Cycle	Occupational	Public
Solar Thermal		
Inhaber	62,000–100,000	9400–520,000
Holdren	7400–15,000	1000–2700
Nuclear (LWR)		
Inhaber	1700–8700	300–1500
Holdren	3100–12,000	300–70,000
Coal Electric		
Inhaber	18,000–73,000	20,000–2,000,000
Holdren	19,000–43,000	20,000–1,500,000
Oil		
Inhaber	2000–18,000	9000–1,900,000
Holdren	3000–19,000	9000–1,000,000

[a] One fatality was assumed equivalent to 6000 person-days lost except for coal workers, in which case a fatality was assumed equivalent to 1000 person-days lost.

data, estimates could not be made for certain power plant emissions. For example, it is known that mercury, nickel, arsenic, and vanadium (or some of their compounds) are toxic to humans and animals, but the impact from the release of 7 tons per year of each of the first three elements from coal-fired plants or of 2000 tons per year of vanadium from oil-fired plants are not included in Table 11-1. Similarly, the table does not include the impacts of radioactive emissions from fossil fuels, the emission of methane and other hydrocarbons from oil- and gas-fired power plants, and oil lost in spillage (USAEC 1974).

The data in Table 11-1 were normalized to estimate the effects of supplying 1 GW(e)yr, and they can thus be readily scaled to various levels of energy demand. These data can be used to illustrate how the choice of electricity supply systems influences economic costs and health. The following illustration is for the United States. In 1977, 28.5 GW(e)yr was supplied by nuclear power plants (*Nuclear News* 1978). If the same amount of electricity had been supplied by coal-fired plants, mean estimates from Table 11-1 suggest that accidents would have caused 114,000 more man-days lost for workers, 47,000 more man-days lost for the public, about sixty more occupational deaths, and ninety more public deaths, as well as some two hundred more deaths from coal-workers' pneumoconiosis and ninety to six hundred more public sector deaths from sulphur dioxide and particulates emissions. Further, the additional economic costs of using coal would have amounted to nearly $\$1.4 \times 10^9$ because of the necessarily higher fuel and environmental control expenditures. Similarly, using either oil or gas instead of coal to supply this amount of electricity would have more than doubled the direct economic cost increases (given for coal) and would have also cost more than nuclear in terms of occupational and public sector injuries and deaths.

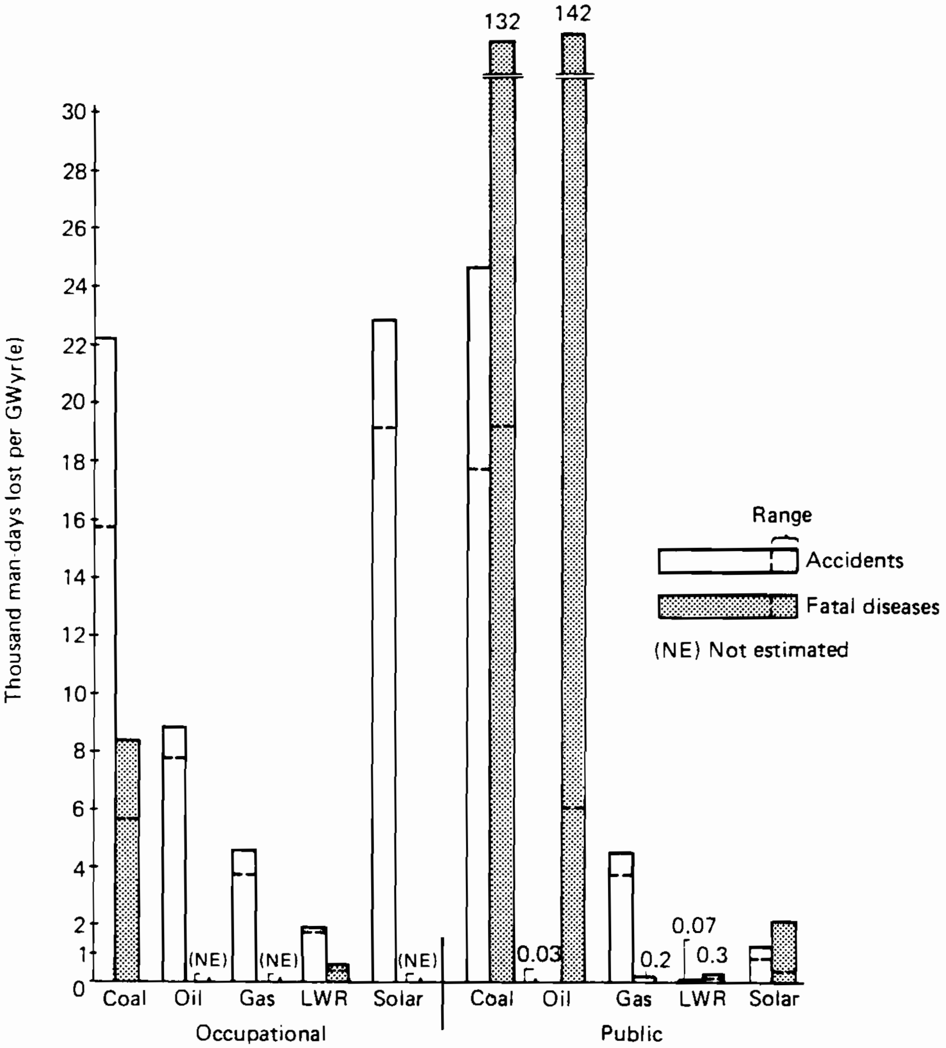
Using the data from Table 11-1, we illustrate in Figure 11-2 the health effects, in both the occupational and the public sectors, resulting from both accidents and fatal diseases. In plotting this figure we have assumed that one fatality is equivalent to 6000 man-days lost for workers (or 1000 man-days lost for coal workers because of pneumoconiosis) in order to be able to sum fatalities and injuries. It can be seen that, numerically, coal and oil would have the largest impacts on the health of the public sector, while coal and solar thermal systems pose the greatest health risk to the worker.

We recognize the large uncertainties in these estimates. Nevertheless, the uncertainties shown in Figure 11-2 would not prevent a definite ranking of systems. The ranges given in Figure 11-2 for public health effects are based on two SO_2 models cited in Hamilton and Manne (1977). The largest uncertainties occur for public health effects from the use of coal and oil, and the range of uncertainty is about six times the lower estimate (see box on page 346). Also, the recent Ford Mitre study concluded: "Despite these large uncertainties, the general conclusion is that on the average new coal-fueled power plants meeting new source standards will probably exact a considerably higher cost in life and health than new nuclear plants" (Ford 1977: 196).

Such comparisons are weak, and more research is needed to improve the data base so as to narrow down the uncertainties and perhaps to incorporate those uncertainties that cannot be incorporated in a single parameter for measuring risks.

Low Probability, High Consequence Events. The numbers shown in Table 11-1 and Figure 11-2 are expected values. Thus, within each of the categories in Table 11-1, no distinction can be made between contributions due

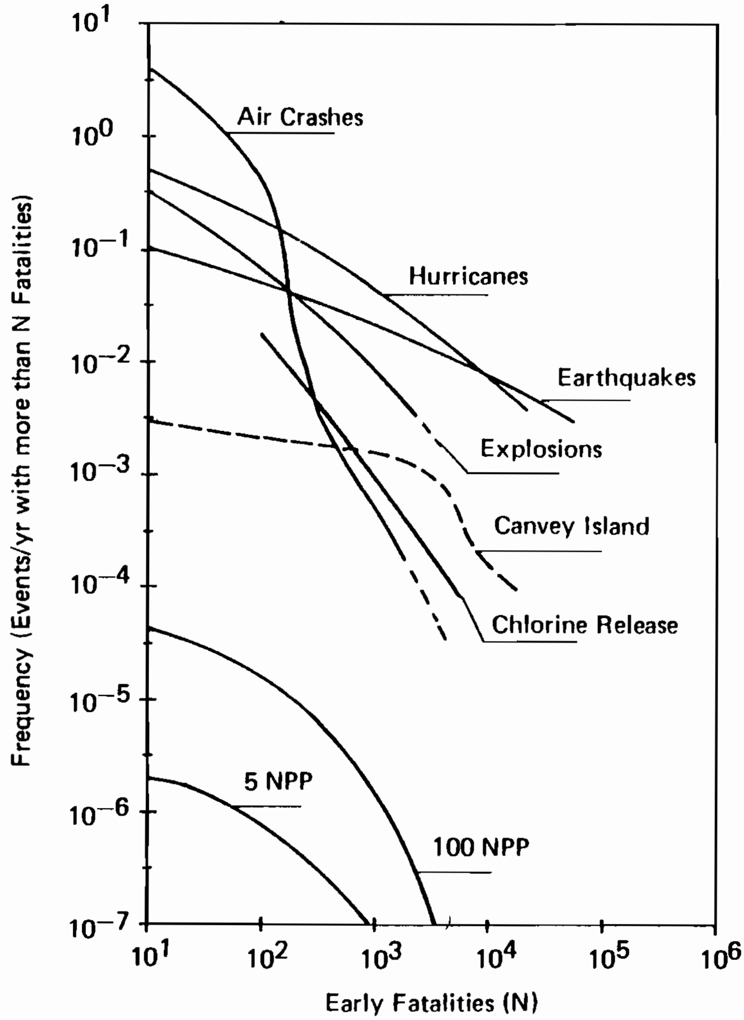
Figure 11-2. Man-days lost annually due to supply 1 GWyr (e) from each of five sources. Power plant life is thirty years.



to low probability, high consequence events and those due to high probability, low consequence events. However, much concern has been expressed specifically about events that fall into the former category—low probability and high consequence. We therefore examined some of the possible risks of some natural and man-made events, plotting frequency versus magnitude of distribution as shown in Figure 11-3.

As can be seen from Figure 11-3, an accident that would kill ten or more people at the Canvey Island petrochemical plants is about two orders of magnitude less probable than other types of accidents that also result in ten or

Figure 11-3. Frequency of events causing more than *N* early fatalities for some manmade and natural events and estimates for similar events from five petrochemical plants on Canvey Island and from five and one hundred nuclear power plants (NPP) located at current sites in the United States. *Source:* Curves for petrochemical plants and for nuclear plants based on Canvey Island Study (1978) and USNRC (1975a), respectively. Data for natural hazards and manmade events are derived from statistical analyses of past events.



more fatalities (excluding nuclear power plant accidents). For larger accidents, the risks from the Canvey Island plants are in the range of other large accident risks. The risks from one hundred nuclear power plants located in the United States at current sites are estimated to be two to four orders of magnitude lower than the risks posed by the plants on Canvey Island.

For the nuclear power plants, the analysis was based on data for system components from approximately 200 commercial reactors that together have some 1400 reactor years of operation. Of course, this is not a sufficient data base since one accident resulting in ten or more early deaths in the public sector is expected to occur only once in about three million reactor years (see Figure 11-3). Nevertheless, the data are adequate for analyzing the failure rates of the system components, which occur at a much higher rate.

Some additional comments on the Rasmussen Report are in order here. Since its publication in 1975, the report has been considered by a number of reviewers, including the Lewis Committee (Risk Assessment Review Group 1978). According to the committee, the uncertainties in the estimates are understated, but the committee was not able to decide whether the median values given were too high or too low. Leverenz and Erdman (1975) also judged the uncertainties in this way, but concluded that the median values would be lower than those given in Figure 11-3. Although both reviews gave different quantitative statements in a number of instances, in general they supported the overall findings of the Rasmussen Report.

A major difficulty in making direct comparisons among data of this type is that in order to make an accurate comparison of such risks, one needs a common reference point. One possible solution would be to normalize the risk of different activities to a common level of social benefits. Such a risk-benefit evaluation seems desirable for social decisionmaking, and therefore in the next section we treat this subject in more detail.

Comparisons of Energy System Risks and Benefits

Once it has been established that a specific risk is not out of proportion with other risks, technologies can be compared by normalizing their risks to a common measure of social benefits. We refer again to our estimates of health risks from different electricity supply systems as given in Table 11-1. There, the benefit of supplying 1 GWyr of electricity was taken as a common basis for comparing the health risks of the five energy sources. Additional benefits may be assigned to different systems, based on the different costs of electricity production and some additional difficult to quantify attributes such as supply reliability and diversification. In this section, however, we consider only the production costs.

The cost directly accounted for by the utility operating, say, a power plant is known as the internal cost[a] and reflects the production cost for generating one unit of electricity. Since the data on internal costs and health effects of various electricity supply systems, even when normalized to the common benefit of supplying one unit of electricity, cannot be compared directly, their costs and risks need to be expressed in common units. This poses the difficult task of assigning a monetary value to a human life. Linnerooth (1975) has considered the following approaches to determining such values:

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[a] Data on internal costs of various power plants are given in Table 17-4.

- Human capital—life is evaluated as the discounted future earnings of those at risk.
- Insurance—life is evaluated on the basis of individual life insurance decisions.
- Court awards—awards made by courts to compensate for loss of life are used as the basis for life value figures.
- Implicit value—life is valued according to the values implied by past policy decisions to reduce mortality risks.
- Willingness to pay—values risk reduction by the public's willingness to pay for it.

Applying some of the above approaches to the present situation in the United States, the monetary value assigned to one human life comes out to be about $300,000.[b] This value reflects a trade-off between the objectives of maximizing GNP and of reducing risks and is therefore only meaningful in the context of risk-benefit analysis. Linnerooth (1977) has suggested that for different applications this value be weighted in order to reflect the characteristics of the specific risk situation.

For illustration, the following calculations are made assuming a monetary value of $300,000 per human life. At an average expected work loss of 6000 man-days per fatality, this is equivalent to $50 per man-day. In the case of injury or illness, society loses the productive work and also incurs expenditures; therefore, a total value of $100 per man-day is used (Sagan 1976).

With these values, the health effects can be expressed in monetary equivalents—namely, external costs. Table 11-2 compares the total (internal plus external) costs of supplying electricity from different types of plants. A definite ranking of the alternative electrical supply systems can be made on the basis of total costs listed in the table. Since the external costs are all much smaller than the differences between the indicated internal costs, the ranking based on total costs turns out to be the same as that determined by the internal costs alone. The last line of Table 11-2 shows external costs as a percentage of the total costs.

The external costs in Table 11-2 indicate that nuclear power would cost $420,000 (equivalent to about one fatality) per GW(e)yr less than any other fuel system. The ordering by external cost would change if different monetary values for a human life were assigned for each fuel system to account for the differing natures of various risks. For example, this value would have to be increased to $700,000 per human life for a nuclear system in order to make its external cost equivalent to that of a gas system and to $57 × 10^6 million per human life to make it equivalent to that of a coal system.

It is appropriate at this stage to say a few words about the external costs of energy systems that are associated with low probability, high consequence accidents—a source of much public concern. In the preceding section we dis-

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[b] Similar considerations if applied to different countries and regions would lead to different monetary value assignments for human lives. Appropriate values should therefore be selected on national bases for use in cost-benefit analysis.

Table 11-2. Costs of electricity generation (10^6 \$/GWyr(e)).

Type of Cost	*Coal*	*Oil*	*Natural Gas*	*LWR*	*Solar/STEC*
Internal	154	256	216	136	297
External	3.5-10.1	1.0-2.8	0.65	0.21-0.23	1.4-1.8
Occupational health	1.6-2.2	0.69	0.37	0.16-0.17	1.3-1.6
Public health	1.9-7.9	0.31-2.1	0.28	0.01-0.02	0.06-0.20
Major accidents				0.04[a]	
Total	158-164	258	217	136	298
External (as % of total)	2.2-6.2	0.4-1.1	0.3	0.15-0.17	0.5-0.6

[a] The expected values for costs of health effects due to major LWR accidents contribute insignificantly to their external costs:

Societal costs (\$/GWyr(e))	
"Acute" deaths	12
"Acute" illnesses	13
Latent cancers	8400
Thyroid nodules	1400
Genetic effects	8400
Property damage	27,000

"Acute" as used here means either death within thirty days or illness occurring within thirty days. Health costs are based on \$300,000 per human life and \$100 per lost working day. Societal costs of major LWR accidents are based on data from USNRC (1975a), assuming fifty man-days lost per illness and fifty man-days lost per case of thyroid nodules.

cussed the probabilities of such events occurring in nuclear power plants and petrochemical facilities and then plotted these probabilities together with those associated with several different man-caused and natural events. It turns out that such low probability, high consequence accidents have an insignificant effect on a cost-benefit analysis of the kind presented above. As can be seen from the footnote to Table 11-2, the expected value of acute deaths due to a large nuclear accident would contribute only about \$12 per GW(e)yr, whereas both the external and the internal costs in the table are given in millions of dollars. Clearly, then, using a multiplicative combination of low probabilities and high consequences to derive expected values does not reflect public opinion.

On the other hand, the public appears to take little interest in the carbon dioxide problem (see Chapter 10 for a discussion of this subject). Yet simulation studies have shown that an increase in the average global temperature of up to 1 K might be caused by the release of carbon dioxide from a fossil fuel consumption of about 700 TWyr over the next fifty years. An electricity production level of 1 GWyr based on fossil fuel plants would make a fractional contribution of about 4×10^{-6} to this temperature increase. The effects of such an increase in global average temperature are difficult to quantify, as they would differ regionally, and resulting climatic trends in one area might be exactly the reverse of trends in another area.

An important effect would be climatic changes affecting agricultural production. Bach (1978) estimated that an average temperature increase of 1 K might lead to a reduction in global food production of 1 to 3 percent. Although there are large uncertainties involved in these estimates, they could still be helpful for a rough risk-benefit analysis of fossil fuel consumption. By means of a stepwise probability function, and with only changes greater than 0.2 percent being considered significant, the expected loss of food production is estimated at about 0.3 percent.

In order to compare this reduction to the low probability nuclear accidents just discussed, let us assign to it a monetary value as follows. The expected loss of food production is estimated as about 0.3 percent. For a risk-benefit analysis, this reduction must be evaluated in terms of its monetary value. Assuming an average annual global food production equivalent to $1 $\times$ 10^{12} (about 15 percent of the gross world product in 1975), the expected agricultural loss from 700 TWyr of fossil fuel consumption would amount to $3 $\times$ 10^9 per year. If this reduction were to last for a period of thirty years, the total expected food production loss caused by fossil fuel consumption equivalent to 1 GW(e)yr (or 3 GW(th)yr) would be about $43.5 $\times$ 10^5, a number much higher than the risk value calculated for major nuclear accidents given in Table 11-2. Again, the message is that comparisons of risks based on expected values and the sorts of monetary values assigned here do not necessarily reflect public opinion.

Cost Effectiveness of Risk Reduction

By comparing risks and benefits as described above, it is possible to compare technical options in terms of their aggregated effects on society. But since any technology can always be made safer at higher economic cost, one must address the question of how safe is safe enough? (Starr 1969). Recognizing the limited resources that society has to allocate to safety, it seems reasonable to distribute efforts for risk reduction among the most cost-effective alternatives. Such a procedure does not lead to an absolute limit for an acceptable risk, but to standard values for the marginal cost of risk reduction. In the nuclear field, for example, a monetary value of $1000 is tentatively assigned to the reduction of one man-rem of radiation exposure risk (USNRC 1975b). Table 11-3 gives a comparison of marginal risk reduction costs, ranging from $30,000 to more than $1 billion per life saved. It appears that the low probability, high consequence accidents are associated with higher marginal costs per life saved. The quoted value of $1000 per man-rem reduction implies marginal costs of $10 million per life saved.

It is generally assumed that the economic law of diminishing returns is applicable to risk reduction—that is, the marginal cost of risk reduction would increase with the level of safety achieved (USEPA 1976, Niehaus and Otway 1977). This implies that any limit on safety represents an arbitrary trade-off between the objectives of achieving highest safety and of minimizing economic costs, since the risk could be reduced below any given value

Table 11-3. Marginal costs of risk reduction.

	Cost per Life Saved (\$$10^6$)
Food poisoning control	0.03
Automobile seat belts	0.3
Fire control in high rise flats	40
50% flue-gas desulphurization applied to coal-fired power plant with	
30 m stack	0.2
120 m stack	2.5
Nuclear plants with	
Recombiners	17[a]
6 charcoal beds	43[a]
12 charcoal beds[b]	300[a]
Iodine treatment[b]	1000[a]
Remote siting	10,000[a]

[a] Based on one fatal effect per 10^4 man-rem.

[b] Proposed but not implemented.

Source: Based on data from Niehaus and Otway (1977); Sagan (1976); and USEPA (1976).

with sufficient expenditures. However, this law is applicable only if one considers just the partial system (e.g., the power plant alone) and neglects the fact that a power plant is part of the total economic system. In fact, the components of the safety equipment have to be produced in various branches of industry, implying an occupational and public risk associated with their production. Using accident statistics of industry and economic input-output tables, it is possible to calculate the total risks to workers involved in the production of goods and services with regard to a specific economic structure. This method is similar to that used for energy accounting (Niehaus 1975). The same methodology could be applied, in principle, to public risk calculations. Representative data are not available, but such risks would most likely be in the same range as the occupational risk. Calculations for the FRG (Black, Niehaus, and Simpson 1979) show that for each \$$10^9$ worth of machine tool products and electrical equipment, there result 8.2 deaths due to occupational accidents and to accidents while commuting and 52,000 lost working days.

If safety equipment consists principally of these products, then by using the equivalence of one fatality and 6000 man-days, this may be aggregated to either roughly seventeen deaths or 10^5 lost man-days per \$$10^9$ worth of safety systems. By including the risk to the public, the production of \$$3 \times 10^7$ worth of safety equipment would be associated with one fatality.

Marginal expenditures for safety at rates greater than \$$3 \times 10^7$ per life saved would therefore lead to increased rather than decreased risks. Consequently, for determining the minimum risk to be associated with a given technology, one should consider the maximum expenditure for safety that is to be involved. The value of $\$3 \times 10^7$ per life saved is obviously exceeded in certain cases in Table 11-3.

Before moving on to the next section, some comments are in order about, first, the cost effectiveness calculations just described and, second, the general risk-benefit approach discussed in this and the previous section.

First, the cost effectiveness calculation fails to incorporate at least two factors of importance. It makes no distinction between a death caused now in producing safety equipment and the expectation of saving one life during operation of the facility. Furthermore, we estimate that $\$3 \times 10^7$ worth of safety equipment costs society not only one life but also 600 man-years of work. Thus, the figure of $\$3 \times 10^7$ per life saved could use some refinement. But for the moment it serves, on the one hand, to illustrate the use of cost effectiveness calculations and, on the other, to give a perspective on the order of magnitude of a reasonable maximum limit for safety expenditures.

More generally, the risk-benefit calculations of these last two sections have several generic weaknesses, some of which we have already alluded to. For example, expressing risks in terms of expected values does not allow a distinction to be made between a low probability, high magnitude risk and a high probability, low magnitude risk with an identical expected value. Yet such a distinction may be critical if one wants to accurately reflect the social costs that we, as a society, seem to attach to different risks. Another observation that was made earlier is that monetary values derived for a particular situation in a particular country are not necessarily transferable to other situations or countries. These and other limitations are discussed more fully in the reference literature. In our presentation here we have attempted mainly to illustrate the methods and to show the order of magnitude of the results that they produce.

Public Preferences

As noted, there seems to be a large discrepancy between the results of risk-benefit calculations as described above and the public perception of these risks. The question therefore arises of how one might examine more directly the preferences of various public groups. There are essentially two methods: revealed preferences—that is, the retrospective examination of the manifest choices made by society in similar situations in the past—and currently expressed preferences obtained directly through interviews or questionnaires.

Revealed preferences are often derived from national level statistics (see Pochin 1977). Otway and Cohen (1975) point to the difficulty of extracting from these statistics the underlying reasons for past risk behavior. Furthermore, the method assumes that those at risk had good information about the risk (for which the statistics were obtained at a later period). And finally, using past behavior as an indicator for future behavior does not seem justified in rapidly changing industrial societies, especially since the sometimes militant rejection of technologies is, to some extent, also a rejection of the decisions and the decisionmaking process of the past.

In order to gain insight into public perception of risks from different energy supply systems, the Joint IAEA/IIASA Risk Assessment Project concentrated on measuring and analyzing expressed preferences. The attitude concept was used because, within the repertoire of established social science methodologies, "risk perception" seemed best defined as an attitude toward a particular risk situation. Also, attitude is a well-defined concept. The attitude-behavior relationship has been clarified (attitude predisposes a person to behave consistently to form a characteristic behavioral pattern), and attitude can be measured as a function of the beliefs held about the object of the attitude (Fishbein and Ajzen 1975). Thus risk perception may be defined as an attitude and the determinants of risk perception as the beliefs held about the attitude object, where beliefs are the "learned" associations between the attitude object and some set of characteristics or attributes. It is the total number of "salient" beliefs—that is, beliefs within a person's attention span at any given time—that determines his or her attitude. The number of salient beliefs is usually judged to be between five and nine.

The model that we used was developed by Fishbein and his associates (Fishbein 1963; Fishbein and Ajzen 1975). It assumes that the strength of belief, weighted by the evaluation of the attribute (i.e., the goodness or badness of the attribute), can be summed to form a measure of attitude. These variables can be measured using questionnaires. By aggregating the responses of individuals, it is possible to determine the beliefs and values of different social groups.

In order to explore the underlying determinants of attitudes toward the use of five alternative energy systems (nuclear energy, coal, oil, solar, and hydroelectric power), we applied this attitude measurement technique to a stratified, heterogeneous sample ($n = 224$) of the general Austrian public (Thomas et al. 1980a). The beliefs examined in the questionnaire were based upon an earlier pilot study by Otway and Fishbein (1976); a total of thirty-nine determinants (attributes) were used, and emphasis was given to the perceptions of the subgroups ($n = 50$) most PRO and most CON nuclear energy. Detailed analyses of results specific to nuclear energy have been reported by Otway and Fishbein (1977) and by Otway, Maurer, and Thomas (1978).

Table 11-4 shows the mean attitudes of the PRO and CON nuclear groups toward each of the five energy supply systems. The groups essentially were in agreement with respect to hydroelectric and solar power, but there were statistically significant differences for the other sources. The largest disagreement concerned the use of nuclear energy. Figure 11-4 shows the smoothed frequency distributions over attitudes for the whole sample, and some distinct differences among attitudes about the five energy sources may be seen. Solar and hydroelectric power have almost identical distributions, with mostly positive attitudes. Coal and oil also have identical distributions, but with more negative attitudes than for solar and hydroelectric power. The shape of the nuclear distribution, in contrast, is almost trimodal, with clusters in the area of neutral attitudes and at the extremes.

Table 11-4. Mean values of attitude of those PRO and CON nuclear energy toward five energy sources (possible attitude scores range from -15 to 15).

Nuclear	*Solar*	*Hydro*	*Coal*	*Oil*	*All*[a]
PRO (N = 50) (10.2)	12.2	12.3	8.3	9.7	10.6
CON (N = 50) (-10.1)	11.1	11.2	6.2	3.1	7.9
Significance of difference among groups	Not significant	Not significant	Significant at 5% level	Significant at 1% level	Significant at 1% level

[a] All energy sources except nuclear.

Source: Based on Thomas et al. (1980a).

Beliefs held by the public with respect to the use of nuclear energy were then subjected to a factor analysis in order to identify the determinants of differing perceptions. Factor analysis identifies the minimum number of independent dimensions needed to account for the variance of the larger set of intercorrelated variables. In this case, the set of intercorrelated variables consisted of the thirty-nine beliefs about the use of nuclear energy that comprised the questionnaire.

The thinking of the respondents toward nuclear energy was characterized by four belief dimensions—psychological aspects (anxiety inducing); economic and technical benefits; sociopolitical implications; and environmental and physical risks. Table 11-5 lists those of the thirty-nine beliefs that characterize these four dimensions. Table 11-6 shows how these dimensions contributed to the PRO and CON attitudes of the groups concerned. The attitudes of the PRO group were largely determined by the positive contribution made by beliefs about economic benefits and the perceived absence of

Figure 11-4. Smoothed frequency distribution of attitudes toward energy sources.

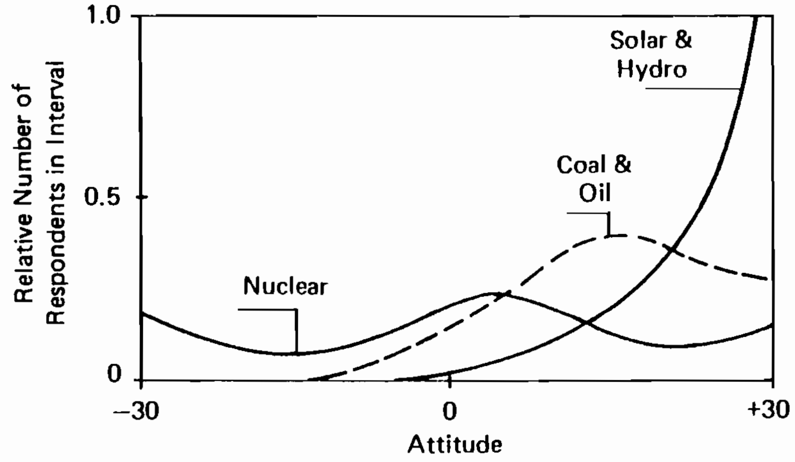

Table 11-5. Belief dimensions and most characteristic belief items about the use of nuclear energy.

- Psychological Aspects
  - Exposure to risk without my consent
  - Accidents that affect large numbers of people
  - Exposure to risk that I cannot control
  - Threat to mankind
  - Risky
- Economic and Technical Benefits
  - Increased living standard
  - Increasing Austrian economic development
  - Good economic value
  - Increased national prestige
  - New forms of industrial development
- Sociopolitical Implications
  - Rigorous physical security measures
  - Production of noxious waste
  - Diffusion of knowledge for construction of weapons
  - Dependency on small groups of experts
  - Transport of dangerous substances
- Environmental and Physical Risks
  - Exhausting our natural resources
  - Increasing occupational accidents
  - Water pollution
  - Air pollution
  - Making Austria dependent on other countries

Source: Based on Thomas et al. (1980a).

environmental risks; the negative attitudes of the CON group were determined mostly by their concern about psychological aspects and sociopolitical implications.

Problems of policymaking often arise because of different perceptions of risks by experts, policymakers, and the general public. In many instances, it can be assumed that the policymakers rely more or less on the experts' opinions, with some modifications dictated by political considerations.

Table 11-6. Contribution[a] of belief dimensions to PRO and CON attitudes about nuclear energy.

Belief Dimensions	PRO *Nuclear Group*[b]	CON *Nuclear Group*[b]
Psychological aspects	-1.6	-6.4
Economic benefits	3.4	0.2
Sociopolitical implications	-1.2	-3.2
Environmental and physical risks	1.8	-1.4

[a] Contributions can range from +9 to -9.

[b] All differences between PRO and CON groups significant at 1 percent level.

Source: Based on Thomas et al. (1980a).

However, the public has become increasingly suspicious of both experts and policymakers. Therefore, we attempted, first, to compare the perceptions of policymakers and the general public to risks from nuclear energy and, second, to test the accuracy of the policymakers' perceptions of public positions on this controversial topic.

The respondents of this study (Thomas et al. 1980b) were a group of senior civil servants ($n = 40$) who were in a position to influence policy in a ministry responsible for energy matters. The measuring instrument was the same used earlier to measure the attitudes and underlying beliefs of the Austrian public sample. The "policymakers" completed the questionnaire twice—once with respect to their own positions and, on the second occasion, in the role of a typical member of the Austrian public who was either PRO or CON the use of nuclear energy.

The policymakers' own attitudes toward the use of nuclear energy were found to be significantly more favorable than those of the total public sample. In terms of the four factor structure described earlier, this was primarily because the policymakers' beliefs about the psychological (anxiety-inducing) aspects made a significantly smaller negative contribution to attitude and their beliefs about environmental risks made a significantly larger positive contribution. The policymakers were able to shift their own (personal) responses in the directions indicated by their role-playing assignments to accurately reproduce the overall attitudes of the PRO and the CON groups, although there was a tendency to overestimate the positive attitudes of the pronuclear group. In terms of the underlying belief dimensions, there was a significant failure to recognize the extent to which issues of psychological significance contributed negatively to the attitudes of both PRO and CON public groups. The policymakers underestimated the negative values that both groups assigned to these risks as well as the extent to which the public believed that nuclear energy would lead to such risks. In summary, anxiety-inducing psychological aspects made a smaller negative contribution to the personal attitudes of the policymakers; likewise, the policymakers seriously underestimated the anxiety-inducing potential that nuclear energy had for both PRO- and CON-nuclear groups.

Multiattribute Utility Measurement. There is no simple way of combining the "hard" numbers of the formal risk-benefit studies previously mentioned with the relatively "soft" numbers reflecting public attitudes and preferences as discussed in the preceding section. Nevertheless, it would be useful for decisionmakers to have some quantitative evaluation reflecting varying emphases on the above two types of risk analysis. Such evaluations can be carried out using multiattribute utility theory (Keeney and Raiffa 1977)—a decision-theoretic methodology for evaluating alternatives on the basis of a set of different attributes, some of which may have natural numerical measures and others of which may be rather "soft" variables. In multiattribute utility measurement, the value-relevant objectives are listed, and a measurable attribute is then associated with each objective. Value functions are constructed, reflecting the decisionmaker's relative preferences, and weights are assessed characterizing the relative importance the decisionmaker gives to each attribute. Finally, values and weights are aggregated (usually by a multiplicative or additive model) to come up with an overall evaluation.

Our research on the possible use of multiattribute utility measurement in risk evaluation was largely exploratory. For example, in one experiment we applied this method to the problem of evaluating nuclear waste disposal sites (Otway and Edwards 1977). Public attitudes were treated as one attribute of the many aspects that decisionmakers intended to consider. The results showed, first, that the procedure is feasible to the extent that decisionmakers can make orderly judgments of the sort required for utility measurement and, second, that there was reasonable agreement among various judgments as to the importance of weights.

Methodologies such as multiattribute utility measurement are generalizations of the rather restrictive risk-benefit approaches discussed earlier. Cost-benefit analysis is, in a sense, a special case of multiattribute utility measurement in which all attributes are expressed directly in monetary terms. As has been noted, such conversions (e.g., the value of human life) are hardly straightforward and are very much open to criticism.

RISK MANAGEMENT: STUDIES ON STANDARD SETTING

The identification, quantification, and evaluation of the potential risks of energy systems are prerequisite to the difficult task of risk management—namely, the translation of analytic results into policy and regulatory decisions. The policy tools available include market approaches (e.g., emission taxes, incentives), regulations (e.g., safety and emission standards), and more severe direct intervention such as the banning of certain activities (Majone 1978).

Of the available tools for reducing environmental risks and hazards, standard setting has emerged as the most practical and commonly used. Since the late 1960s, environmental and regulatory agencies worldwide have issued numerous standards—for example, for sulphur dioxide emissions from coal-fired plants and for radiation from nuclear plants. And what has emerged as a powerful tool for risk management has also become a major constraint for industrial operations and a driving force for technical development. Especially for the energy sector, standards have started to shape long- and short-term decisions ranging from operational decisions about single plants to long-term planning of optimal energy mixes.

The interest of the IIASA Energy Systems Program in standards as a major risk management tool was triggered by a series of modeling efforts to analyze present and future supply-demand structures. (See the discussion of these supply-demand considerations in Part IV of this book.) The nuclear option was studied in detail (see Chapter 4), including analyses of all (normal operation and accidental) risks and hazards involved in the large-scale use of nuclear energy (Avenhaus, Häfele, and McGrath 1975, 1977). The question was asked, Which environmental burden(s) of nuclear energy systems could be tolerated and what should be the criteria for limiting them at both the individual and the societal level?

Mixed energy strategies were also analyzed, taking into account environmental constraints. Nordhaus (1977) developed a two sector model with a constraint for the upper limit of the global carbon dioxide content. Agnew, Schrattenholzer, and Voss (1979) analyzed the effects of different standards for sulphur dioxide, nitrogen oxides, and other pollutants on the cost of alternative energy systems. At this stage nothing was said about the appropriate—that is, socially acceptable—numerical inputs in the form of standards and the like. They were simply treated as parameters of the problem, as had been done by other modeling groups (e.g., Hoffman 1972).

At the next stage, we proceeded to determine equilibrium states and cost-optimal strategies for parametrically fixed constraints. The question was how to reach such equilibrium states under given social conditions, considering the institutional and political realities of environmental decisionmaking and regulations, and in particular, the realities of standards and standard-setting procedures.

It was clear from the beginning that an investigation of the political and social nature of standard setting required appropriate analytical tools. A study was made of public policymaking under uncertainty and with conflicting interest groups and objectives, with risks and impacts of a large scale, and with only limited possibilities for traditional experimental and incremental approaches. The initial literature survey on analytical approaches and procedures for standard setting led to research in legal studies (e.g., NAS 1975); environmental economics (e.g., Baumol and Oates 1975); policy analysis (e.g., Holden 1966; Majone 1976). The tools considered were cost-benefit analysis (e.g., Karam and Morgan 1975); simulation and simulation gaming (e.g., Birr et al. 1976); decision theory (e.g., Raiffa 1968; Howard 1968); and game theory (e.g., Luce and Raiffa 1957).

Based on the expertise of the researchers and on their judgments of the limits and possibilities of these different analytical approaches, several decisions were made. First, the study of standard-setting procedures should use actual cases and involve interaction with real decisionmakers. Second, two main lines of case-oriented research should be pursued—policy analyses of continuing or past standard-setting processes with a largely descriptive and problem-oriented focus and development of decision and game theoretical models with a descriptive and normative focus, the latter for aiding regulatory decisionmakers in standard-setting tasks.

Three cases of past standard setting were studied—radiation standards, chronic oil discharge standards, and noise standards. Folllowing the analysis of decisionmaking processes in these examples, two decision-theoretic models were developed. The salient features of these models and their application to two specific cases of relevance to energy systems will be described later in this chapter. However, we will begin our presentation by first tracing the historical evolution of radiation standards.

A Brief History of Radiation Protection and Nuclear Safety Standards

A look at the historical development of radiation protection standards, as documented by the International Committee on Radiation Protection (ICRP), points to the complexity of setting environmental protection standards. It demonstrates the need for procedural and organizational efforts in standard setting and also how paratechnical "political" issues interact with the standard-setting process.

The harmful effects of radiation became known in 1896 when skin burns were correctly traced to the newly discovered X-rays. Initial attempts to establish radiation tolerance limits by measuring exposure with photographic emulsions–a procedure still widely used–data back to 1902 (Taylor 1971; Serwer 1976). Efforts to provide radiation protection were made by the British Roentgen Society in 1915, and the first sets of radiation protection recommendations were developed from 1920 to 1922 by a committee of the American Ray Society. In 1925, Mutscheller first quantified a "tolerance dose" as 1 percent of the threshold erythema dose, amounting to about 6 R per month or 70 R per year.

In 1928, the Second International Congress of Radiology formed an International Committee on X-ray and Radium Protection, which later became the ICRP. Because of difficulties in developing an international consensus of opinion, national committees were formed with more than one individual per country allowed to become members of the ICRP. The maximum recommended dose levels in the 1930s were about 0.1 to 0.2 R per day or about 25 to 55 R per year. Until then, all biological evidence had shown this level to be safe for an individual. By 1940, however, the genetic studies of Hermann Muller indicated that doses of about 50 R to large parts of the population might produce harmful genetic effects (Muller 1940).

In 1948, the U.S. National Commission for Radiation Protection (NCRP) approved a more sophisticated concept, lowering the permissible limit for the blood-forming organs of radiation workers to 0.3 R per week (or about 12 to 15 R per year), but allowing higher limits for older persons and, in extreme cases, single doses of 25 R. Internal exposure arising from incorporated radionuclides was also taken into account in the 1940s, when maximum permissible body burden was set as 0.1 μ Ci Ra.[c] Also, the concept of risk-benefit was introduced in the field.

In general, until the mid-1950s the goal of radiation protection was mainly to eliminate the risk of those radiation effects showing a threshold in their dose response relationship (nonstochastic effects). Protection would be guaranteed when the total dose in any organ or tissue, from all sources, was kept below the threshold. The common exposure limit at that time–0.3 R per week–was judged sufficient to prevent nonstochastic effects.

In 1955, the ICRP introduced the rem[d] as the dose equivalent unit (ICRP

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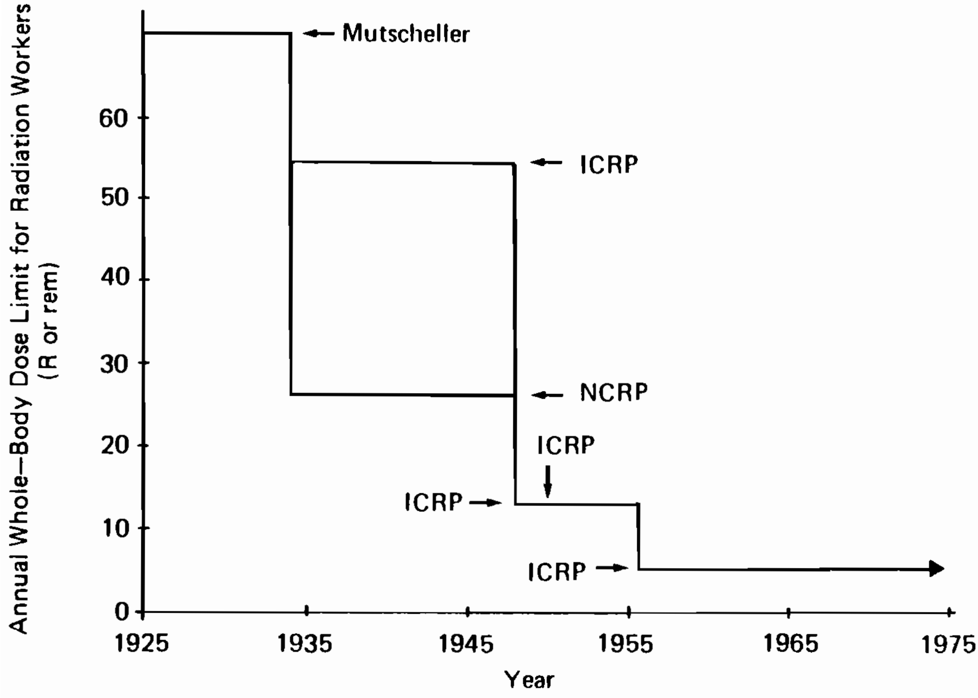
[c] μ Ci Ra is a microcurie of radium.

[d] The dose in rem is the product of the dose in rad (R) and a factor called the relative biological effectiveness (RBE) of the radiation used. The rem is taken to be that dose for any radiation that produces biological effects in man equivalent to 1 R of X-rays.

1977). Obviously, 0.3 rem per week could lead to an accumulation of 750 rem over a working lifetime of fifty years. This dose, distributed over a long time, was not expected to be harmful, but there was concern expressed that there may be additional stochastic effects (e.g., cancer and genetic harm) for which recovery might play a less important role at continued exposure at low dose levels. In 1956, the ICRP recommended a weekly dose equivalent of 0.1 rem to be used for planning, corresponding to an annual dose of 5 rem. All these limits referred to occupational exposure, but in 1956, ICRP recommended that there also be a dose limit for the public of 0.5 rem per year. These limits are still valid today, although their meaning has undergone subtle modifications. Figure 11-5 shows the gradual decrease in radiation limits over the years. No further decreases are expected in the foreseeable future.

The related topic of safety standards for nuclear power plants was again publicly debated in the 1960s. While previously the safety-standard-setting process was largely determined by the exchange of expert opinion in committees, now increasingly public pressures and political considerations entered the process. What once appeared as a purely technical and scientific issue now became a procedural and methodological one. This led to consid-

Figure 11-5. Evolution of radiation standards with time. ICRP is the International Committee on Radiation Protection. NCRP is the U.S. National Commission for Radiation Protection.



erable redundancy in the area of nuclear standards (including safety standards, equipment performance standards, engineering design standards). A catalogue by Fichtner, Becker, and Bashir (1977), for example, lists about 2700 nuclear safety standards, rules, and regulations, which by the end of 1976 had been developed in thirty-one countries by 145 different organizations and institutions.

Obviously, the implementation of such standards, or the licensing delays caused by a lack of standards, can substantially increase the costs of constructing and operating nuclear facilities. The precise costs are difficult to quantify, but expenses for a large nuclear power plant not in operation can run as high as \$0.5 to \$1 $\times 10^6$ per day. With capital costs for a 1200 MW(e) LWR block of the Biblis type approaching (and in some cases exceeding) the \$1 $\times 10^9$ mark, licensing costs at 5 percent amount to about \$5 $\times 10^7$ per unit. Much larger (estimated at 20 to 30 percent of total costs) are the costs due to backfitting changes during construction, which could be substantially reduced with proper standards. These costs far exceed the expenses for standard development. Other factors that affect the cost of meeting standards and that therefore have to be considered by the standard-setting governmental or nongovernmental organizations include the consistency of national standards and their agreement with international standards, dissemination, transparency, and accessibility, as well as degrees of legal relevance (Winterfeldt et al. 1978).

Policy Analysis of Some Past Standard-Setting Processes

Most standards are set by national or international committees of experts from industry, science, and governmental organizations. However, the growing public concern about risks and hazards from energy systems necessitates that this voice be more clearly heard. In order to clarify involvement of various parties in the standard-setting process, several environmental standard-setting cases were studied, and interviews were conducted with experts, governmental and industrial representatives, and members of public interest groups.

Two cases of past standard-setting processes were studied in detail—chronic oil discharge standards for offshore oil production platforms in the United Kingdom (Fischer and Winterfeldt 1978) and noise standards for trains (the Shinkansen system in Japan) (Winterfeldt 1978a). Chronic oil discharge standards were set on the basis of equipment availability, costs, and performance. The reason for this technical orientation in standard setting was that biological information on the effects of low level hydrocarbon concentration in the seas is still sparse. Noise standards for trains, on the other hand, were set almost exclusively on the basis of noise complaint relationships, with the goal of setting a standard at a noise level that would limit the number of complaints. Available technical and cost data were more or less ignored.

The two cases differed greatly in national definitions of standards and the legal basis on which standards are issued. While chronic oil discharge standards in the United Kingdom were set on the basis of the "best practical means" principle, noise standards in Japan were set as environmental quality standards—that is, targets or desirable goals for the future without direct binding force.

The case of radiation protection standards provides a further example of how definitions of standards can differ. In 1955, the ICRP recommended that "every effort be made to reduce exposure to all types of ionizing radiations to the lowest possible level." This wording was changed in 1958 to a recommendation that all doses be kept as low as practicable; and, in 1965, that all doses be kept as low as is readily achievable, economic and social considerations taken into account. In 1973, it was suggested that the word "readily" should be replaced by "reasonably". Such differences in definitions, together with the different institutional setups and organizational constraints, appear to shape the outcome of standard-setting procedures substantially.

There are, however, some important similarities among the different cases that were studied. In every case there are three main groups of "actors" involved in standard setting:

- The regulator—members of environmental agencies or other institutions with the task of setting and enforcing standards.
- The developer—industrial organizations and construction firms whose activities are regulated by standards.
- The "impactees"—those groups of people or public interest groups who would benefit from standards.

Besides these core actors, there are usually international organizations involved in standard setting, as well as scientific experts from outside the governmental or industrial sphere (i.e., from universities or independent research institutes).

All these groups have different, often conflicting, objectives and interests. The regulator usually has important political objectives (e.g., consistency with international and national environmental policies), and the developer typically focuses on cost considerations, while the impactee's interests are to reduce potential impacts and risks from the construction and operation of the systems involved.

Decision Models for Standard Setting

After examining past standard-setting processes, we used what we had learned to develop two decision-theoretic models for aiding regulatory agencies in standard setting. We assumed that only three actors/decisionmakers—the regulator, the developer, and the impactees—were needed to describe the standard-setting process. However, since the process generally involves interaction among the actors, with possibilities of learning and adaptation at various stages, its description requires a multistage game theory approach. A game theory decision model was developed at IIASA by Höpfinger and Avenhaus (1978) (see Appendix 11A for the model description). The model treats multiple stages in which the transitions from one stage to another are probabilistic either because of probabilistic changes in the environment or because of probabilistic responses of the players. This model was applied to standard-setting problems of carbon dioxide concentrations in the environment (Höpfinger 1978) and to noise levels from Shinkansen trains (Höpfinger and Winterfeldt 1978). Here, we will discuss only its application to setting carbon dioxide standards.

In addition to the multistage model mentioned above, a simplified one stage decision-theoretic model was developed at IIASA by Winterfeldt (1978a). The model was applied to the problem of chronic oil discharges in the North Sea (Winterfeldt 1978b), since a multistage model would not have been suitable. The use of both models is discussed in the following sections.

Dynamic Standard Setting for Carbon Dioxide. As discussed in Chapter 10, carbon dioxide emissions in the atmosphere because of fossil fuel combustion are increasing at an alarming rate, and concern has been expressed about possible global climate impacts. However, neither the physical processes associated with the carbon cycle in the atmosphere nor the natural variations of the average atmospheric temperature are sufficiently understood to allow accurate predictions of climatic effects.

Given these substantial uncertainties about the climate, decisions about energy supply systems are of particular importance. In the research described here, this problem was viewed as a conflict situation among the following three groups—governments, producers emitting carbon dioxide, and populations. The problem was analyzed by Höpfinger (1978), who adapted the multistage decision model that had been developed by Höpfinger and Avenhaus (1978).

In order to reflect the global aspects of the problem, the three parties to the game were taken as (1) the regulator, an international agency; (2) the producer, an organization of all producers; and (3) the impactees, everyone who would suffer from a climatic catastrophe. Internal conflicts among different governments, different producers, or different population groups, such as possible conflicts between groups from developed and developing countries, were neglected. It was further assumed that a continuous increase of atmospheric carbon dioxide beyond a critical value would lead to irreversible catastrophic climate changes.

The states of the game are characterized as follows:

$$\{(C,L,k) \mid C_p \geqslant C \geqslant 0,\ L \geqslant 0, k \geqslant 0\}$$

where C is the amount of atmospheric carbon dioxide, L is the upper bound of carbon dioxide emissions during a period, C_p is the maximal amount of carbon dioxide if all fossil fuel were to be burnt, and k is the critical value for the catastrophe. We considered k a parameter since its precise value is not known.

Let (C^1, L^1) denote the first state. C^1 can be assigned the value of the current amount of atmospheric carbon dioxide, and L^1 that of the current maximal emission of carbon dioxide. At each of the following stages, a component game of perfect information is played that is completely specified by a state. The player's choices control not only the payoffs but also the transition probabilities governing the game to be played at the next stage. Each player has his or her own subjective estimate of the transition probability, and this is related to his subjective probability distribution for the true value of k, the critical amount of carbon dioxide.

To simplify the model, the assumption is made that the subjective probabilities associated with k concentrate at points denoted by C_R, C_{Pr}, and C_I for the regulator, producer, and impactee, respectively. The model assumes $C_R \leqslant C_{Pr}$ and $C_I \leqslant C_{Pr}$, thus allowing the producer to neglect a possible catastrophe. By making a series of assumptions about the form of the transition probabilities and the utility functions of the three players, and by assuming that the total utility accruing to each player is the undiscounted sum of the component state utilities, several solutions for the game can be derived.

The game has a large number of equilibrium points (solutions), two of which are illustrated in Figures 11-6 and 11-7 in the regulator-impactee payoff plane. Final choices of the regulator thus may depend on the relationship between C_I and C_R or, respectively, on the relative distance of the equilibrium points from the point of maximal payoffs (which itself cannot be

Figure 11-6. Payoff diagram for regulator and impactee ($C_R < C_I$). *Source:* Höpfinger (1978).

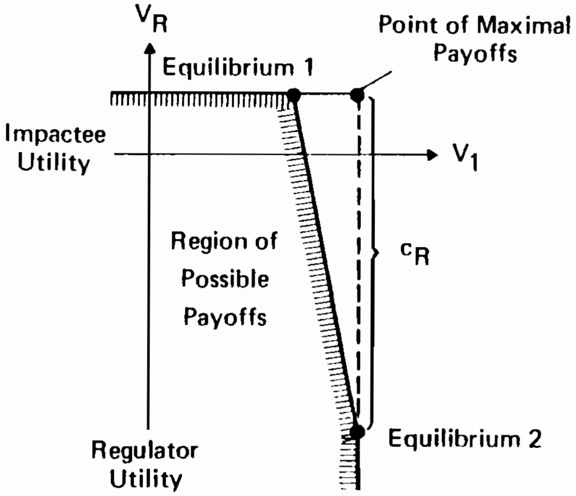
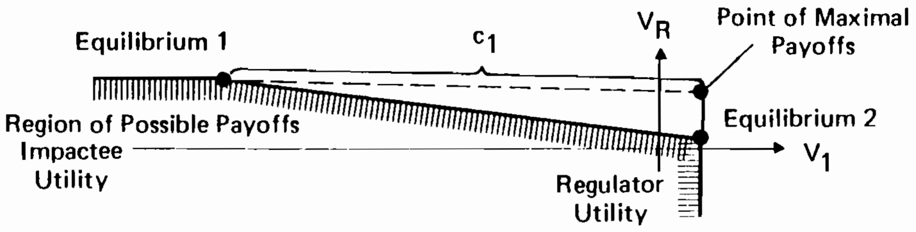


Figure 11-7. Payoff diagram for regulator and impactee ($C_R > C_I$). *Source:* Höpfinger (1978).



achieved). For example, in Figure 11-6 the regulator may wish to choose a strategy leading to equilibrium point 1, while in the case of Figure 11-7 he or she may choose equilibrium point 2. In contrast, the hierarchical solution would always lead to the first equilibrium point, which is based on the estimate C_R as the critical value.

What can be learned from an analysis of this multistage decision model? If one assumes that the set of equilibrium points represents a set of solutions in any sense, then one can clearly see how far any solution is from being the "ideal" solution (represented by the point of maximal payoffs)—one gets insight into the structure of the conflict between the three game players. Furthermore, because there are many equilibrium points, it is important that the purpose of such an analysis be defined precisely—be it descriptive (e.g., to evaluate value functions using case studies), be it normative (to give decision aids for regulators), or be it predictive (e.g., to see whether or not actions are necessary).

It remains open at this stage of development whether models of this kind can be refined in such a way that they can be applied in practice in the sense described above.

Standards for Chronic Oil Discharges in the North Sea. Two major sources of oil pollution in the seas are oil blowouts from production platforms and the continual chronic or operational oily water discharges of these platforms. Although accidental spills are dramatic and have large visible impacts on fish, birds, and beaches, continuous discharges may be equally dangerous, since they involve the possibilities of mortality or toxicity of marine organisms, long-term effects on spawning behavior, and ecological imbalances. Environmental agencies therefore seek to limit these chronic oil discharges through appropriate regulations.

Fischer and Winterfeldt (1978), in their analysis of the decision process for setting chronic oil discharge standards for North Sea production platforms, focused on the actors, their conflicting objectives, the decision alternatives, and the information-processing and evaluation strategies. A one stage decision-theoretic model was developed by Winterfeldt (1978a), who also applied it to gain some insights into the problem of setting standards to control chronic oil discharges (Winterfeldt 1978b). The structure of this model is shown schematically in Figure 11-8. In the model, after the regulator announces the standard *r*, an expected utility model determines the optimal response of the developer, *d(r)*. The impactees, in turn, are assumed to respond to the developer's decision *d(r)* with an optimal response, *a* [*d(r)*]. This set of decision, together with the associated utilities U_R, U_D, and U_A accruing to the three decision units, permits exploration, before actual decisions are made, of the relative benefits of different standards from the point of view of all parties affected.

Table 11-7 presents the model's major inputs: The regulator's alternatives are formalized by a set of possible standard levels of oil concentration in the effluent (four national standards were considered), by a set of monitoring and inspection procedures (four procedures were considered), and by a

Figure 11-8. Schematic representation of the single stage decision model.

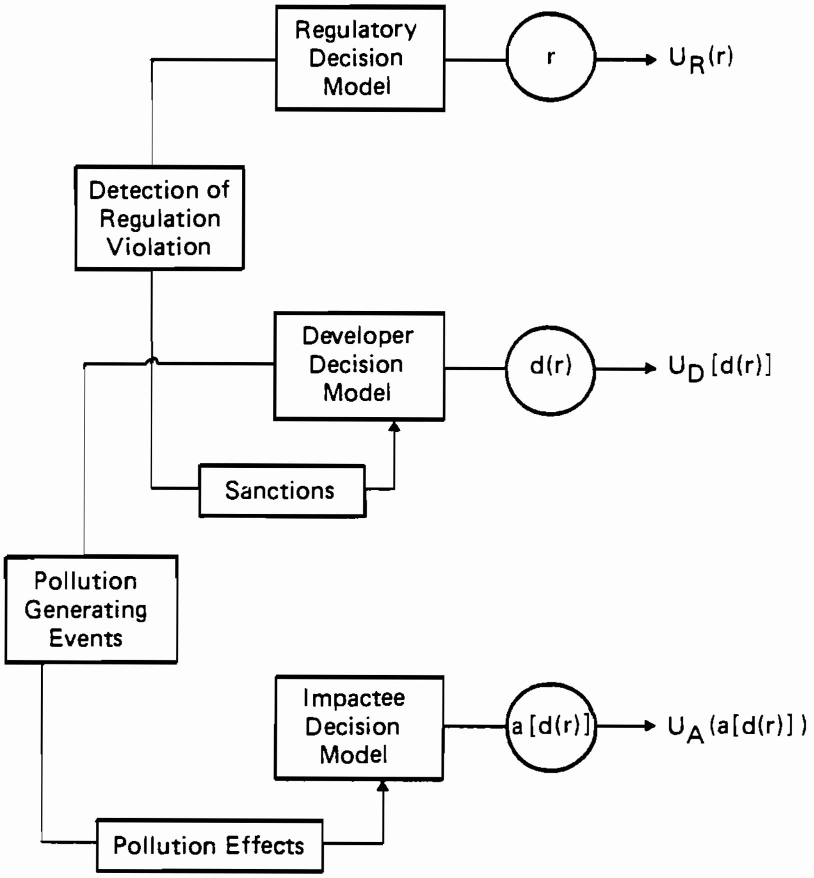


Table 11-7. Qualitative inputs for one stage decision model for chronic oil discharge standards in the North Sea.

	Decision Unit	*Alternatives*	*Objectives*	*External Events*
Regulator	Petroleum production division, United Kingdom	Standard level Sanctions Sample size, exemptions, inspection procedure	Agree with other national standards Satisfy international demands for a clean North Sea Agree with national energy policy Agree with national environment policy	None considered
Developer	Offshore oil operators	No treatment Simple gravity tank Corrugated plate interceptor (CPI) CPI and gas flotation (GF) CPI, GF, and filters (F) CPI, GF, F, and biological treatment Reinjection of oily water into empty reservoir	Minimize investment cost for treatment Minimize operation cost for treatment Minimize penalties of regulation violation	Detection versus nondetection of standards violation
Impactee	Fishermen, ecologists, public	No actions considered, viewed as "sufferers"	Minimize mortality of commercial marine organisms Minimize tainting and chronic toxicity of fish and other marine organisms Minimize ecological disturbances	Random pollution levels

Source: Fischer and Winterfeldt (1978).

set of sanctions. The regulator's utility function was defined as an aggregate of four utility functions, expressing the degree to which the four regulator's objectives (as given in Table 11-7) were met. The developer's alternatives are given in Table 11-7. Total costs of these alternatives were calculated on the basis of a fifteen-year lifetime of the production platform and undiscounted operations costs. The developer's decision depends crucially on whether his or her treatment leads to a detection of a violation or not. In the event of no detection, the developer pays only the cost of treatment; in the event of detection, he or she pays the cost of treatment plus a penalty plus an incremental cost to improve treatment to the next best level. The probability of detection depends on the choice of treatment, the standard level, and the inspection and monitoring procedure. The impactees are assumed to have no action alternatives. As the random emission level is assumed to be a "proxy" measure for the degree to which the impactees' objectives are met, their utility function was defined as the negative emission level.

This is a one stage decision model. As there are only a limited number of alternatives, it was sufficient to perform a dominance analysis—that is, to look for those alternatives that are not worse for all three parties than any other alternatives. Since there were no real assessments by the actors, the quantifications in the model were hypothetical, reflecting the author's perceptions of the actors' values and options. Nevertheless, some interesting results were obtained. Examples of these and their implications are given below.

- The nondominant standards tended to cluster around "cutoff points"—points at which the cost of the next best treatment is equal to the expected cost of detection—thus stressing the need for the regulator to focus attention on the location of such cutoff points.
- The location of these cutoff points is controlled largely by the uncertainty about equipment performance and the definition of the monitoring and inspection procedures (sample size, exemptions from detection, etc.).
- Penalty variations and nonlinear utility functions do not strongly affect cutoff points.

CONCLUSIONS

Risk assessment as a field involving both the evaluation of risks in all their manifestations and the incorporation of these into the decisionmaking process is relatively new. Obviously, our study can be only a beginning to a more rigorous consideration of risk in decisionmaking. Here, we have begun to explore the relationship between what are often called the "hard" sciences and those political, societal, legal, and public aspects sometimes labeled "soft." We have established categories and defined concepts in order to provide a framework for more formal research in this field.

More specifically, we looked into human health risks associated with the fuel cycles of various electricity supply systems. Based on the conversion factors and estimates cited in the text, our illustrative risk-benefit exercise came up with the following results.

- For both normal operation and unplanned events, nuclear power has the lowest potential human health impact per unit electricity supplied.
- Human health risks from normal operation of nuclear power are relattively well understood. The largest uncertainties in estimating risks are for coal, although it has the longest documented history as a prime energy carrier.
- The external costs associated with the human health impacts of electricity production are only a small percentage of the total production costs and are much below the range of internal cost estimates. This is especially true for the expected values of accident consequences.
- Safety expenditures in energy systems and especially in the nuclear field

> are approaching the point where the risk reduction achieved is balanced by the risk of producing this safety equipment.

However, a study of attitudes toward energy-related risks revealed large discrepancies between the sorts of results just described and the corresponding public perceptions of these risks. For nuclear power, our analysis revealed, first, a limited number of belief dimensions and, second, that the PRO-nuclear group perceived the problems in very different dimensions than did the CON group. This suggests that in their interactions these groups are often talking past one another.

For example, the PRO-nuclear group rated environmental and physical safety aspects very positively, while the CON group assessed these aspects negatively. Also, our comparative analysis of public attitudes toward the risks of five alternative energy systems revealed that the CON-nuclear group is significantly less favorable than the PRO-nuclear group toward coal and oil, whereas there were no significant differences between the groups with regard to solar and hydroelectric power.

In a related study, decisionmakers were able to reproduce public attitudes of PRO-nuclear and CON-nuclear groups quite accurately. These are encouraging results and indicate that the discrepancy between formal evaluations of risks and corresponding public perceptions may perhaps be bridged by developing appropriate methodologies.

Finally, we have provided some initial conclusions on how to tackle the difficult task of risk management. Two quantitative models for risk management by standard setting (for chronic oil discharges in the North Sea and for the atmospheric carbon dioxide content) were developed at IIASA, providing insight into managing the conflicting interests of the parties involved. The model applications have demonstrated how one might take into account both actual data and subjective values when formalizing risk management processes.

APPENDIX 11A: THE MULTISTAGE GAME THEORETIC DECISION MODEL FOR STANDARD SETTING (Höpfinger and Avenhaus 1978)

Assuming that only three actors are needed to describe the standard-setting process, a general game theoretic model can be developed as follows. Assume that only time periods or stages have to be considered rather than a time continuum. A game is played at each stage, and the player's strategies control not only the payoff but also the transition probabilities governing the game to be played at the next stage. Each *component game* is determined by the states of the play, which contain the relevant physical states of the world (e.g., amount of oil in water or sulphur dioxide in the air and their distribution) and the relevant economic state. *Perfect information* is assumed for the component game by the following structure: at each stage the regulator makes his or her choice first; then the producer is informed about the regulator's choice and makes his or her choice; finally, the impactee learns about the other choices and makes his or her choice. The play proceeds from component to component game with the transition probabilities jointly controlled by the players. Since the transition probabilities are often not known exactly, *subjective* transition probabilities are admitted for the players; these may differ from each other.

Let S denote the set of possible states. For each element of s of S ($s \in S$) the set of the regulator's choices or measures is denoted by $M_R(s)$. Let $M_P(s,m_R)$ denote the set of producer's measures or choices in the case of state s and the regulator's choice m_R. If the producer chooses $m_p \in M_P(s,m_R)$, then $M_T(S^i,m_R,m_P)$ denotes the set of choices or measures possible for the impactee. Furthermore, $P_j(\cdot \mid s,m_R,m_P,m_I)$ ($j = R,P,I$) denotes the subjective probability for the next state, given state s and choices m_R, m_P, m_T.

For each component game, a *utility function* $U_j(s,m_R,m_P,m_I)$—that is, a generalized payoff—is given for the jth player. As one play is given by a sequence $(s^1,m_R^1,m_P^1,m_I^1;s^2,m_R^2,m_P^2,m_I^2;\ \ldots)$ of states and decisions, one possibility for the payoff function is

$$\sum_i q_j^i U_j\ (s^i,m_R^i,m_P^i,m_I^i) \qquad j = R,P,I$$

where $0 < q_j \leqslant 1$ is a *discount factor* for the jth player.

The sets of strategies and the payoff functions describe the game theoretic model. In contrast with a two person zero sum game, generally in a three person game there is *no simple solution concept*—a fact that highlights the problems of such game theoretic models. Here, for brevity, we consider only two concepts.

- *Equilibrium points* are stable, since no player can improve his or her payoff if the other players persist in their equilibrium strategy. Since there is no statement on how to arrive at an equilibrium point, there are no guidelines for action by any of the players; thus the concept may be viewed as appropriate for an impartial descriptive analysis of a past event, since it can give insight into whether or not the players arrived at an equilibrium point.
- Under the assumption that the regulator has to announce his or her strategy first and then the producer, one can determine a *hierarchical solution* that represents optimal responses on the part of the impactee and the producer. This concept, in fact, is appropriate for a normative analysis—that is, an analysis for the purpose of advising the players.

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12 CONSTRAINTS ON ENERGY SUPPLY: THE SUMMARY

INTRODUCTION

In the preceding four chapters, we examined four types of constraints on society's capabilities for supplying energy: market penetration, WELMM (water, energy, land, material, and manpower), climate, and risk. In this chapter, we bring together the findings, emphasizing how these constraints affect different energy strategies.

One important constraint has been omitted here—that imposed by economics. The cost of energy supplies according to various criteria is, of course, important for determining which option to adopt and to what extent. However, cost is highly variable, both as a function of geography and of detailed and local value systems; generalizations on the global basis are therefore difficult. Here, we can make only some qualitative observations on how other constraints might affect economics. Quantitative comments, which require more complete development, are done as a function of the supply system described in Chapter 7 and specifically for both system type and world region as described in Part IV of this book where economic parameters are a major criterion of supply allocation.

Social behavior has many unknowns, and we have looked for phenomenological descriptions of this behavior as it applies to the energy system. The analysis of the market penetration process is a particularly fortunate description for our purposes, for it reveals a very great regularity in the displacement of old energy forms by newer ones, even though the causes of that regularity are unknown or only qualitatively known. The social system, through forces that are intrinsically economic, psychological, or behavioral, seems to impose a limit on the rate of replacement of one energy form by another. Large-scale changes in global consumption patterns do not occur overnight, and time thereby becomes a significant constraint on any new type of energy system that is to be deployed.

Likewise, environmental factors affect decisions about whether to install energy systems of various kinds. Many factors come to mind, including water consumption, land disturbance and preemption, and destruction of species habitats. The evaluation of these would require detailed attention to specific proposals, which was beyond the scope of our work as described here. Yet we must, if only in a very generalized way, take them into account. The WELMM approach permits us to do just this. By comparing the requirements of energy systems for water, land, and materials, we derive insights into the total environmental disturbance of these systems. This affects policy in several ways, not the least of which being the physical requirements that are revealed. By introducing energy and manpower into the WELMM system, we also obtain insights into what capital costs are likely to be needed for various energy systems and in that sense develop a quantitative understanding of the basic economic factors. Thus WELMM requirements are not in themselves constraints on energy supply systems; rather, they are input for evaluating environmental and (to a limited extent) economic constraints. They are more appropriate for estimating rank of desirability among options than for setting limits on any one of them; this in itself is a powerful constraint on low rank systems.

The climatic effects of energy supply are potentially far reaching, but their progress is slow. Thus, in considering these effects, we are talking of global phenomena of great importance. There is hope, however, that eventually we may be able to master the problems of fully understanding the mechanics of climate and then to reliably estimate the consequences in time to affect policy. Of course, if policy does not act on knowledge, the impacts of climatic changes could be severe. We therefore characterize this constraint as a crucial one, but one with a possibility of being eventually scientifically definable.

Risk is a different matter. We have used the term in a restricted sense to characterize direct risks to individuals, by way of impacts of energy systems on human health and mortality. This brings us out of the area of physical objectivity, for human beings take a highly subjective view of such matters: they not only ask what is the average long-term effect on people as a whole but also what can it do to me. We can, within definable bounds of precision, give only probabilistic answers to such questions. Yet this is unsatisfactory to many people, both because people vary in their willingness to accept personal risks and because health effects and mortality are essentially stochastic: no matter how great the odds are, it could happen to "me." Thus risk definition alone is not enough, although it is all that a physical approach can achieve. In addition, there must be an understanding of risk perception (what people rightly or wrongly believe to be the risk) and of risk management, defined as the reconciling of risk and its perception into a beneficial policy. Clearly, these concepts can be manipulated by social forces, which are constantly changing. The result is that risk management and perception translate into a political problem, thus adding uncertainty to the prospects of realizing fully the benefits of technologies perceived to be "risky."

CONSIDERATIONS ON MARKET PENETRATION OF NEW ENERGY SOURCES

Since the supply of cheap and easily exploitable fossil resources will soon be depleted, we will have to make the transition, first, to the use of more expensive and difficult to exploit categories of fossil fuels and, ultimately, to the use of nonfossil energy sources. How much time is needed for a given supply system to incorporate a new energy form?

We developed a simple, self-consistent method for describing the historical evolution of energy systems. A phenomenological model was designed and applied that treats energy sources as commodities competing for their respective shares in a market. The fractional shares of new energy sources in each energy supply system follow logistic growth paths of the same sort as competing products and technologies of other types. A logistic curve decline follows as even newer technologies penetrate the market in their turn. The model was validated by fitting data from about 300 cases with data for some cases, covering a span of more than one-hundred years. The historical evolution of various energy systems was fitted extremely well.

The model deals with the fractional shares of energy sources only and not with their absolute magnitudes. By working with fractional shares, we were able to nearly filter out all fluctuations in total growth from economic, political, and other events. The model applies to an energy source, primary or secondary, only after this source has acquired a significant share (2 to 3 percent) of the energy market. It was also found that the larger a system, the closer the fit of the model to the observed data.

So far as the past is concerned, there seems to be a characteristic time for the share of any new technology to grow from 1 to 50 percent of the energy market, depending only on the scale at which one views the energy system. This time is one-hundred years globally, thirty years for the continental system of Europe, and possibly even less for a single small country.

Clearly, certain insights can be gained from this analysis. First, the logistic evolution of the shares of new energy sources is a typical characteristic of all energy systems, irrespective of their size and the type of energy market covered, primary or secondary. Second, alteration of the structure of an energy system takes time, but smaller systems can be more easily manipulated than larger systems.

Although the logistic substitution model discussed above was developed phenomenologically, its structure is supported by two theoretical formulations recently attempted at IIASA to explain the technological substitution process. These two approaches differ in that one derives the final regularity of the substitution process from a set of stochastic—that is, "free"—decisions, while the other explains the same phenomenon through a more classical route that treats economics as the driving force in the substitution process. Nevertheless, the end results are the same as those given by the phenomenological model, thus giving further credence to the insights obtained from our analysis.

Some additional clarification is in order here. Throughout the book we have used the results of the market penetration technique for orientations and not as an iron clad rule for determining future developments. It would indeed be comforting if future energy strategies, such as the ones described in Part IV of this book, would be consistent with the orientations taken from the past and applied to the future. But even our own two scenarios, which we consider realistic and in the middle of the road, are not consistent in that sense. Such inconsistency we interpret as a quantitative indication of the seriousness of the situation.

Considerations on Physical Input Requirements

For assessing the environmental and physical aspects of future energy systems, it is important to consider the requirements of different technologies for such inputs as land, water, various materials, and manpower. Examining these inputs for typical systems may also help to identify potential bottlenecks that could limit the application or the exploitation of a particular technology or a resource. We developed the WELMM approach, which identifies, on one hand, the requirements of water, energy, land, materials, and manpower for different technologies and energy resource exploitation efforts and, on the other, the availability of these resources in different parts of the globe. Two types of data bases were used—a facility data base containing detailed WELMM requirements for constructing and operating typical energy facilities (e.g., coal mines, oil fields, refineries, power plants, transportation facilities) and two resource data bases containing information on potential availability of WELMM categories of resources in different geographical areas.

A comparison was made of the WELMM requirements for the construction and the thirty-year operation of different, equivalent electricity supply chains (plants and their auxiliary facilities), based on STEC, LWR, LMFBR, and coal-fired plants. The supply chains took into account activities related to mining, transportation, and processing of fuel; plant operation; reprocessing; waste disposal, and so forth. Of the cases examined, the lowest land- and material-handling requirements would be associated with a LMFBR chain, followed by a LWR chain, which, as currently used, is based on 2000 ppm U_3O_8 ores. If the LWR chain were to be operated using very low grade ore, say with 70 ppm U_3O_8 ore, then its land- and material-handling requirements would exceed those of typical coal-based chains. In spite of the zero mining operations of the solar chains, the requirements of land for these chains would be several times higher than those chains using coal-fired plants. Solar chains would also use more construction materials than either coal-fired or nuclear plants, but would recover their advantage relative to the coal chains when the materials needed for their operation were also taken into account.

A preliminary assessment was made of the WELMM constraints that may be associated with the supply of liquid fuels through coal liquefaction or through the exploitation of oil shales and of tar sands. It turns out that each of these approaches applied to known giant and supergiant deposits of the corresponding fossil fuels would put considerable strain on the available water and land resources, would pose severe material-handling and waste disposal problems, and would have relatively higher requirements of technical manpower than have been experienced with conventional oil fields. The consumption of energy (including autoconsumption of the resource) for different projects is estimated to be about 0.1 to 1.3 times the energy output in the form of oil. This is one to two orders of magnitude higher than that required even for the difficult conditions of North Sea oil.

If one were to compare the above processes only with respect to the three parameters—water, land, and manpower requirements—then coal liquefaction would appear to be the least favorable process. However, the relative differences are not very large, and local conditions also need to be taken into account. For example, the water requirements for the exploitation of oil shales (per unit of oil produced) are estimated to be lower than those for tar sands; but, for example, the water scarcity in the state of Colorado where major oil shale resources exist may turn out o be a serious problem for exploiting its shale beds. By contrast, water does not now seem to offer any problem in the region of the Athabasca tar sands.

The various WELMM rankings suggest that LMFBR nuclear systems offer many advantages related to environmental values as compared with other ways of generating electricity. For the production of synthetic oil from shale, tar sands, or coal, WELMM rankings seem to favor shale oil. However, the differences depend strongly on local conditions and are not easily generalized.

Considerations on Climate

Three types of climatic perturbation were examined—from the release of waste heat from energy conversion and use; from local interference with the earth's radiation balance because of changes in surface characteristics; and from interference with the earth's radiation balance because of carbon dioxide buildup in the atmosphere. (The potential climatic effects of deploying renewable energy sources such as wind, ocean current, ocean thermal, or tidal power are discussed in Chapter 6, where estimates of specific constraints are made for the various technologies.)

To investigate the first of these effects, a general circulation model was used that simulated the impact of heat inputs on atmospheric circulation and thereby climate patterns. The model explored incremental annual energy releases globally, ranging from 30 to 300 TW. In order to pronounce the perturbation of the global climatic system, the energy was released in limited geographical areas, while previous studies using a general circulation model investigated the response of the model atmosphere to homogeneous additions of waste heat amounting to 300 TW over all continental and ice regions. It was concluded that the thermal pollution effects were not greater than the inherent noise level of the model. A concentrated addition of 150 to 300 TW to the model atmosphere leads to a response of the simulated atmospheric circulation not just in the area of the input. The response varied significantly according to the location, amount, and method of heat input. At the level of a waste heat release of some 30 TW, the results of the global circulation model experiments suggest that waste heat is a ''nonproblem'' on a global scale, since it is unlikely to perturb the global average climate state in the foreseeable future. This is not to say that there could not be serious impacts of large waste heat releases in the multigigawatt to the terawatt range in the vicinity of such operations.

The climatic effects due to changes in surface characteristics were examined with a mesoscale model of the atmosphere by simulating conditions for a STEC facility. The surface heat balance was altered in a limited region because of changes in the albedo and the release of waste heat from the cooling towers of the STEC facility. The changes were, in this case, restricted to a limited geographical area in southern Spain. Mesoscale effects of some consequence are observable when changes in the surface heat balance reach the range of tens of gigawatts. This result is considered not to differ in degree from the direct effects of heat addition.

The third effect, that of changes in atmospheric radiation characteristics because of the buildup of carbon dioxide and other gases in the atmosphere, is the well-known greenhouse effect. Although there are uncertainties about the rates of exchange of carbon dioxide between the atmosphere and the various sources and sinks of this gas, still, it is possible to assess the increase in global temperature due to different energy strategies on the basis of our present understanding of these interactions. We used a carbon cycle model and a climate model, assuming several different hypothetical energy strategies. For one of these strategies leading to a global energy consumption of 50 TWyr/yr by 2050, with all energy being supplied by fossil fuels, the average global temperature was found to increase by about 2 K in 2030 and by about 4 K by the end of 2050. For another strategy it was assumed that the global energy consumption would increase to 30 TWyr/yr by 2050, but that the use of fossil fuels would peak at around 2000 and would decline thereafter, down to the 3 TWyr/yr level by 2030. Most of the energy after 2010 was assumed to be supplied by nonfossil sources—solar and/or nuclear; for this strategy, the global temperature was found to increase only until 2030, when it would be about 0.5 K higher than its 1975 value.

Even on the average global level, these are rather large changes, comparable to those of historical and prehistorical significance. For example, some two million years ago the average global temperature was about 4 K higher than the current temperature and was associated with an ice-free Arctic. An increase in average global temperature by 4 K might therefore lead to a similar situation with a consequent increase in sea level that would flood most coasts of the world. Changes at regional levels will be much larger in certain areas, with resulting impacts on precipitation and rainfall and on regional agricultural practices as probably the most significant. Although the results could be welcomed in certain areas, they are likely to be negative in many more places.

At the present time there are many uncertainties about the specific climatic impacts of large-scale deployment of any of the major energy sources. It seems likely, however, that the global impacts of waste heat and changes in surface conditions will be felt at a more distant time than those from changes in concentrations of carbon dioxide. A period of five to ten years is needed and can probably be afforded for vigorous research in order to narrow down uncertainties, in particular for the carbon dioxide issue. Because of the present uncertainties about the climatic implications of raising the carbon dioxide level, it is premature to implement policy measures requiring the reduction of the use of fossil resources. Nevertheless, it is most important to maintain flexibility in energy supply policies at this time.

Considerations on Risk

The considerations on risks associated with different energy supply systems have received little attention except with respect to nuclear power. In assessing the risks of energy systems, one therefore runs into the difficulties of the lack of data, the inadequacy of evaluation techniques, and a complete absence of decisionmaking formalisms for setting standards.

On the bases of available information and experience, a comparison was made of the human health risks associated with one unit generation of electricity, using different types of plants—coal-, oil- and gas-fired plants; LWRs; and STEC plants. Such a comparison, including the effects of accidents and diseases on occupational staff as well as on the public, showed that the coal-fired plants present the largest risks. The risks associated with LWRs amount to only a small fraction (less than 6 percent) of those relating to coal-fired plants.

These results may appear surprising. Many people view nuclear power plants as being associated with much greater risks than other facilities. In a survey conducted on a heterogeneous sample of the Austrian public, risks were perceived as lowest for solar and hydroelectric power systems and slightly higher but still small for fossil fuel energy sources, while opinion was divided with respect to nuclear energy. An analysis of the beliefs underlying the attitudes of the PRO- and CON-nuclear energy groups revealed that psychological (anxiety-inducing) aspects and sociopolitical implications of nuclear power contributed negatively to the attitudes of both groups. However, for the PRO group, this contribution was sufficiently low to be overridden by positive contributions from their beliefs on other aspects.

Thus, the risk evaluation process faces a dilemma: public opinion does not reflect the risks evaluated on purely technical considerations. Psychological factors and attitudes toward matters related only slightly to risk affect people's perception of risk. It appears that the general public is very concerned about the possibility of large accidents, even though the probability of their occurrence is quite small. Yet, low frequency, high consequence events generally make only minor contributions to the aggregated risk. It also appears that positive and negative belief systems color individual attitudes toward resolution of well-publicized conflicts. For example, a general faith in the benevolence of "progress" will predispose a person to accept the technical judgment that the probability of, say, a catastrophic nuclear accident is comfortably small, while a person's suspicion of "the system" would predispose her or him to believe that such a judgment is likely to be corrupt.

Thus more than one measure of risk is needed to correlate public perception of risk with technical evaluations. Multiattribute utility measurement is making progress in this direction, but it is still an imperfect tool. Yet even if a calculus existed for estimating the relative acceptability of not merely different average risks but also different risk distributions, other considerations would still color perceptions. The development of energy systems must resolve conflicts between the best technical judgments and the expressed wishes of the public. Neither of these factors can, ethically, be overridden. What is needed is described as risk management.

One possible way to resolve this conflict is to reduce any type of risk below a desirable level by incurring additional effort and investment. However, the economy has limited resources that need to be directed toward the most cost-effective alternatives. For identifying such alternatives, the risks are expressed in monetary terms as loss of production to the economy. With this approach, the marginal costs of risk reduction are found to be much higher for low frequency, high consequence events than for high frequency, low consequence events. Furthermore, the energy system is just one part of the overall economic system. Thus it is not useful to reduce a certain amount of risk in any energy installation, since this calls for an effort that would incur the same amount of risk through some other channel.

Intimately connected with the issues of proper risk evaluation (including the aspects of public perception) and the cost effectiveness of risk reduction is the problem of setting standards for energy systems. A policy analysis of several standard-setting procedures on environmental issues revealed the problem of often conflicting interests and objectives of the three main parties—the regulator, the developer, and the impactee. The regulator generally has political objectives, and the developer concentrates on cost considerations, while the impactee is interested in having potential risks reduced. In order to formalize the interactions, two theoretic game-decision models were developed and applied to considerations of standards on various issues, including the environmental pollution from carbon dioxide emissions. However, in their present state of development, these models can be used only to gain insights and not for operational applications.

The results of our risk analyses indicate the discrepancy between the best technical evaluations of risk and the public's perception of risks. The technology that currently carries the highest steady risk is coal, yet it has wide public acceptance. The technology that poses the greatest threat of catastrophe is hydroelectricity, which is also broadly accepted. Using these technologies as yardsticks, one could argue that, within reasonable limits of exploitation, no technology is too risky. Still, a large segment of the population believes that, specifically, nuclear power is too risky to use. We face a dilemma that has not been resolved by multiattribute utility measurement, risk reduction, or standard setting. Risk management, which can be defined as the process of resolving the dilemma, obviously must be further developed.

SOME FINAL WORDS ON CONSTRAINTS

Our elaboration on constraints, as reported in Part III of this book, functions essentially as a sensitizer for our study of the global energy system. But to a large extent, it is a qualitative procedure. There is a considerable drive to be quantitative, but we found it difficult and not scientifically defendable to operationally introduce quantitative conclusions from Part III into Part IV. On the contrary, the findings of Part III enter extensively into the implications and assessments of the study presented in Part VI.

IV BALANCING SUPPLY AND DEMAND: THE QUANTITATIVE ANALYSIS

The eight chapters of Part IV[a] represent a synthesis of many separate studies. They take much of what has been reported in Parts II and III as inputs. They make use of mathematical models (Chapter 13) to perform a quantitative, long-term, global and region-by-region analysis of the two scenarios (defined in Chapter 14). Energy demand (Chapter 16) and energy supply (Chapter 17) are analyzed, and their interpretations in economic terms are offered (Chapter 15). Alternative cases also are examined (Chapter 18), and their impacts on the economy are compared with those of the two scenarios (Chapter 19). The entire effort is summarized (Chapter 20).

The quantitative analysis reported here combines an array of real world constraints in order to build up, in a "bottom up" way (starting with details), a range of plausible energy futures. This is done regionally, starting with 1975 data, and has as a goal the balancing of energy supply and demand in a least cost way within the assumed constraints.

By contrast, much of the other work of the Energy Systems Program reported elsewhere in this book is "top down" (starting with broad, general considerations), done globally and not regionally. This other work has a "vision"—a vision portrayed in the discussions of the chapters in Parts II and III in particular. The vision sees a truly sustainable global energy system

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[a] Throughout Part IV, except where noted, primary energy excludes the noncommercial use of fuels (e.g., fuelwood, animal and farm waste).

over the very long term (say, one hundred years from now), with a secondary energy carrier based on the eternally available heat from breeder reactors and solar facilities. The sustaining "endowments" of plutonium or of the sun would be tapped by technologies whose development may, the vision suggests, be a matter of priority.

The vision and the two scenarios are complementary. The vision seeks to explore the bounds of the possible; the scenarios seek to balance constraining factors in order to identify the plausible. The vision defines a long-term goal; the scenarios chart a path with no explicit goal. But the implications of the scenarios may lead toward a more rapid development of the energy systems of the vision.

A number of specific studies that contribute to the vision also play a role in shaping inputs to the scenario analysis. The fossil fuel resource estimates of Chapter 2 are essential inputs to the scenarios; the estimates from that chapter are modified somewhat here in Part IV to match the format of the analytical tools used for scenario projections. The scenarios use such resource estimates to generate maximum production rates of each fossil fuel type. These production rates distinguish the constrained scenario analysis from the potential-seeking studies of Part II.

Similarly, the uranium resource estimates of Chapter 4 and, to a certain extent, the solar and other renewable sources estimates of Chapters 5 and 6 also provide bases for more constraining inputs to the scenario analysis. The full potentials of coal and nuclear energy (Chapters 3 and 4) are not reached in the scenario projections. But the scenarios could not be generated without the maximum constraints provided by these studies. And the scenarios, in any case, do not attempt to elaborate on these important topics but simply to weigh and balance them. The elaboration is in Part II.

Constraints on the scenarios also come from the studies reported in Part III. While potential climate impacts or risks of alternative energy strategies are not fully implemented in these scenarios, they are not completely ignored. Specific scenario numbers affected by these considerations are cited where appropriate in the following eight chapters. The carbon dioxide accumulation resulting from the scenarios is discussed in Chapter 17.

Time is a major constraint on energy system evolution. The so-called "market penetration" considerations of Chapter 8 enter the scenario analysis by providing historically based estimates of the maximum buildup rates of new energy technologies. These system lead times are very important; in a sense, they incorporate comprehensively the pragmatic difficulties of shifting the world from its present energy systems to those of the vision or of any other radically different possibility.

The scenarios and alternative cases discussed here in Part IV are, then, the pragmatist's integrated guide to a range of plausible, global long-term energy futures. They will disappoint those searching for revelation or an elaboration on a special theme; they (hopefully) will satisfy those searching for a balanced perspective on difficult and often conflicting choices.

The work on Part IV has been a team effort. The acknowledgments in the

Preface to this book name the principal contributors. The work is also not the result of a moment–it took more than two years of intensive effort. Part IV is offered as a learning tool–an experimental foray into an uncertain, but critically important, global energy future. It should also be noted that this book was written in the fall of 1979 and that, as observed in Part I, political events were not applied explicitly to the work reported therein.

13 THE ANALYTICAL APPROACH

It becomes increasingly tiresome to say—or to hear—that the energy problem is complex and multidimensional. Still, repetition does not diminish the truth of the statement, and the seemingly endless stream of advocates of easy answers evidences a certain lingering disbelief of it. When designing analytical approaches to energy studies, one should keep in mind the sobering dimensions of the problem. The preceding chapters of this book convey some of the broad range of energy-related considerations taken up during five years of energy research at IIASA—the complexity of the problem and the lack of simple solutions. In particular, Part I presents the logic and arguments underlying the many distinct research topics summarized in the chapters of this final report of the IIASA Energy Systems Program.

In spite of the breadth of topics treated in this research, clearly one cannot hope to deal with all of the important components of "the energy problem." But one can hope to select a set of vital issues, based on a perception of key components of the problem and on perceived needs of decisionmakers, and design an analytical approach for understanding and eventually acting intelligently on those issues. In Part IV, the quantitative analysis of a selected set of issues is reported. This includes a description of the analytical approach—the steps carried out, the assumptions made, the results. The description of the approach takes up the arguments of Part I, restating them here for the reader of the scenario analyses.

THE PROBLEM AND THE NEED FOR QUANTITATIVE ANALYSIS

Can the globe meet its energy needs in the future? At present, the world depends heavily on oil and gas. But there is a finite supply of these resources. More to the point, the cheaply accessible portions of these resources are already nearing depletion; a transition to something other than inexpensive and nonrenewable oil and gas is inevitable. Will the transition be prolonged and painful, difficult and divisive, or can it be well managed, a smooth and cooperative era? Will it lead the world over the long run to sustainable energy supply or to a reliance on some different (perhaps more expensive) depletable resource?

Clearly, energy demand and supply will always balance. The issue is whether the balance will occur at a level that will satisfy "reasonable human requirements," dependent to a large extent on population growth and economic development. No theory exists that permits precise predictions of the energy needed to support a given population and size of economy, although historical experience provides some evidence. Thus, assumptions must be made about future energy demands.

Consequently, the problem translates to: For an assumed projection of energy demand, can the globe carry out a smooth transition from cheap oil and gas? An understanding of the character of, and constraints binding on, the energy transition is a primary objective of the quantitative analysis to be described. This understanding necessitates a degree of quantification for several reasons. Quantification lends a certain specificity and thus unambiguousness to complex considerations. In such a data- and statistics-heavy field as energy, numbers are the inescapable common language.

Quantification also facilitates desirable generalization or detailing—aggregation or disaggregation. Here, analyses are performed for the world as a whole, by world regions, by economic sector within regions, and by energy type within sectors. Results are plotted over time and integrated over time. Numbers allow microscopic inspection of details and telescopic views of aggregates. Finally, quantification aids attempts to reach the requisite measure of consistency in demand and supply, in intra- and interregional energy balancing. Numbers cannot guarantee consistency, but they can help significantly.

So, a quantitative analysis was done. Yet, perhaps ironically, but not contradictorily, the quantification is seen here as only providing insights. The numbers themselves (especially the numbers describing future energy prospects) cannot be taken too literally. The aim of quantification is to help in the intellectual challenge of understanding the dominant characteristics, trends, possibilities, and constraints in global and regional energy considerations.

Consistent with this is the recognition that the scenarios deal with an unknown (and to a large extent unknowable) future. But future looking has value; prudence in actions today follows, at least in part, from the ability to recognize what can, and what cannot, be foreseen for tomorrow.

As noted in Part I, the analytic approach adopted for energy studies at IIASA assumes an essentially surprise-free world—no global-scale disasters, no sweeping scientific discoveries. A major war could put an end to the rather stable energy projections of these chapters; an unlikely early breakthrough in, say, photovoltaic technology could offset the figures by several years and alter the results. These things could happen and should not be forgotten. The fact that these are not included in the scenarios reflects the belief that such events are not likely to occur and that even if they were, they could not be rigorously treated.

One would be hard pressed to identify any historical fifty-year period without either major disasters or life-altering technological advances (or both). Yet one observes the astounding smoothness—in the aggregate—of energy growth over the past decades. And one observes the same smoothness blurring the impacts of the automobile, the telephone, the transistor—all of which have transformed society in irreversible ways.

All of this leads to a belief (or hope) that the scenarios here are robust, that they can stand up against events whose impacts, in human terms, may be large. Should some occurrence or occurrences in the next fifty years make erroneous this belief, so be it. But such things cannot be planned for, cannot be foreseen. Still, it seems prudent to at least attempt to look responsibly toward the future, to postulate some scenarios, to calculate some indicative numbers, and to gain some insights.

THE BASICS OF THE ANALYTICAL APPROACH

The quantitative, analytical approach developed within the IIASA Energy Systems Program to conceptualize the energy problem integrates other aspects of the program's studies; it is broadly outlined and explained in Part I of this book. (The reader familiar with Part I can safely skip to the discussion of the IIASA set of energy models in this chapter.) To deal with the possibly very long transition, a fifty-year perspective is taken (1980–2030). To cover both global comprehensiveness and local specialness, mutually exclusive and exhaustive world regions are studied.

The choice of regionalization is neither haphazard nor easy. In one sense, energy problems are global ones, but wide differences among peoples, economies, and geographic locations are masked by global aggregates. In another sense, energy problems are national ones, but the broad perspective of true long-term possibilities and the prospective balance or imbalance in world trade are lost in narrow national views. And the IIASA energy study is not able to consider 140 separate national cases.

The regions are selected more for their economic and energy similarities than for their geographic similarities. That is, there are developed market economies with significant energy resources and without significant energy resources; there are centrally planned economy regions; there are developing regions with and without energy resources. The regionalization seeks to preserve broad national similarities within each region and to allow for treatment of major energy trade patterns among regions. Seven such regions are defined in Figure 1-3 and used throughout the quantitative analysis. A complete listing of the countries of each of the regions is given in Appendix 1A.

The analysis begins with postulates of basic development variables for each of the seven world regions to the year 2030. The two basic development variables are population growth and economic development (as measured by growth in gross domestic product—GDP). Two sets of estimates are made, in order to bound from above and below the set of likely developments over the next fifty years. These estimates may be (and are, in practice) modified as further energy-related insights are gained. Chapter 14 describes the iterative process of making these projections—a process of selection, definition, characterization, and evaluation of scenarios. It offers some criteria for the ultimate acceptability of the scenarios.

Given the initial scenario-defining estimates of population growth and economic development, consequent energy consumption patterns are calculated for each of the regions. While the objective here is aggregate energy demand consistent with the postulated economic development over fifty years, each region's energy consumption is examined in considerable detail. Key assumptions about technology, lifestyle, and penetration of specialized energy sources (e.g., solar, district heat, heat pumps) for each region and for each time interval drive the estimation procedure. The details enable a more careful examination of the linkages of energy and the economy and help to keep straight the many and complex end uses of energy. In this way, some notion can be gained of the requirements for reducing energy consumption growth. Chapter 16 records both the steps and the key assumptions in this analysis and its results.

These aggregate energy consumption projections provide one kind of input to energy supply system analysis. Adding constraints that act upon the total energy supply system—estimates of the amount, rate, cost, and time of availability of each prospective energy source—enables calculation of alternative energy supply mixes for the future. The chapters of Part II of this book provide the substantive basis for the more detailed estimates used here. Water availability, hostile local environment, difficult and costly transportation requirements, skilled labor limitations, and other local or regional conditions also must be incorporated in some way. In Chapter 17 these various inputs and constraints are detailed; in many cases it is necessary to select some quantitative constraints (e.g., and upper limit on annual coal production within a region) to represent, generally, the aggregate of a number of restrictive factors—water supply, suitable transportation, and so forth.

These constraints are based generally on the in-depth analyses of the chapters of Parts II and III of this book. The aim of the scenario analysis in Part IV is to integrate and sum these constraints so as to evaluate the implications for the total energy supply system.

Yet not every conceivable constraint on energy supply systems received full treatment here. For example, potential risks to life and health, environmental constraints, and potential climate impacts are not incorporated explicitly in these quantitative analyses. They may still affect subjective assumptions about alternative energy sources (see Chapter 17).

The general approach is to consider the energy system from resource extraction through end use with sufficient detail so as to reflect the most important constraints and to produce the "best" energy supply mix within such constraints. This must be done in order to ensure overall global consistency, while not unduly sacrificing regional specialness, for a plausible scenario range (High and Low). The specific approach is to use an optimization program to find the combination of energy sources that satisfies the specific temporal sequence of regional final energy demands, subject to (often very dominant) given constraints, while minimizing the discounted total cost.

This procedure is iterated from demand estimation to supply optimization until the demand and supply projections are judged to be "reasonable" and consistent. An important part of the iteration and global consistency is the treatment of energy trade (see Chapter 17); the goal is to produce balanced, consistent world scenarios without energy "gaps." An example of the overall iterative procedure for scenario analysis is given at the end of this chapter.

Once two globally consistent energy scenarios are produced in this way, the results can be evaluated in terms of their consequences for cumulative resource consumption (see Chapter 17), the direct and indirect investments (see Chapter 19), and other criteria of interest. It is important, in this highly iterative analytical approach, to evaluate the complete scenario specification and results in as many ways as are useful for determining reasonableness and identifying misfits (see Chapter 15). Then one can iterate wherever necessary and/or appropriate in order to alter unacceptable results. Once acceptable scenarios are generated in this way, variations can be examined.

Ultimately, the identification of at least one strategy that meets the assumed demand projections, subject to the resource and technology availabilities and constraints, establishes the technical feasibility of the global transition from oil and gas. The evaluation in terms of the various criteria of prospective concern will indicate whether the technically feasible path is likely to be acceptable in other ways as well. If not, the optimization program can be adjusted in order to constrain values of the sensitive criteria to acceptable levels. The result should be one or more technically feasible and acceptable strategies for the transition.

Alternative strategies are considered in Chapter 18, with necessarily less detail and sophistication than the two main scenarios. With sufficient repetitive analysis, judgments about the sensitivity of results to changes in certain assumptions provide a further measure of technical feasibility.

The analytical approach just outlined relies on considerable iteration among its components. This point is an important one, reflecting a recognition of the interdependence of the many aspects of the energy problem; each of the chapters in Part IV illustrates different dimensions of a sequential, yet highly interactive, quantitative analysis.

ANALYTICAL TOOLS: A SET OF ENERGY MODELS

In order to carry out the analytical approach just described, a set of tools was developed at IIASA or, in some instances, brought to IIASA and adapted for specific purposes. These computer models are described, as a coherent set, in this chapter.

The remainder of this chapter is, then, largely methodological—setting down for the interested reader or researcher the logic and structure of the formal tools supporting the analysis. Those interested primarily in results can safely skip to the next and subsequent chapters of Part IV.

In November 1976, Academician M. Styrikovich of the Academy of Sciences of the USSR suggested making the studies within the IIASA Energy Systems Program more comprehensive by building a set of computer models to reflect the high interdependence among world regions, in view of the many interrelated issues surrounding future energy prospects. With this impetus came the full realization of a set of energy models at IIASA—by adapting existing models where possible and building new ones where necessary. The starting point was the existing linear programming model of Wolf Häfele and Alan Manne (1974), built as one of the first stages in the energy research at IIASA. At the first IIASA Conference in May 1976, the motivation and logic behind the then fledgling modeling effort were presented (Häfele 1976).

During the course of designing and building the models, IIASA benefited greatly from cooperation with Dr. Kenneth Hoffman, then head of the National Center for the Analysis of Energy Systems at Brookhaven National Laboratory in the United States, and with Professor Makarov and others at the Siberian Power Institute (SPI) of the Siberian branch of the Academy of Sciences of the USSR. At SPI, a similar set of energy models was under design at the same time that the IIASA models were being developed. Continuous and active interactions with SPI have greatly aided these efforts.

The set of computer models now in use in the IIASA Energy Systems Program provides a means of synthesizing the many elements of the specific energy studies reported in this book (in Parts II and III). The models formalize certain perceptions and assumptions, yet they do not rigidly drive or force the logic and findings of the analyses. The essential judgments, logic, and interpretation of results rest with the researchers themselves.

Purpose and Goals of Energy Modeling

Given a subject as complex, confused, and polarized as is the current thinking about the world's future energy prospects, one might well ask why computer models should be thought to offer much help. It is a fair question. Perhaps a clarification of the general purposes of computer modeling will help to place the possibilities of such models in an appropriate context and thereby aid in identifying the real utility and benefits of these models.

Computer modeling has one central and specific purpose: to aid in understanding the complex interconnections with systems—economic, technical, social, or, in this case, energy systems. There are perhaps three characteristics, or at least desirable attributes, of properly applied computer models that enable them to be worthy of such a purpose.

First, models provide insights, by integrating system parameters too numerous for the individual analyst to assimilate. Models should be designed for gaining insight and understanding, not (necessarily) for mathematical sophistication.

A second characteristic of computer modeling is that models provide results that should be reproducible from basic logic; model results, once seen, should be obvious.

Finally, computer models provide consistency of calculation. For highly complex and quantitative subjects, modeling provides an essential accounting framework—a necessary classification scheme—to aid in the otherwise laborious if not impossible task of simultaneous calculations with hundreds or thousands of variables.

Computer modeling has at least one other distinct advantage. With a great many interdependent variables to consider in typical systems problems, it is difficult to know which ones are critical, which ones deserve close attention by planners and decisionmakers. Models can aid in identifying such parameters through, for example, sensitivity tests and consideration of alternative scenarios.

Recognizing these characteristics, the particular set of energy models at IIASA was conceived, with perhaps four general objectives in mind:

1. To study the long-term, dynamic (transitional), and strategic dimensions of regional and global energy systems;
2. To evaluate alternative strategies—to compare options—of a physical and technological kind, including their economic impacts;
3. To develop a global framework to enable the assessment of the global implications of long-term regional or national energy policies; and
4. To explore the embedding of future energy systems and strategies into the economy, the environment, and society.

In some way, point 4 is the ultimate objective of the model system, as a set. Is there enough time to manage the transition from today's energy system to asymptotically satisfactory systems? The aim also in this regard is to identify the capital requirements of the transition and to study their acceptability to the world's economies in view of constraints such as conservation of the environment and competing social needs. The fulfillment of this objective involves the coupling of capital requirements for strategic energy investments to other elements in the economy, in order to make trade-offs and to ensure consistency. It also involves the consideration of capital and financial flows among countries, balance of payments limitations, and financial aid. Much work remains to be done, even in designing the approach for meeting this objective. The IIASA set of energy models was developed with the aim of extending the debate on the impacts of future energy alternatives—of evaluating plausible energy strategies in a full systems context with a truly global perspective.

The Structure of the Set of Energy Models

Large monolithic computer models often suffer from overcomplexity and rigidity. Small and simple models offer relative clarity and understandability, while sacrificing (in many instances) methodological sophistication. Uncertain functional relationships in the first model type are replaced by uncertain human judgments in the second.

IIASA's energy-modeling work has generally adopted the latter approach—the linking of several relatively simple models into a coherent whole. In Figure 13-1 the model set is illustrated and the most important (of many) linkages are shown. Here, only the general scheme and structure of the set as a whole is described. In the next section, attention is given to each of the models. A description of several of the models, including general methodologies used, status, and certain central formulations of relationships, is appended to this chapter.

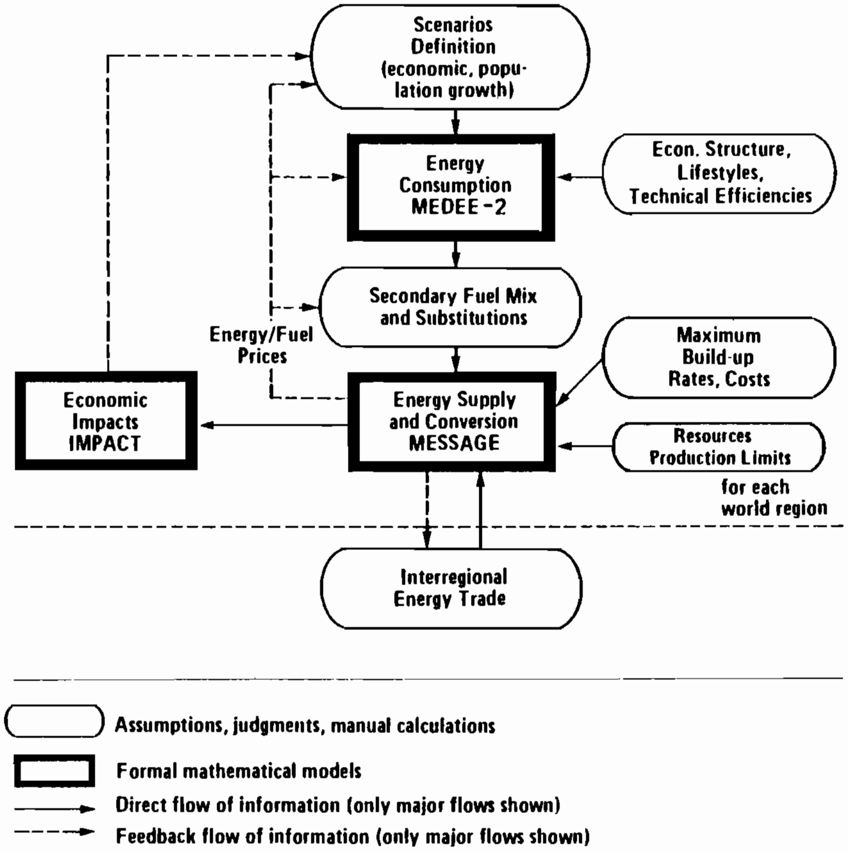
The approach, as is apparent in Figure 13-1 and has been repeatedly stressed (here and in Part I), is a highly iterative one. The initiation of assumptions and judgments leads to calculations and results that feed back and modify those assumptions and judgments. Most of the feedbacks are manual. An original assumption about the relative rate of penetration of liquid fuels into (or out of) residential energy use markets (for example) is decreased (or increased) as relative fuel prices (stemming from supplies) show a disadvantage for liquid fuels. While the flow of information is mechanized, the impacts of changes in one set of inputs on another are not. An example of the operation of the modeling loop and its several interactions is given in the last section of this chapter.

The energy-modeling activity begins with scenario definitions (top of Figure 13-1). A scenario is a plausible future—a reasonable outcome of a set of reasonable assumptions. It is neither a forecast nor a prediction. It is closer to a hypothesis.

In the IIASA energy research, two such scenarios are selected—two plausible futures believed to span a reasonable to expect range. (Chapter 14 presents the definition of these scenarios in some detail.) They are defined by "high" and "low" economic growth within regions and consequent high and low energy demand growth. Population growth is also a scenario-defining variable, although at present just one projection of population is used in the IIASA energy studies. Other factors vary from scenario to scenario according to judgments about internal consistency.

The scenarios, once defined in this way, do not remain inviolate. At least in principle, the procedure is more than a partial equilibrium one. Feedbacks

Figure 13-1. IIASA's set of energy models: a simplified representation.



from the resulting energy calculations can, and do, modify original economic growth assumptions. For the analyses reported in these chapters, this has been done judgmentally. Formalization of the procedure depends on the availability and suitability of modeling tools.

The scenario projections of economic and population growth for each of the seven world regions provide the basic inputs for detailed calculations of future final energy consumption consistent with the scenarios. Disaggregation of these overall economic and demographic projections enables consideration of economic and energy-consuming activities in three macrosectors—transportation, household-service, and industry (agriculture, construction, mining, and manufacturing). An array of judgments about lifestyle developments, improvements in efficiencies of energy-using devices, and the rate of penetration of new and/or improved energy-using equipment augment the disaggregated economic and demographic assumptions for each region. All of these details are meant to be consistent with the general scenario parameters and are recorded in a model called MEDEE-2[a], where calculations lead to estimates of useful and final energy consumption in the macrosectors. Following considerations of the penetrations of certain energy sources such as solar and district heating and electricity, final energy consumption (as nonsubstitutable and substitutable fuels) of each of the scenarios is calculated.

A further step divides the fossil fuels used for heating among liquid, gaseous, and solid fuels. This step completes the secondary energy demand calculations required as input to the energy supply and conversion model MESSAGE,[b] as shown in Figure 13-1. All of these energy demand calculations—from disaggregation of the scenario economic growth assumptions through secondary energy demands by fuel type—are presented in Chapter 16.

MESSAGE calculates the required supplies of primary fuels to meet the secondary energy demands at lowest cost and within often quite tight constraints on resources availabilities, energy production limits, and the rates of buildup of new energy facilities. Resource constraints are specified as maximum pools of oil, natural gas, coal, and uranium available at specified costs. As prices rise, several high cost alternatives can compete. Limits on the maximum rate of buildup of new energy facilities reflect the inherent lead times as well as limitations of manpower, materials, and the like in a region. The assumptions and results—which represent, in some ways, the core of the energy studies reported in this book—are presented in full in Chapter 17.

Interregional energy trade considerations (also reported in Chapter 17) provide time profiles of imports and exports of fuels for each regional MESSAGE run. Relatively simple allocation rules distribute available exports of fuels (e.g., oil) from exporting regions (e.g., the Middle East) to competing importing regions (e.g., Western Europe and Japan or Africa and Southeast Asia).[c] Allocations are done iteratively with MESSAGE runs (Figure 13-1) so that a globally consistent balance is achieved.

MESSAGE gives fuels production over time and the path of different primary fuels through conversion processes to a fixed set of secondary demands. In addition, MESSAGE provides the marginal production costs of primary fuels, leading to estimates of time trajectories of fuel and electricity prices. These prices are fed back (Figure 13-1) to several points in the loop, in order to iteratively modify initiating assumptions and judgments.

[a] MEDEE stands for Modele d'Evolution de la Demande d'Energie. It was developed initially at the Institut des Etudes Juridiques et Economiques at the University of Grenoble by B. Lapillonne and B. Chateau and adapted for use at IIASA by B. Lapillonne and M. Müller (see Lapillonne 1978). A version called MEDEE-2 was operated for the scenarios reported here by Khan and Hölzl (1980).

[b] MESSAGE stands for Model for Energy Supply Systems Alternatives and Their General Environmental Impact. It was developed by A. Voss, L. Schrattenholzer, and M. Agnew (see Agnew, Schrattenholzer, and Voss 1979) following extensions of the Häfele-Manne (1974) model. MESSAGE was operated for the scenario reported here by L. Schrattenholzer, M. Agnew, and J. Eddington.

[c] This procedure, whose calculations are now carried out by A. Papin, will be formalized through the use of a gaming model. This model originates with A. Makarov at the Siberian Power Institute. A. Papin is currently adapting it for use at IIASA.

To be specific, prices in this procedure affect three calculations. First, price changes alter macroeconomic growth patterns—increased prices can constrain overall growth and/or can shift activities from more to less energy-intensive sectors. These changes are made judgmentally at present, based on estimates of experts inside and outside of IIASA.

Second, price changes alter lifestyles and technological efficiencies of energy-using devices. Such alterations can be at best informed guesses; as prices increase, efficiencies tend more toward the technical potentials, and lifestyles adapt to lowered energy use. Assumptions are made clear and open, and the potential of energy savings from both categories are assessed at the maximum levels judged feasible. The specific measures that may be required to induce the lifestyle or the efficiency changes are not the emphasis here; the aim is rather to indicate the energy demand results if such lifestyle or efficiency projections were to occur.

Finally, relative price changes among different fuels and electricity can cause a change in the mix of secondary energy demand; relative increases in prices of liquid fuels induce shifts toward gaseous fuels, for example. No formal or precise elasticities of substitution are used here; again, best informed judgments describe the approach. After the analysis is completed, demand elasticities can be (and are) calculated (see Chapter 15).

The energy facilities required to meet the energy supply scenarios of MESSAGE have direct costs—capital, manpower, and materials costs. An IMPACT[d] model (Figure 13-1) calculates the required direct and indirect (energy-related) costs of new energy facilities and thus provides the basic information for assessing whether or not an economy can afford a given energy scenario. Exogenous assumptions about facility-specific size, material, and manpower requirements are made for IMPACT in order to calculate the direct and indirect requirements of a given energy strategy. In addition, a separate, detailed WELMM analysis (see Chapter 9) can be done following the IMPACT run. The assumptions and results from IMPACT are reported in Chapter 19.

With IMPACT-calculated costs, one can begin to ask whether energy will absorb unacceptably high shares of economic product. What forms of capital and financial aid will be required by developing countries? What level of nonenergy exports are necessary to pay for large energy imports?

Finally, a MACROeconomic model[e] could accept exogenous assumptions about demographics and institutional parameters such as productivity, taxes, and trade and could calculate investment and consumption rates consistent with the costs from IMPACT. This could allow assessment of the magnitude of change in, for example, the capital-output ratio if and when energy becomes increasingly capital intensive. This in turn could enable both

[d] IMPACT was developed at the Siberian Power Institute by Y. Kononov and V. Tkchachenko and was adapted for use at IIASA by Y. Kononov, with the help of T. Balabanov (see Kononov and Por 1979).

[e] MACRO was developed (in its initial form) by M. Norman and has been extended significantly by H.-H. Rogner. It is not yet implemented as part of the modeling loop (see Norman 1977).

a recheck of the original estimates of GDP for each region and a reentering of the iterative process. MACRO is being revised and adapted for these purposes; it was not used in obtaining the results presented in this book.

The sectoral direct energy requirements as calculated in IMPACT provide (in theory at least) important inputs to the energy demand model (MEDEE-2) for calculation of energy consumption by industrial sectors. For this purpose, implementation of an input-output INTERLINK[f] model is underway. INTERLINK would enable detailed industrial sectoral consistency between IMPACT results and the components of GDP for use in demand calculations in MEDEE-2.

In addition, other models (and modelers) have contributed to the concepts and insights behind the scheme described in this chapter. For instance, J. Parikh adapted a simulation model of India, SIMA, for some case study analyses, and developed a cross-country regression model called SIMCRED that was useful in first attempts at gauging energy use in developing regions (see Parikh and Parikh 1979).

The model set, it must be recognized, deals with only a finite set of issues. In Table 13-1, the scope of activities of the models is summarized—the things the set does, and the things it cannot do.

This description has focused on the IIASA energy models as a set. Yet each model is different, and each performs functions that have value independent of the set.

AN EXAMPLE OF THE ITERATIVE PROCESS: THE CASE OF REGION III (WE/JANZ)

Much has been made in this chapter of the iterative process of analysis inherent in the modeling loop of Figure 13-1. Here, an attempt is made to shed some light on this process through the use of an example (region III [WE/JANZ]). Attention is given here to two possible alterations of initial assumptions (there are others)—changes in the secondary energy shares and changes in relative rates of penetration of alternative final energy types.

Table 13-2 shows the changes in the secondary energy shares (of "substitutable fossil" uses) based on the energy price trajectories from MESSAGE runs. Initially (for example), the gaseous fuels share of fossil sources of heat in residences and commercial buildings was assumed (in the High scenario) to reach 60 percent by 2030. Because of the relative price rise of oil and the somewhat surprisingly flat price trajectory for natural gas, the gas share has been increased for the residential and commercial sector to 70 percent by 2030. Similar increases have been made for the industrial sector, particularly by the year 2000. This clearly is highly judgmental and mostly arbitrary. It reflects the belief of the possible rate of growth of different markets, pushed to feasible limits in this instance in the direction of more

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[f] I. Zimin has extended an input-output model (INTERLINK) of a national economy for potential use within the modeling loop (see Propoi and Zimin 1980).

Table 13-1. Scope of the IIASA set of energy models.

The model set *does not:*

- Take into account most institutional, societal, and political issues
- Predict energy pricing policies, market fluctuations, interest rates, or multisectoral dynamics
- Focus on great, multisectoral detail of useful energy demand
- Treat technological details of small scale
- Simulate carefully the full nuclear fuel cycle or questions of safety or arms control
- Evaluate the effects of specific tax, quota, regulatory, and financial incentive policies in detail

The model set *does:*

- Describe the potential of a reasonable evolution of global and regional energy systems
- Capture the long-term, slowly changing macroeconomic characteristics of developed and developing economies
- Forecast aggregate final energy demand (fuels)
- Model the evolution of the energy supply, conversion, and distribution systems and, in so doing, incorporate resources, capital cost, environmental, and some political constraints
- Calculate the economic impact (capital, manpower, materials, etc.) of alternative strategies
- Produce consistent scenarios on a global and world-regional level

Table 13-2. The iterative process, Example 1: assumed secondary energy shares, changes in region III (WE/JANZ) (%).

	Base Year	*High Scenario*	
	1975	*2000*	*2030*
A. First Estimates			
Industry "Substitutable Fossil"			
Oil	53.0	50	40
Gas	35.1	35	40
Coal	11.9	15	20
Household/Service "Substitutable Fossil"			
Oil	65.2	65	38
Gas	22.9	30	60
Coal	11.6	5	2
B. Final Estimates (after iterations based on relative price movements)			
Industry "Substitutable Fossil"			
Oil	53.0	35	20
Gas	35.1	50	60
Coal	11.9	15	20
Household/Service "Substitutable Fossil"			
Oil	65.2	55	28
Gas	22.9	40	70
Coal	11.6	5	2

gas use. This one change would result in 188 GWyr/yr less oil, and more gas, used in 2030 in this region, for the High scenario.

A second iteration, based on relative energy price movements, was a change in the assumed rate of penetration of electricity into heat markets in region III. This change, one of many exogenous inputs to the MEDEE-2 model, was reduced after successive iterations had revealed the tight supply situation for electricity and, in particular, the pressure on coal as a source of both electricity and essential liquid fuels. Clearly, if electric uses in WE/JANZ could, in general, be substituted by gas, aggregate prices would be lower, domestic coal would be able to meet a higher share of liquid fuel needs, and total energy imports would be lower. Since several items are generally changed during any one iteration, it is not possible to quantify precisely the impacts of any single change; still, Table 13-3 summarizes the changes in electrification assumptions in the iterative process and the resulting (approximate) change in total electricity consumption.

The character of such changes can be quite different in different regions. For example, in region II (SU/EE), estimates of future electricity shares could actually increase as prices for fuels rise faster than prices for electricity, as is expected by many analysts in this region.

Table 13-3. The iterative process, Example 2: assumed rate of electricity penetration, changes in region III (WE/JANZ).

	1975 A Normalized Base	*High Scenario*	
		2000	*2030*
A. First Estimates			
Industrial Process Heat (GWyr/yr)	268	524	751
Electric, resistive (%)	0	7	15
Electric, heat pump (COP = 2) (%)	0	0	0
Household/Service Space Heat (GWyr/yr)	204	390	490
Electric, resistive (%)	4	11	18
Electric, heat pump (COP = 2) (%)	0	1	2
Electricity Used for Heat (GWyr/yr)	8	81	207
B. Final Estimates (after iterations based on relative price movements)			
Industrial Process Heat (GWyr/yr)	268	513	743
Electric, resistive (%)	0	3	4
Electric, heat pump (COP = 2) (%)	0	0	1
Household/Service Space Heat (GWyr/yr)	204	319	374
Electric, resistive (%)	4	5	5
Electric, heat pump (COP = 2) (%)	0	3	5
Electricity Used for Heat (GWyr/yr)	8	36	61

Notes: 1 GWyr/yr ≡ 10^9 Watt-yr/yr; see energy units table in Appendix B to Chapter 1. COP = coefficient of performance.

MESSAGE results serve, iteratively, to modify other assumptions and judgments. As oil prices rise more rapidly than originally expected, for example, domestic crude oil production increases, and imports or perhaps the use of other expensive liquid fuel sources decline. The aim of the process is to reach a consistent picture of future energy prospects for the two global scenarios presented in the chapters of this part.

APPENDIX 13A: FORMULATION AND LOGIC OF INDIVIDUAL MODELS

MEDEE-2

MEDEE-2 is a simulation model for evaluating the energy demand implications of economic and lifestyle scenarios for the long-term evolution of countries or regions. It is a simplified version of a more general approach developed by B. Chateau and B. Lapillonne (1977) at the Institut des Etudes Juridiques et Economiques (IEJE), University of Grenoble, France. MEDEE-2 is based on a disaggregation of total energy demand into a multitude of end use categories such as heating or cooling of dwellings, urban-intercity passenger transportation by mode, and steam generation. When the useful energy demand of a given end use category can be provided by various energy sources (e.g., fossil fuels, district heat, electricity, or solar systems), energy demand is first calculated in terms of useful energy and then converted into final energy terms based on assumptions about the penetration of various energy sources into their potential end use markets and about their end use efficiency.

For nonsubstitutable uses (e.g., motor fuel for automobiles or electricity for electrolysis, lighting, and appliances such as washing machines and refrigerators), energy demand is calculated directly in final energy terms. Table 13-A1 gives an overview of the end use categories considered in MEDEE-2. For each end use category, energy demand (useful or final) is related to a set of determining factors, which can be macroeconomic aggregates, physical quantities, or technological coefficients. The energy demand projections result from the evolution assumed for these factors. Because of this high level of disaggregation and relatively few structural assumptions built into the model, it can be viewed as an accounting framework of the energy uses in a country or a region.

Figure 13-A1 shows the scheme for projecting useful and/or final energy demand used in MEDEE-2. The starting point is a scenario that defines an environment of population growth, economic development, and energy availability and prices envisaged for the future (see Chapters 14 and 15). These general scenario parameters must be disaggregated in terms of economic structure (GDP expenditure and formation and production of certain very energy-intensive basic industry products), demographic structure (labor force participation, urban-rural split, household size; type and size of dwellings and their energy-using equipment; travel distances, automobile ownership, preferences for certain modes of travel), and technological structure

Table 13-A1. Categories of energy end use considered in MEDEE-2. Energy sources are coal (CL); motor fuel—gasoline, diesel, jet fuel (MF); electricity (EL). F is a basic energy demand calculated in final energy forms; U is basic energy demand calculated in useful energy forms.

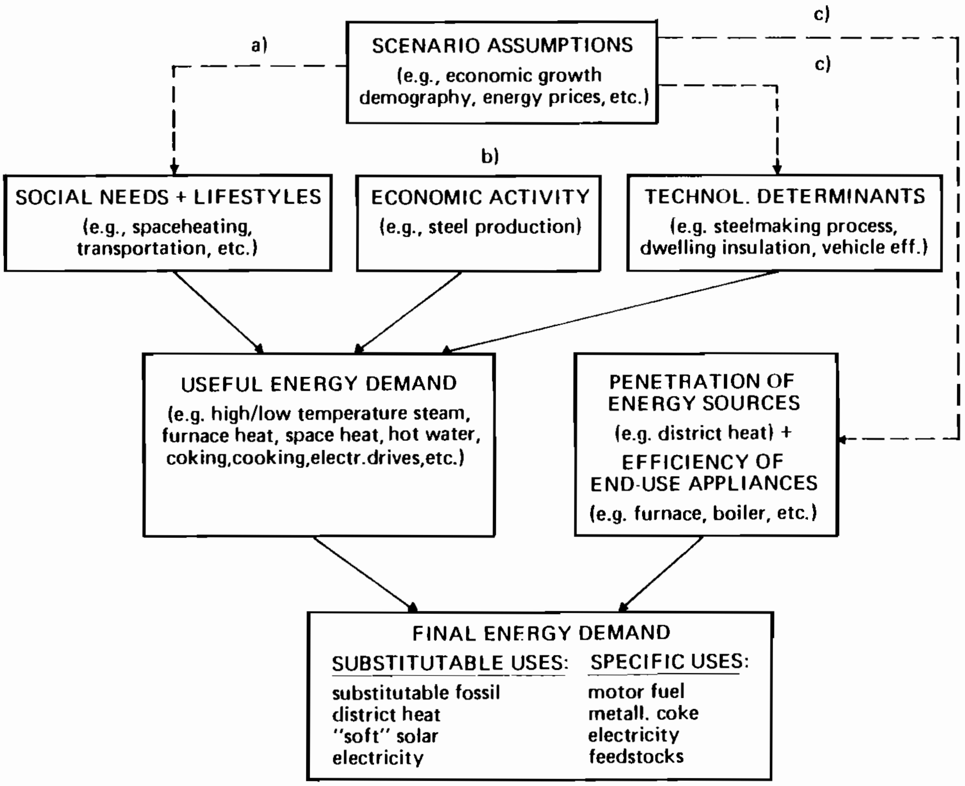
Transportation Module (F)	*Industry Module*		*Household/Service Module*
	Sectors	Processes	
Personal Transportation Urban: car (MF, EL) Urban: mass transit (MF, EL)	Agriculture Construction	Motor fuel use (F) Specific[a] electricity uses (F)	Household Space heating (U): pre-/post-1975 dwellings Space heating (U): multifamily/single family Space heating (U): central heating/other
Intercity: car (ME) Intercity: plane (MF) Intercity: bus (MF) Intercity: train (CL, MF, EL)	Mining Manufacturing Basic materials Machinery and equipment Food textiles, and other	Thermal uses (U) Steam generation Furnace operation Space and water heating	Water heating (U) Cooking (U) Cooling (U) Electrical appliances (F)
Freight Transportation Long distance: truck (MF) Long distance: train (CL, MF, EL) Long distance: barge (MF) Long distance: pipeline (MF)	Energy[b]	Coke for iron ore reduction Use of energy products as food stocks (F)	Service Thermal uses (U): pre-/post-1975 buildings Cooling (U) Electrical appliances (F)
Local truck (MF)			
Miscellaneous (MF) International freight and passenger; air and maritime; transport			

[a] By definition in the model all present uses of electricity are included here.

[b] The energy sector should be considered separately if statistics permit. Its energy consumption should be determined for conversion from primary to secondary energy.

Notes: Of course, the restriction of certain categories here to just one or two fuel types misses other possibilities. For instance, pipelines may use electricity rather than motor fuel; this is seriously considered and planned in the Soviet Union. But the simplifications of the kinds noted here should not materially affect the results.

Figure 13-A1. Schematic description of MEDEE-2.



Scenario Assumptions: a) socio-economic
b) macro-economic
c) technological

(energy intensiveness of industrial sectors, dwelling insulation, fuel economy of vehicles, and the like). Once this disaggregation is done, calculation of energy demand for each end use category is straightforward.

For certain thermal uses (space and water heating, steam generation, and so forth), energy demand is calculated in useful terms. Several energy sources (fossil fuels, electricity, district heat, solar systems, heat pumps) can be used to meet this demand. While the potential markets for each source are defined in the model, the user must specify the penetration of the various energy sources into their potential markets and their efficiency.

Transportation. Three types of transportation are distinguished in MEDEE-2—passenger, freight, and international and military transportation. Passenger transportation is broken down into an urban and an intercity category.

For international and military transportation (a category for which data are often difficult to find), only the use of liquid fuels is considered feasible. The motor fuel demand for this type of transportation is treated as a function of GDP.

The demand for domestic freight transportation (measured in net ton-kilometer) is calculated as a function of the GDP contribution by the agricultural, mining, manufacturing, and energy sectors. The modal split—that is, the allocation to the various modes (rail, truck, inland waterways or coastal shipping, pipeline)—must be specified exogenously, as well as the energy intensity (per ton-kilometer) of each mode. Except for rail, where electricity and coal can also be used as an energy source, only liquid fuels are assumed to be used.

Passenger transportation is treated in more detail, because it accounts in most countries for a major share of energy consumption.

Total demand for intercity passenger transportation (measured in passenger kilometers) is calculated in MEDEE-2 from data on population and average distance traveled per person per year. Automobile travel is calculated from data on population, automobile ownership, average distance traveled per automobile per year, and an average load factor (passenger kilometer per vehicle kilometer). The remainder is allocated to public transportation modes (rail, bus, airplane) according to exogenously specified shares. The corresponding vehicle kilometers are calculated from average load factors for each mode. The energy intensities (per vehicle kilometer) also have to be specified. As for transportation, only liquid fuels are assumed to be used, except for railways.

The demand for urban transportation is related to the population in large cities (those with more than 50,000 inhabitants) where mass transportation is feasible. From data on the average distance traveled per day per person in urban areas and on the total population in these areas, the demand for transportation is calculated and allocated to two modes—private automobile and mass transportation systems. Using average load factors, the passenger kilometers are converted to vehicle kilometers. Liquid fuels or electricity can be used as energy sources. The allocation has to be specified by separate parameters, as well as the energy intensity for each mode (per vehicle kilometer). All energy demand calculations for the transport sector are made only in terms of final energy.

Industry. All economic activities except those of the service sector are included under this label in MEDEE-2. Specifically, these are agriculture, construction, mining, three manufacturing subsectors, and energy (electricity, gas, water). The energy consumption of the energy sector (and other energy-related activities, if they can be isolated) is neglected, because the energy consumption of conversion activities is calculated at a later stage by the MESSAGE model. Three types of end use categories are considered—specific uses of electricity (for lighting, motive power, electrolysis, and so forth), thermal uses (space and water heating, low and high temperature steam generation, furnace operation), and motor fuel use (mainly for motive power in nonstationary uses such as in agriculture, construction, and mining).

Because it is in most cases impossible to obtain energy balances in this detail, all present uses of electricity in industry are considered "specific," and all fossil fuels, except motor fuel, are assumed to be consumed for thermal uses. This implies that electricity penetration into thermal uses must be interpreted as incremental penetration above the levels reached today. The activity level (value added) and the energy intensities (per unit value added) for each sector are required for the energy demand calculations. The energy intensities must be specified in terms of final energy for motor fuel and electricity and in terms of "electricity equivalent" for thermal uses. The breakdown of thermal uses (space and water heating, low and high temperature steam generation, furnace operation) is assumed to be constant. If the breakdown is not known for each subsector, an average split must be specified.

The change in energy intensities should reflect a change in the specific energy demand per unit of output due to changes of the product mix or to process integration and other operational improvements.

For thermal uses, the penetration of electricity, district heat, cogeneration, heat pump, and soft solar technologies must be estimated. The remaining energy demand is assumed to be met by fossil fuels and is converted to final energy demand using exogenously specified end use efficiencies for heating systems, boilers, and furnaces (these must be given relative to electricity). Electricity can penetrate into virtually all thermal uses; the potential market of the other alternatives is restricted to steam and low temperature uses.

The demand for coke and for petrochemical feedstocks is calculated separately in MEDEE-2, since they account for a major share of total industrial energy consumption. Coke demand is related to pig iron production, which in turn is related to steel production, and petrochemical feedstock demand is directly related to the value added of basic materials industries.

Household-Service Sectors. It is well known that in the presently developed countries space heating accounts for the major share of energy consumption in this sector and that with improved insulation this energy demand could be reduced considerably. Thus, buildings constructed after the world's awakening to the energy crisis in 1973 have or will have better insulation. To capture this difference, pre-1975 and post-1975 buildings are treated separately in MEDEE-2. In addition, three types of dwellings are considered—single family housing units with central heating, apartments with central heating, and dwellings with room heating only. This is done in order to capture the large difference in the average heat loss of these dwelling types.

The change in the housing stock of the residential sector is determined from data on average family size and population, on demolition of existing dwellings by type, and on construction of new dwellings by type. Allowance is made for the reduction of heat loss in old dwellings through retrofitting; the heat loss of post-1975 dwellings is calculated from data on the average size and the specific heat loss (in W/m^2) for each type of dwelling. Energy demand for water heating, cooking, air conditioning, and the electricity consumption of secondary appliances (such as washing machine, refrigerator, freezer, dish washer, clothes dryer, vacuum cleaner) is calculated from exogenously specified ownership fractions and/or average annual consumption rates.

The change in the building stock of the commercial-service sector is calculated from data on the average floor area per worker and labor force and on the demolition of existing floor area. Allowance is made for improving the insulation of old buildings. Besides thermal uses (space and water heating), two other end use categories are distinguished—namely, air conditioning and specific electricity uses, for which penetration and/or average consumption rates must be given.

The energy demand calculations for this sector are generally made in terms of "electricity equivalent." For air conditioning, electricity is considered the only energy source; this is also true for heat pumps. In all other instances, the penetration of alternative sources such as electricity, district heating, heat pumps, or soft solar technology must be estimated; the remaining energy demand is assumed to be met by fossil fuels and converted to final energy demand using exogenously specified end use efficiencies. The potential market for district heat is restricted to urban areas, and the potential market for solar is restricted to post-1975 single family housing units in the case of space heating. Penetration of solar technology for thermal uses in the commercial-service sector is also assumed to be feasible only in low rise buildings.

A complete description of MEDEE-2 is given in Lapillonne (1978).

Message

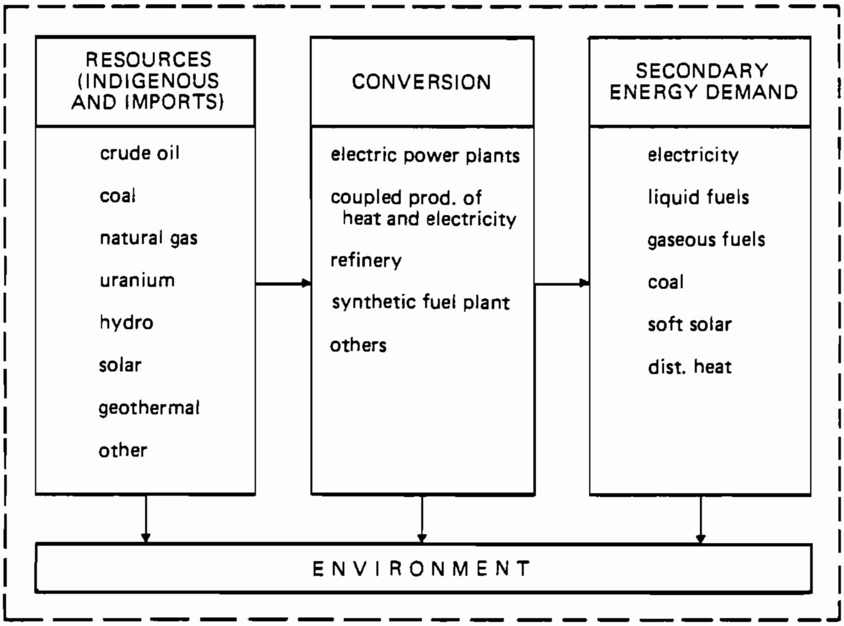
The fundamental features of the MESSAGE model are summarized in Figure 13-A2. A number of primary energy sources and their associated conversion technologies are considered. These include resources and technologies that could permit an essentially unlimited supply of energy—the fundamental point of the whole exercise being to explore possible transitions to energy systems states based on more or less unlimited resources such as ^{232}Th, ^{238}U, and solar energy.

Each primary energy source (except solar and hydroelectric power) is subdivided into an optional number of classes in MESSAGE, taking account of the cost of extraction, quality of resources, and location of deposit. These primary sources are then converted directly (e.g., by crude oil refining) or indirectly (e.g., electrolytic hydrogen) into secondary energy. Secondary energy is exogenous to MESSAGE and is provided by the MEDEE-2 model as time series data for electricity and for soft solar, solid, liquid, and gaseous fuels. The variables of the model are expressed in period averages of annual quantities.

The objective function is the sum of discounted costs for fuels (primary energy)—operating, maintenance, and capital costs for providing the energy demand over the planning horizon (1975-2030).

In the equations of the models—given roughly below—indexes are sometimes omitted if it seems to facilitate understanding.

Figure 13-A2. Schematic description of MESSAGE.



A comprehensive description of the MESSAGE model—its logic, mathematics, and scope—is available in Agnew, Schrattenholzer, and Voss (1979).

The Objective Function. The objective function of the MESSAGE model is the sum of discounted costs of capital, operating and maintenance, and fuels (primary energy):

$$\sum_{t=1}^{n} \beta(t)\; 5\{b^{\mathrm{T}} r(t) + c^{\mathrm{T}} x(t) + d^{T} y(t)\}$$

where

t is current index of time period,
n is number of time periods,
$\beta(t)$ is discount factor,
5 is number of years per period,
b is vector of energy resources costs,
r is vector of resource activities (linear programming variables),
c is vector of operating and maintenance costs,
x is vector of energy conversion activities (linear programming variables),
d is vector of capital (investment) costs, and
y is vector of capacity increments (linear programming variables).

The discount factor is calculated from an annual discount rate of 6 percent, applied to a constant dollar investment stream. As MESSAGE is intended to minimize societal costs, this discount rate is to be understood as a pretax one.[a]

The cost of increments to capacity still operating at the end of the planning horizon is corrected by a "terminal valuation factor," tv:

$$tv(t) = (1 - \beta^{5(n+1-t)})$$

for example, the terminal valuation factor for the last time period is

$$tv(n) = 1 - \beta^5$$

Resource Constraints. The following resource constraint is defined for each resource and for each category:

$$\sum_{t=1}^{n} 5r(t) \leqslant Av$$

where $r(t)$ is annual extraction in period t, and Av is availability of resource.

Resource Requirements. The following equation is specified for each time period and for each resource:

$$\sum_{j=1}^{J} r_j(t) \geqslant \sum_{1} v_1 x_1(t) + 5w_1 y_1(t) - 5w_1 y_1(t-6)$$

where

j is index of resource category,
J is number of resource categories,
v_1 is specific consumption by production activity x_1, and
w_1 is inventory requirement for capacity increment y_1.

Capacity Equations. The following equation is specified for each technology and for each load region supplied by this technology:

$$x_j \leqslant Cap \times h_j \times pf, \qquad \left(Cap(t) = \sum_{\tau=t-5}^{t} 5y(\tau)\right)$$

where

j is index of load region,
Cap is capacity,
h_j is load duration of load region j, and
pf is plant factor.

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[a] In these analyses, taxes are taken as part of the difference between prices and costs and so are not included in these cost minimization calculations. Because of this fact, the discount factor here may be thought of as a "social" discount factor, applied equally to all world regions.

Demand Constraint. The following equation is specified for each time period, for each demand sector, and for each load region:

$$\Sigma\, \eta_{ij} x_i \geqslant DM_j$$

where j is index of demand sector, η_{ij} is conversion efficiency (or equal to O if x_i does not supply demand sector j), and DM_j is annual secondary energy demand.

Buildup Constraints. The following equation is specified for some (primarily new) technologies and for each time period:

$$y(t) \leqslant \gamma y(t-1) + g$$

where γ is growth parameter, and g is constant, allowing for startup.

Emission Constraints.[b] The following equation is specified for each type of pollutant and for each time period:

$$b = \sum_i em_i x_i$$

where b is total emissions (LP variables), and em_i is specific emissions of technology i.

Pollutant Concentration Constraints.[b] The following is a nonbinding constraint that is defined for each time period and for those pollutants whose concentrations are to be calculated (e.g., krypton, carbon dioxide):

$$\sum_{\tau=1}^{t} 2^{5(\tau-t)/t2} \times b$$

where 5 is the number of years for each time period, and $t2$ is the half-life of pollutant.

Impact

Once an optimal energy strategy is identified, it is necessary to understand the requirements for corresponding direct and indirect energy investments. The first version of the IMPACT model was built at the Siberian Power Institute by Yuri Kononov and Victor Tkchachenko. At IIASA the model was developed further and adjusted to the purposes of identification and comparison of long-range regional strategies of the transition to new energy sources.

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[b] These constraints, although available, were not directly used in the MESSAGE runs reported in Chapter 17.

Modeling Techniques. IMPACT belongs to the set of energy-oriented dynamic input-output models, explicitly accounting for lags between the start of investment and the putting into operation of production capacities. It consists of linear and nonlinear equations that describe the following for each year of the period concerned—the balance of production of individual products and services and their consumption in operating and building the energy systems and related branches; the conditions for introducing extra capacities in energy-related branches; and investment and WELMM requirements.

Model Capability. For each given energy strategy, the model determines:

- Investment in energy system development;
- The required putting into operation of capacities in energy-related branches of industry and corresponding (indirect) capital investment;
- The required output of different types of materials, equipment, and services to provide operational and construction requirements of the energy system and related branches; and
- Direct and indirect WELMM requirements.

All these indicators are evaluated for each year of the period considered.

The model describes the building up of production capacities as a direct part of the energy supply system (ESS) and its related branches. In this way, lead times of construction and related consumption of equipment and material are taken into account. This is done by identifying input-output relations between the following sectors of the economy important for the energy supply systems:

iron ore mining
primary iron and steel manufacturing
fabricated metal products
nonferrous metal ore mining
nonferrous metals manufacturing
chemical products
plastic and synthetic materials
petroleum products
stone, clay, and glass products
lumber and wood products
miscellaneous materials
engines and turbines
electrical equipment
mining equipment
oil field equipment
construction equipment and machineries
material handling equipment
metalworking equipment
instrument and control equipment

transportation equipment
special industry equipment
general industry equipment
fabricated plate products
miscellaneous equipment
export goods I
export goods II
construction in energy sectors
construction (nonenergy)
transport (nonenergy)
maintenance and repair construction

The Equation System of Impact.[c] The direct requirements of the ESS for products of energy-related sectors are expressed as

$$Y_e(t) = A_1 \bar{X}_e(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_1^{(\tau-t)} \bar{Z}_e(\tau)$$

where

$Y_e(t)$ is the vector of direct investment and operational requirements of the ESS for products of energy-related sectors in the year t;
$\bar{X}_e(t)$ is the vector of annual energy production in the year t;
$\bar{Z}_e(t)$ is the vector of required additional capacities of the ESS in the year t;
A_1 is the matrix of contribution coefficients of energy-related sectors to the construction and operation of energy production per unit of activity;
$F_1^{(\tau-t)}$ is the matrix of contribution coefficients of energy-related sectors in the year t to putting into operation the additional capacities of the ESS in the year t $(t \leqslant \tau \leqslant t + \hat{\tau})$; and
$\hat{\tau}$ is the vector of the time lag introduced by construction times.

Total (direct and indirect) material and equipment requirements of the ESS are expressed as

$$X_1(t) = A_2 X_1(t) + A_3 X_2^{in}(t) + Y_e(t)$$

where

A_2 is the matrix of input-output coefficients;
A_3 is the matrix of materials and equipment requirements coefficients per unit of investment in energy-related sectors;
$X_1(t)$ is the vector of output in energy-related sectors; and
$X_2^{in}(t)$ is the vector of indirect capital investments in energy-related sectors.

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[c] Matrix notation is used throughout the section. The letters t or τ in parenthesis denote vector-valued time functions. A bar denotes an exogenously given input.

Direct capital investment in the ESS is expressed as

$$X_2^d(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_2^{(\tau-t)}\, \overline{Z}_e(\tau)$$

Indirect capital investment in the ESS is expressed as

$$X_2^{in}(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_3^{(\tau-t)}\, Z_1(\tau)$$

Total (direct and indirect) capital investment in the ESS is expressed as

$$X_2^{(t)} = X_2^d(t) + X_2^{in}(t)$$

where

$F_2^{(\tau-t)}$, $F_3^{(\tau-t)}$ are, respectively, the matrixes of capital investment coefficients in the year t to put into operation the additional capacities of the ESS and energy-related sectors in the year t;

$Z_1(t)$ is the vector of new additional capacities in the energy-related sectors in the year t; and

$X_2^d(t)$ is the vector of direct capital investment in the ESS.

Vector $Z_1(t)$, with vector components $Z_1^{(1)}, \ldots, Z_1^{(k)}$, must satisfy the following conditions[d]:

$$Z_1^{(i)}(t) = \begin{cases} \min\limits_{\tau \leqslant t} \, [X_1^{(i)}\,(t+1) - X_1^{(i)}(\tau)] \\ O \end{cases}$$

if this value is positive; otherwise for every $i \in \{1,2, \ldots, k\}$.

Vector notation is used in the model for simplicity reasons. This equation is therefore written as

$$Z_1(t) = max \left[\min\limits_{\tau \leqslant t} \left(X_1(t+1) - X_1(\tau) \right) ; O \right]$$

The structure of IMPACT is shown in Figure 13-A3.

The model also includes an equation for calculating the direct and the in-

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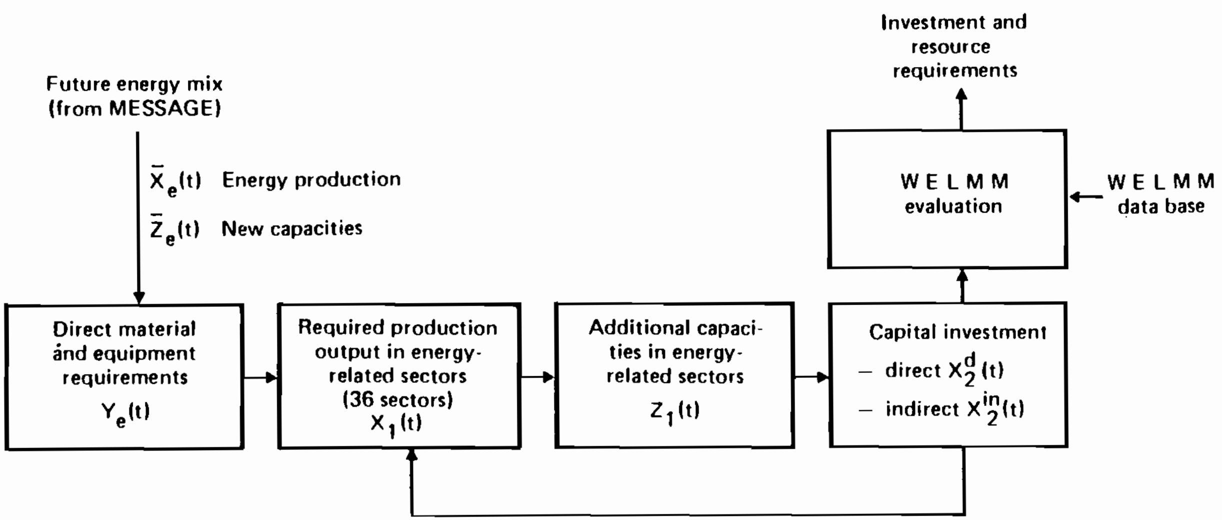
[d] In order to take into account installed capacity requirements, this expression can be replaced by

$$Z_1^{(i)}(t) = \begin{cases} \min\limits_{\tau \leqslant t} \left[X_1^{(i)}\,(t+1) - \dfrac{X_1^{(i)}(\tau)}{(1-p)^{t-\tau+1}} \right] \\ O \end{cases}$$

if this value is positive; otherwise for every $i \in \{1,2, \ldots, k\}$ where p is the rate of replacement.

Figure 13-A3. Schematic description of IMPACT.



$$Y_e(t) = A_1\bar{X}_e(t) + \sum_{\tau=t}^{t+\hat{\tau}} F_1^{(\tau-t)}\bar{Z}_e(\tau)$$

$$Z_1(t) = \max\left[\min_{\tau\leq t}\left(X_1(t+1) - X_1(\tau)\right); 0\right]$$

$$X_1(t) = A_2X_1(t) + A_3X_2^{in}(t) + Y_e(t)$$

$$X_2^d(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_2^{(\tau-t)}\bar{Z}_e(\tau)$$

$$X_2^{in}(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_3^{(\tau-t)}Z_1(\tau)$$

direct expenses of the WELMM resources. This equation is written as

$$X_3(t) = A_4\bar{X}_e(t) + A_5X_1(t) + A_6X_2^{in}(t) + \sum_{\tau=t}^{t+\hat{\tau}} F_4^{(\tau-t)}\,\bar{Z}_e(\tau)$$

where

$X_3(t)$ is the WELMM expenditures in the year t;
A_4 is the matrix of direct operational WELMM coefficients;
A_5 is the matrix of indirect operational WELMM coefficients of energy-related sectors;
A_6 is the matrix of indirect constructional WELMM coefficients of energy-related sectors; and
$F_4^{(\tau-t)}$ is the matrix of direct constructional WELMM coefficients in the year t to put into operation new energy capacities in the year t.

Equations for evaluating air and water pollutant emissions of the ESS and the energy-related sectors can be written analogically.

The drivers for IMPACT's relations are $\bar{X}_e(t)$ and $\bar{Z}_e(t)$; these exogenous variables can be obtained from an energy supply model (e.g., the IIASA MESSAGE model).

An algorithm has been developed for solving equations iteratively. This algorithm, as well as other details of IMPACT's structure, logic, and scope are described in Kononov and Por (1979).

The Gaming Model

The gaming model (GM), developed by Professor Makarov at the Siberian Power Institute, offers the capability to assess interregional oil trade—and oil balancing, within regions—in a systematic way. Its implementation at IIASA is still in an early stage.

The gaming model has been designed to allow an aggregate assessment of the long-term tendencies in world oil trade. By means of sophisticated data on liquid fuel demand and oil production by groups of countries (regions) over time, the model yields estimations of oil price dynamics and quantities of internationally traded oil.

The approach to world oil market modeling assumes that economic factors are primary ones in affecting conditions of long-term world energy development; social and political factors are treated as relatively more temporary. Thus, economic factors were chosen as the subject for modeling, while political and social factors can be introduced as exogenous controls.

In the gaming model, the process of trading in the world oil market is simulated as a game (developing in time) of some partners or groups of countries (regions). Each region is characterized by specific conditions of energy development–in particular, economic values of oil imports and exports–and objectives (interests) as a participant in world oil trading.

These characteristics, when incorporated, form regional submodels within the GM that allow the multiple optimization of regional oil supply systems during the process of simulation.

Regional results are coordinated with the special "compromise-searching" procedures of GM. These are based on three different assumptions about the world oil market–equilibrium (ideal competition among exporters and importers), dominance of exporters with full unity among members of their coalition (monopoly), and dominance of exporters with competition among members of their coalition (cartel).

In its dialog regime, GM allows variations in certain critical regional and interregional oil trade factors–for example, regional oil demand and supply elasticities, potentials and costs of regional oil production, exporters' and/or importers' oil trade quotas, and composition of coalitions of oil traders. In this way, one can simulate a broad spectrum of evolutionary paths for the world oil market.

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14 TWO SCENARIOS DEFINED

A scenario, as used here, is a logically consistent statement or characterization of a possible future state of the world. Often the scenario statement also specifies a logical sequence of events that could transform the reference or base year state into the postulated future state. The postulated future state can represent the consensus of many experts or be outrageously absurd, provided that it is internally consistent and follows from the assumptions made. A scenario, therefore, is not a prediction, but simply one of infinitely many future states that might happen.

Scenario development and analysis can serve many varied purposes. Depending on one's purpose, one can be interested in scenarios that are most unlikely to happen—as, for example, in contingency planning or developing emergency preparedness. In contrast, for the purpose here, scenarios are used to provide synthesis for conceptions and projections about a wide variety of global energy issues in the long term. This is above all a learning process; the scenarios are an aid to this process. As the primary goal of this quantitative analysis is to learn about the smooth evolution of energy demand and supply, discontinuities, abrupt changes, and radically changed lifestyles have been excluded from the scenario set.

The development of scenarios is necessarily subjective. Certain assumptions must be made that cannot be defended rigorously. Choosing what to make assumptions about is even more subjective. While acknowledging this subjective input to the scenario definitions of this chapter, we offer no apology; it is necessary in order to serve the purpose of synthesis and learning. It should also be understood that these projections do not necessarily represent either the most preferred future state of the world or the most probable. The two scenarios are internally consistent and span a range of economic and energy supply and demand futures. The real future could certainly be "higher" than the High scenario or "lower" than the Low scenario, but the range was selected such that the expected future value is more likely within the range than outside it.

In this chapter, the criteria for developing scenarios are described, followed by several general characteristics of the two scenarios used. The final section presents in detail the numerical projections of population and gross domestic product (GDP) for each of the seven world regions defined for the quantitative analysis within the IIASA Energy Systems Program.

The scenarios here can be seen as a pragmatic, detailed integration of the various specific studies discussed in the chapters of Parts II and III of this book. That is, while the latter studies attempt to explore the upper potentials for supply sources and the global bounds of various constraints, the scenarios aim to produce an integrated, "real world" picture of future energy prospects.

CRITERIA FOR DEVELOPING SCENARIOS

It was pointed out in the previous chapter that the development of scenarios is an iterative process. That is, make assumptions about basic input variables, then develop energy demand and supply estimations in detail, and analyze them in many different ways. When inconsistent or unreasonable implications are identified, make appropriate changes to basic input variables. As part of this process of analyzing implications and feeding back changes for another iteration, criteria must be used for judging whether changes should be made and what changes to make. Indeed, without being specific about the criteria for accepting a scenario, it is difficult to set values for variables to start the iterative process. Four guiding criteria are outlined below, and specific characteristics of the two scenarios defined are given in the following section.

The most important criterion for developing a scenario is consistency. Consistency was assured among the details through the use of detailed accounting systems and models. This procedure ensured that the supply of each fuel and energy type was consistent with the projected demand for energy of each fuel and type for each region. Consistency evaluations were made among and across regions with respect to energy availability and supply costs and utilization of globally traded energy commodities, with respect to energy use by economic sectors in various stages of development, and with respect to energy price response and conservation.

A second important criterion is that the scenario projections in their totality must not be unreasonable. Application of this criterion required judgment—judgment made collectively by accepting and soliciting comments and reactions from experts. This criterion of reasonableness is the subjective extension of the first criterion of consistency. Scenario projections were analyzed first for quantitative consistency; then the same characteristics and implications were further judged for reasonableness. For example, during an early iteration, one scenario was judged to be consistent in that each region had balanced supply and demand within the given allocation of interregional energy trade, but it was also judged unreasonable that one region had a much higher energy resource cost than another. A change to the interregional energy trade flow was made in later iterations. In another case, energy demand was reduced by lowering GDP projections and increasing conservation.

A third criterion is the degree of continuity or smoothness of the scenario projection. Not only are the values of key parameters and variables expected to be evolving smoothly during the projection period, they also must be connected to the past. The inertia of accumulated capital cannot be ignored. Again, a judgment was needed; it was never intended in these analyses that scenario projections be an extrapolation of historic data ("business as usual" scenarios), but that assumed changes to historic trends would develop in an orderly fashion.

The fourth criterion is the degree of variation between scenarios. An important determinant of the long-term transition in energy use away from petroleum is the level of energy use. At least two scenarios are required, and these must span a sufficiently wide range in order to incorporate the unavoidable uncertainties. Thus, iterations originally affecting only one scenario often resulted in related changes to the other scenario so as to preserve the necessary range between the two.

SCENARIO CHARACTERISTICS

There are two basic development variables that drive the long-term scenario projections—population growth and macroeconomic development (as measured by growth in GDP). In making population projections, one usually considers the many factors influencing both birth rates and death rates. Assumptions about these factors could be made, leading to a variety of population projections, by linking various scenario values (such as economic conditions or energy usage) to these factors. This was not done. Instead, a single, fixed projection of population was preferred—one that fell within the range of numerous recent population projections. This is not to deny the existence or the importance of economic and environmental factors on population. This approach was taken in part to reduce the complexity of analysis, but mainly to focus attention on the implications of the long-term energy transition.

In making projections of economic activity, a range of values was selected for examination. A range of economic growth estimates serves two primary purposes—first, it reflects the large uncertainties associated with making such projections and avoids having a single estimate projection mistaken for a prediction; second, it yields a range of energy use projections (this being a criterion for scenarios). This is not to say that energy use and economic activity must necessarily go hand in hand; in fact, this relationship is examined in Chapter 15.

Projections of GDP are considered to be within the loop of the iteration process (see Chapter 13). In some cases, especially for the developing economy regions, original values of GDP projections were reduced after examining the implications of the requirements for energy. Because of such adjustments during the iteration process, it is no longer precisely correct to characterize the GDP projections as inputs. Final values for the two basic development variables are given in the last section of this chapter.

In general, the scenario projections exhibit (assumed) ever-decreasing growth rates of population and economic growth through the time period up to 2030. This assumption is reinforced for energy consumption—especially for the developed economy regions—by assuming increasing improvements in the efficiency of energy use (Chapter 16).

It is assumed here that there will be no major changes in the sociopolitical environment or in lifestyles except those that accompany economic development.[a] For example, transportation would, in the scenarios, continue to be a primary factor in determining energy use even with major increases in efficiencies. No breakthroughs in the development of new energy-related technologies are assumed here, although coal liquefaction, advanced breeder reactors, and large-scale solar electric technologies are assumed to be commercially available (although not necessarily exploited) on a large scale around the turn of the century. No major cost changes for energy technologies are assumed (although it may be that these costs and the resource extraction costs used are optimistically low).

In the development of the energy supply scenarios (Chapter 17), no explicit constraints were imposed with respect to environmental problems, including the buildup of carbon dioxide in the atmosphere, or with respect to problems of risk. These issues are addressed in Chapters 10 and 11, respectively. The quantities of carbon dioxide that would be released from the burning of fossil fuel at the levels in the supply scenarios are reported in Chapter 17.

The two scenarios were selected to focus on the transition away from petroleum resources. Making very low or no growth projections of population, economic development, and energy use would not highlight the problems to be faced during this transition. Thus these two scenarios have moderate to moderately high projections of these basic variables. As well, by focusing on the transition, the analyses inevitably become oriented toward supply considerations. Indeed, it may be that the world will face a two-part

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[a] In some sense, the two scenarios defined in this chapter could be seen as two versions of one scenario, in that neither touches the possibility of wholly different states of the economic, social, and political world.

Table 14-1. Overview of basic scenario projections, aggregate global results.

	Base Year		*High Scenario*				*Low Scenario*		
	1975		*2000*		*2030*		*2000*		*2030*
Population (10^9)	4.0		6.1		8.0		6.1		8.0
(Growth rate (%/yr))		(1.7)		(0.9)		(1.7)		(0.9)	
GDP per capita ($1975)	1600		2800		5000		2200		2800
(Growth rate (%/yr))		(2.4)		(1.9)		(1.3)		(0.9)	
Primary energy per capita (kWyr/yr)	2.1		2.8		4.5		2.2		2.8
(Growth rate (%/yr))		(1.2)		(1.6)		(0.3)		(0.8)	

Notes: Rounded data.

All growth rates are average annual growth rates over each time interval. For energy unit conversion factors see Appendix B in Chapter 1. For population, see Table 14.2 for detailed projections. GDP is in constant (1975) U.S. dollars; see Table 14.5 for detailed projections. For primary energy per capita, electricity counted at fossil replacement basis, see Table 15.2 and Chapter 17 for detailed projections.

energy supply transition—first, away from cheap petroleum resources and, second, away from fossil fuels and toward more renewable energy sources.

Energy supply and demand for all fuels, for all regions, and for the globe must balance at each given time. Relying on conclusions of supply shortfalls resulting from other studies and realizing that energy supply costs must still increase, strong energy conservation trends were built into the scenario demand projections from the beginning. Energy prices and elasticities were not, however, assumed at the outset and thus were not used for projection purposes. Rather, energy prices were inferred from energy costs and then elasticities were calculated from detailed scenario projections. These results were then used in the iteration process and in many cases resulted in lower energy use projections based on even stronger conservation measures.

In summary, these scenarios can be characterized as having declining growth rates, increasing energy costs and prices and—as reactions to these increased prices—greatly improved energy use efficiencies and conservation. Table 14-1 gives an overview of detailed projections and results that are described later in this book.[b] As shown in this table, global population is projected to double by 2030 and average per capita GDP to increase by 3.2 and 1.8 times in the High and the Low scenarios, respectively, by 2030. In both scenarios, primary energy would increase from 2.1 kWyr/yr per capita in 1975 to 4.5 kWyr/yr per capita in the High scenario and to 2.8 kWyr/yr per capita in the Low scenario (on average) by 2030. This means that (commercial) global primary energy use would increase from 8.2 TWyr/yr in 1975 to approximately 36 TWyr/yr in the High scenario and to 22 TWyr/yr in the Low scenario by 2030.

[b] Energy units and conversion factors for the scenario projections are given in Appendix 1B.

SCENARIO PROJECTIONS: POPULATION AND GDP

As noted earlier, these analyses use a disaggregated, seven region world. These regions were selected as a minimal disaggregation, accounting for differences and similarities with respect to geography, economic system and energy use, and resources. It is desirable to limit the number of separate regions in order to minimize the burden of calculations, but also to separate developed and developing economies, market and centrally planned economies, and regions with large and small resources. The seven world regions are defined in Figure 1-3; the countries in each of these regions are listed in Appendix 1A. Both the roman numeral designators (I through VII) and the abbreviated letter designators are used throughout the chapters of this part.

Population

World population has already passed four billion. At current growth rates, the population would double in thirty-five years. No present-day demographer, however, would project world population for the next thirty-five or fifty years with today's growth rate.

Examination of world population over the past 225 years shows that growth rates have varied considerably. The growth rate for the world as a whole increased from four persons per thousand per year (0.4 percent per year) in 1750 to nineteen persons per thousand per year in 1975. Yet these world average growth rates do not indicate the large changes that have taken place separately in the developed and the developing countries. The presently developed countries experienced a rapid increase in growth rate up to the middle of the nineteenth century (from four to ten persons per thousand per year) and a gradual leveling off. The presently developing countries had very low and decreasing growth rates in the previous century but have recently shown very high growth rates (twenty-two per thousand per year) (see Chant 1980).

The population projections used here (Keyfitz 1977) assume the achievement of a bare replacement level of fertility in developing regions by 2015. Projections based on achieving this level earlier would be lower. The population projections for the seven world regions are presented in Table 14-2. Examination of the growth rates of these projections shows a gradual decrease globally from the current peak of 2 percent per year to less than 1 percent per year by 2030. As shown in Table 14-3, the growth rates for the developing regions (IV-LA, V-Af/SEA, and VI-ME/NAf), however, are more than three times the growth rates of the developed regions (I-NA, II-SU/EE, and III-WE/JANZ); region VII (C/CPA) is close to the world average.

Three observations are worth noting with respect to these population projections. First, the world is in a transition during which global population will double in the next fifty years; after 2030, global population will likely stabilize with only a further 13 percent increase. Figure 14-1 puts the cur-

Table 14-2. Population projections by region, High and Low scenarios (10^6 people).

Region	Population		
	Base Year	Projection	
	1975	2000	2030
I (NA)	237	284	315
II (SU/EE)	363	436	480
III (WE/JANZ)	560	680	767
IV (LA)	319	575	797
V (Af/SEA)	1422	2528	3550
VI (ME/NAf)	133	247	353
VII (C/CPA)	912	1330	1714
World	3946	6080	7976

Notes: 1975 data are midyear estimates from United Nations *Monthly Bulletin of Statistics*, January 1978.

Source: Keyfitz (1977).

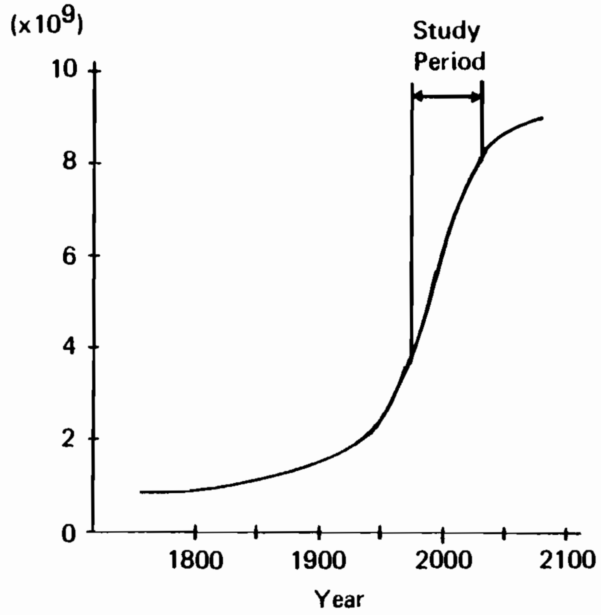
rent population growth rate and the assumed future decline in growth rate in perspective with historical data.

The second observation is that as a stable population is approached, a striking change occurs in the age structure. The fraction of population over age sixty-five increases substantially, as can be seen by examining the ratio of population between the ages of fifteen and sixty-four to the population age sixty-five and over. In simple terms, this ratio indicates the number of people who must produce, in an economic sense, not only for themselves and for their children but also for one additional adult who has retired from economic production. In region I (NA), this ratio would drop from 6.3 in 1975 to 4 in 2030. Regions II (SU/EE) and III (WE/JANZ) exhibit a similar pattern. In region IV (LA), typical of the developing regions, the rate would drop from over 14 in 1975 to about 9 in 2030. These declining ratios would tend to limit the potential for average per capita economic growth in the next fifty years.

Table 14-3. Population growth rates, High and Low scenarios (%/yr).

Region		Average Annual Growth Rate			
	1950–1975	1975–1985	1985–2000	2000–2015	2015–2030
I (NA) + II (SU/EE) + III (WE/JANZ)	1.2	0.8	0.7	0.4	0.3
IV (LA) + V (Af/SEA) + VI (ME/NAf)	2.4	2.8	2.1	1.3	1.0
VII (C/CPA)	1.7	1.9	1.3	1.0	0.7
World	1.9	2.0	1.6	1.1	0.8

Figure 14-1. World population, historical and projected. Source: Keyfitz (1977).



The third observation of these population projections has vital importance for projecting energy use—increasing urbanization, particularly in the developing regions. High power densities are required in cities; this carries large multiplications for both energy supply and concentrated environmental pollution. In region IV (LA), for example, the relative population in cities of greater than 100,000 people would increase from 37 percent in 1975 to 69 percent in 2030; and in region V (Af/SEA) from 13 percent in 1975 to 44 percent in 2030. These projected trends are examined further in Chapter 15.

Economic Growth

Global economic production exceeded 6 trillion (10^{12}) U.S. dollars in 1975. Many caveats and explanatory notes must be added to this statement before it can be properly interpreted. It is, however, one measure of the "size" of the global economic system.

The explanatory notes include the following: 1975 U.S. dollars and 1975 official exchange rates and prices (except for centrally planned economies[c])

[c] For the centrally planned economies the estimates of GDP given by the World Bank (1977) in the *World Bank Atlas* were used. These estimates are based on a comparison of physical indicators of economic product among centrally planned and market economies for 1965. (This comparison was done by the U.N. Economic Commission for Europe.) The data for real growth for both centrally planned and market economies were used to estimate the GDP of centrally planned economies for 1975.

are used throughout these analyses, and GDP is measured first by country and is then aggregated to the seven regions and finally to the globe. The caveats include the obvious ones involved whenever GDP estimates of different countries are compared or aggregated into regions: economic structures differ considerably from country to country (especially from developing to developed economies), and so GDP estimates are not really comparable, and official monetary exchange rates do not necessarily reflect "real" equivalences.

The aggregate GDP measure of economic activity is not sufficient for measuring the welfare of a country or region. It is not even sufficient for projecting energy use, as will be seen in Chapter 16. It is, however, the single most important aggregate measure of economic activity and, to that extent, it provides a useful yardstick for broad comparisons and for scenario definition.

For making initial projections of GDP, the projections and results of other similar recent studies, including those of WAES (1977) and WEC (1978), proved invaluable. The projections here differ from those of WAES and WEC in having lower economic growth and consequently lower energy demand—so that energy supply and demand could balance at a more "reasonable" energy supply situation. The main criterion used in extending the projections to the year 2030 and for developing the two scenarios in greater detail was the constant checking for internal consistency and consistency among world regions. Even though the application of this and other criteria for selecting scenario variables involved mostly the exercise of judgment, the procedure was very useful for eliminating potential scenario values that superficially appeared reasonable. Consistency within a scenario at any level of detail, however, is clearly only a necessary, and not a sufficient, condition for reasonableness.

As part of the exercise of setting economic projections, therefore, there were several iterations of making assumptions, analyzing implications, checking for consistency, and refining assumptions. The projections here are the result of this process.

The two scenario projections for the growth rate of regional GDP are given in Table 14-4. The general trend in the projections, which is exhibited in all regions, is the ever-decreasing growth rates in later and later periods. Many factors are likely to contribute to this trend, including a host of social and institutional ones, but the two most important factors are decreases in population growth rates and the increasing scarcity of basic resources. Decreases in population growth rates in these projections have already been discussed; the growth rates of GDP per capita (Table 14-5) also exhibit the general trend of decreasing growth rates in the projections. This decline in per capita growth rates is attributed mainly to the depletion of resources and the concomitant increase in real cost of these resources. In the IIASA energy study, this factor is most evident with respect to energy resources, but other basic resources will most likely follow a similar pattern.

The economic growth rates assumed here do not, surely, reflect the desires for development in each region. The Low scenario, in particular, may be unacceptably low in many regions. The point here is not to predict the most likely rates, but to test a plausible range and to evaluate the implications.

ECONOMIC GROWTH PROJECTIONS: OTHER STUDIES

For reference purposes, it may be helpful to compare the growth rate projections of the IIASA Energy Systems Program with those of other published studies. The WAES (1977) economic growth projections, as shown below, are somewhat higher for regions I and III, but their analysis indicated that with these rates there would be a gap between oil demand and supply.

The Leontief United Nations study presented two economic growth scenarios: one based on the so-called New International Economic Order growth targets; and one in which economic growth rates were determined by constraints on available labor, investment potential, and balance-of-payments. The New Economic Order (NEO) scenario calls for much higher economic growth rates in the developing regions while maintaining a relatively high growth rate in the developed regions.

WAES (1977) Economic Growth Projections (%/yr)

Region	*Case C 1976–1985*	*Cases C-1,2 1985–2000*	*Case D 1976–1985*	*Cases D-7,8 1985–2000*
North America (region I)	4.3	3.7	3.0	2.6
Western Europe, Japan, Australia, New Zealand, South Africa (region III)	5.4	3.5	3.2	2.4
Developing countries (regions IV (LA) + V (Af/SEA) + VI (NE/NAf)	6.4	5.1	4.4	3.8

UN Economic Growth Projections (Leontief et al., 1977), 1977–2000 (%/yr)

			IIASA 1975–2000	
Region	*NEO*[a]	*OEO*[b]	*High Scenario*	*Low Scenario*
Developed countries (regions I (NA), II (SU/EE), and III (WE/JANZ)	3.6	3.9	3.9	2.8
Developing countries (regions IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA)	6.9	5.4	5.3	4.0
World	4.5	4.2	4.2	3.1

[a] New Economic Order Scenario C (low population growth which is closest to our population projection).

[b] Old Economic Order Scenario A.

Table 14-4. Historical and projected growth rates of GDP, by region, High and Low scenarios (%/yr)

	Historical		*Scenario Projection*			
Region	*1950–1960*	*1960–1975*	*1975–1985*	*1985–2000*	*2000–2015*	*2015–2030*
A. High Scenario						
I (NA)	3.3	3.4	4.3	3.3	2.4	2.0
II (SU/EE)	10.4	6.5	5.0	4.0	3.5	3.5
III (WE/JANZ)	5.0	5.2	4.3	3.4	2.5	2.0
IV (LA)	5.0	6.1	6.2	4.9	3.7	3.3
V (Af/SEA)	3.9	5.5	5.8	4.8	3.8	3.4
VI (ME/NAf)	7.0	9.8	7.2	5.9	4.2	3.8
VII (C/CPA)	8.0	6.1	5.0	4.0	3.5	3.0
World	5.0	5.0	4.7	3.8	3.0	2.7
I + III[a]	4.2	4.4	4.3	3.4	2.5	2.0
IV + V + VI[a]	4.7	6.5	6.3	5.1	3.9	3.5
B. Low Scenario						
I (NA)	3.3	3.4	3.1	2.0	1.1	1.0
II (SU/EE)	10.4	6.5	4.5	3.5	2.5	2.0
III (WE/JANZ)	5.0	5.2	3.2	2.1	1.5	1.2
IV (LA)	5.0	6.1	4.7	3.6	3.0	3.0
V (Af/SEA)	3.9	5.5	4.8	3.6	2.8	2.4
VI (ME/NAf)	7.0	9.8	5.6	4.6	2.7	2.1
VII (C/CPA)	8.0	6.1	3.3	3.0	2.5	2.0
World	5.0	5.0	3.6	2.7	1.9	1.7
I + III[a]	4.2	4.4	3.1	2.1	1.3	1.1
IV + V + VI[a]	4.7	6.5	5.0	3.8	2.9	2.6

[a] Presented for purposes of comparison with data of WAES (1977) and of other global studies that exclude centrally planned economies.

Note: Historical and projected values of GDP in constant (1975) U.S. dollars are given in Chant (1980).

The interregional trade implications of these regional economic projections were not examined. The assumption was made, however, of a continuing dependency of the developing regions on trade with the developed regions as a major stimulant for growth. Because of this, the developing economies would be limited in their growth potential (by assumption) to one or two percentage points greater than the growth rates of the developed economies. This interregional linkage[d] of economic growth rates is not universal and may prove unfounded for a fifty-five-year projection period; but the projections are based on this assumption. Some countries, notably those of the

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[d] This assumption has been used in some World Bank studies, in particular in a contribution to the WAES (1977) study. See also Hicks et al. (1976).

Table 14-5. 1975 per capita GDP, historical and projected real growth rates for two scenarios to 2030.

Region	*Historical Growth Rate of per Capita GDP (%/yr) 1950–1975*	*GDP per Capita (dollars) 1975*	*Projected Growth Rate of per Capita GDP (%/yr)*			
			High scenario		*Low scenario*	
			1975–2000	*2000–2030*	*1975–2000*	*2000–2030*
I (NA)	1.9	7046	2.9	1.8	1.7	0.7
II (SU/EE)	6.7	2562	3.6	3.2	3.1	1.9
III (WE/JANZ)	4.0	4259	3.0	1.8	1.7	0.9
IV (LA)	2.9	1066	3.0	2.4	1.6	1.9
V (Af/SEA)	2.5	239	2.8	2.4	1.7	1.4
VI (ME/NAf)	5.7	1429	3.8	2.8	2.4	1.2
VII (C/CPA)	5.1	352	2.8	2.4	1.6	1.4
World[a]	3.1	1565	2.4	1.9	1.3	0.9

[a] These global per capita growth rates may appear inconsistent with the values for the regions, but they are correct. Growth rates of aggregate ratios (e.g., GDP per capita) need not always be within the range of their component parts when both numerator and denominator grow at different rates.

Note: All growth rates are average annual growth rates (rounded) over the time period shown; actual projections have decreasing growth rates. See Chant (1980).

Middle East in region VI, are assumed to be limited not by this linkage but by their capability to absorb the favorable trade balance due to oil exports.

The GDP aggregate measure of economic activity gives no hint of the evolving structure of the underlying economy. A dollar of GDP in 2030 is different from a dollar of GDP in 1975 in many different ways—for example, in the High scenario it is composed of approximately one-half as much agriculture. This is true for all regions: the share of agriculture drops from 6 to 3 percent in region III (WE/JANZ), from 12 to 5 percent in region IV (LA), and from 36 to 16 percent in region V (Af/SEA). The same trend is exhibited in the Low scenario, but to a lesser extent (see Chant 1980).

An important difference between developed regions I, II, and III and developing regions IV and V is evident in the industry share of GDP. Although the relative shares for the two types of regions are currently all between 26 and 50 percent, industry's share in the developed regions is projected to decrease (from 32 to 29 percent for region I, from 50 to 41 percent for region II, and from 46 to 39 percent for region III in the High scenario); for the developing regions it is projected to increase from 36 to 47 percent for region IV and from 26 to 38 percent for region V in the High scenario. The service sector shares in the developed regions increase as the economies evolve into the postindustrial phase, while for the developing regions this share is relatively constant over the study period. Region VI (ME/NAf) is something of a special case in this regard because of the large role played by the petroleum sector. In this region, the industry sector is projected to decrease from a share of 66 percent (currently) to 47 percent in the High scenario and to 54 percent in the Low scenario. (Detailed projections were not made for region VII-C/CPA.)

The fact that economic activity is changing with time is evident from these changing sectoral shares. There are also tremendous changes within these sectors over this long time period.

These population and GDP projections are the basic development variables in the two scenarios. Based on these, detailed projections of energy demand were made (Chapter 16), and corresponding energy supply scenarios were developed (Chapter 17). Before proceeding to these detailed energy projections, the next chapter presents these energy results in summary form and analyzes the relationships among population, economic development, and energy use in an aggregate way.

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15 INTERPRETATION OF SCENARIO PROJECTIONS*

Energy serves two distinct purposes. First, energy is an input to (or factor of) production; it drives machines and produces heat in industries. Second, energy is consumed as an end product; it provides comfort and mobility for people. That is, the economy requires energy as an input, and the economy provides income that allows people to consume energy as a product. As the economy expands, the consumption of energy expands. Or does it necessarily? This question is examined in this chapter.

In the past, energy use and economic activity have gone hand in hand. This fact was used for making numerous business as usual projections of energy demands.[a] But energy prices are changing, and that makes a difference. Faced with higher energy prices, industry looks at options that use less energy. With higher prices, the householder thinks again about how he or she spends income. And the relationships between energy use and economic activity change.

This chapter describes the relationships among energy use, population, economic activities, and energy prices, examining them in an aggregate way for the data of the recent past and for the projections. This examination was

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*The analyses reported in this chapter are described in full, and the data are presented in more detail, in Chant (1980).

[a] The terms "energy demand," "energy use," and "energy consumption" are used interchangeably in this chapter; in economics, demand has a broader interpretation.

performed essentially after the fact of detailed scenario development. But since these analyses were also done during the iteration process of the scenario development, modifications to the projections were made, based on this kind of interpretation. Thus, the data presented in this chapter are basically results—but since similar results calculated during the iteration process have influenced the projections, the data are also in a very limited sense inputs.

The purpose of presenting the aggregate analysis at this point is twofold: first, to introduce the scenario results by means of a few essential variables; and second, to interpret the detailed scenario projections (presented in Chapters 16 and 17) in a simple and traditional way so as to highlight the differences and similarities between the projections and history and between the projections of this study and other similar projections.

The detailed scenario projections of energy supply and demand are presented in Chapters 16 and 17 and are summarized here in the next section. With these projections of energy use and the projections of population growth and gross domestic product (GDP) growth from the previous chapter, one has the data base for examining the relationships among energy use, population, and energy densities that are presented in the second section of this chapter. The relationships between energy use and economic activity in the aggregate are presented in the third section. The fourth section is concerned with energy as an input to production in the industry sector and examines the possible substitution between energy and nonenergy inputs (capital and labor).

ENERGY USE IN THE TWO SCENARIOS

The population and GDP growth projections presented in the preceding chapter were used as driving variables for determining energy demand. Chapter 16 explains how energy requirements in terms of useful energy (e.g., a heated room) and of final energy (e.g., furnace oil in the basement) were linked to these driving variables. These requirements for final energy were translated into secondary energy[b] (e.g., furnace oil at the refinery) and given as demands to an energy supply optimization model (as described in detail in Chapter 17) that provided detailed requirements for primary energy (e.g., crude oil). After several iterations of this process, two scenarios were selected.

Final energy projections for the years 2000 and 2030 are summarized in Table 15-1 (A), presented along with values for the base year (1975) and for 1950. As shown in the table, the projections for the world indicate a four-

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[b] Only so-called commercial final and secondary energy requirements are analyzed by the supply model. For developing regions (IV, V, VI, and VII), and to a limited extent in region II (SU/EE), part of the useful energy demand is met by noncommercial energy sources such as wood and animal and agricultural wastes. Noncommercial energy was accounted for in the determination of energy requirements as described in Chapter 16.

Table 15-1. Summary of scenario energy projections, final energy.

A. Final Energy for 1950 and 1975 and Projections to 2030 (TWyr/yr)

	Historical		*High Scenario*		*Low Scenario*	
Region	*1950*	*1975*	*2000*	*2030*	*2000*	*2030*
I (NA)	0.96	1.87	2.63	3.67	2.26	2.64
II (SU/EE)	0.36	1.28	2.39	4.11	2.17	2.95
III (WE/JANZ)	0.55	1.59	3.04	4.38	2.39	2.99
IV (LA)	0.05	0.26	1.01	2.64	0.73	1.66
V (Af/SEA)	0.05	0.25	1.06	3.17	0.80	1.88
VI (ME/NAf)	0.01	0.11	0.58	1.64	0.43	0.87
VII (C/CPA)	0.03	0.39	1.23	3.20	0.85	1.59
World	2.01	5.74	11.93	22.80	9.64	14.56

B. Final Energy Growth Rates for 1950-1975 and Projections to 2030 (%/yr)

	Historical	*High Scenario*		*Low Scenario*	
Region	*1950–1975*	*1975–2000*	*2000–2030*	*1975–2000*	*2000–2030*
I (NA)	2.7	1.4	1.1	0.8	0.5
II (SU/EE)	5.2	2.5	1.8	2.2	1.0
III (WE/JANZ)	4.3	2.6	1.2	1.7	0.7
IV (LA)	6.8	5.6	3.3	4.3	2.8
V (Af/SEA)	6.7	5.9	3.7	4.7	2.9
VI (ME/NAf)	10.4	7.0	3.5	5.8	2.3
VII (C/CPA)	10.8	4.7	3.2	3.1	2.1
World	4.3	3.0	2.2	2.1	1.4

Notes: These data for final energy include nonenergy feedstocks but exclude noncommercial energy such as wood, agriculture and animal waste. See Appendix 1B for the definition and conversion of energy units. Estimates of historical final energy are taken from Chant (1980). Data and world totals are rounded; totals may appear to not add exactly. Growth rates were calculated using nonrounded data and then rounded to one decimal place; these rates may therefore appear to not apply exactly in part A of the table.

fold increase over the 1975 value in the High scenario and a 2.5 increase for the Low scenario. These increases over the fifty-five-year projection period appear modest compared with the 2.85 increase of 1975 over 1950. These relative increases are shown more clearly in Table 15-1 where average annual growth rates are presented. The declining growth rates over time are clearly shown here for the world and for each of the world regions, especially for regions I (NA) and III (WE/JANZ).[c] The corresponding data for primary energy are given in Table 15-2 and are examined in more detail in the following sections.

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[c] See Figure 1-3 for the definition of the IIASA world regions and Appendix 1A for the list of the countries in each region.

Table 15-2. Summary of scenario energy projections, primary energy.

A. Primary Energy for 1950 and 1975 and Projections to 2030 (TWyr/yr)

	Historical		*High Scenario*		*Low Scenario*	
Region	*1950*	*1975*	*2000*	*2030*	*2000*	*2030*
I (NA)	1.14	2.65	3.89	6.02	3.31	4.37
II (SU/EE)	0.42	1.84	3.69	7.33	3.31	5.00
III (WE/JANZ)	0.67	2.26	4.29	7.14	3.39	4.54
IV (LA)	0.06	0.34	1.34	3.68	0.97	2.31
V (Af/SEA)	0.06	0.33	1.43	4.65	1.07	2.66
VI (ME/NAf)	0.01	0.13	0.77	2.38	0.56	1.23
VII (C/CPA)	0.03	0.46	1.44	4.46	0.98	2.29
World	2.39	8.21[a]	16.8	35.7	13.6	22.4

B. Primary Energy Growth Rates for 1950–1975 and Projections to 2030 (%/yr)

	Historical	*High Scenario*		*Low Scenario*	
Region	*1950–1975*	*1975–2000*	*2000–2030*	*1975–2000*	*2000–2030*
I (NA)	3.4	1.5	1.5	0.9	0.9
II (SU/EE)	6.1	2.8	2.3	2.4	1.4
III (WE/JANZ)	5.0	2.6	1.7	1.6	1.0
IV (LA)	7.1	5.7	3.4	4.3	2.9
V (Af/SEA)	7.1	6.1	4.0	4.8	3.1
VI (ME/NAf)	10.7	7.5	3.9	6.2	2.6
VII (C/CPA)	11.1	4.7	3.8	3.1	2.9
World	5.1	2.9	2.5	2.0	1.7

[a] Primary energy for the world for 1975 includes 0.21 TWyr for bunkers.

Note: See notes to Table 15-1.

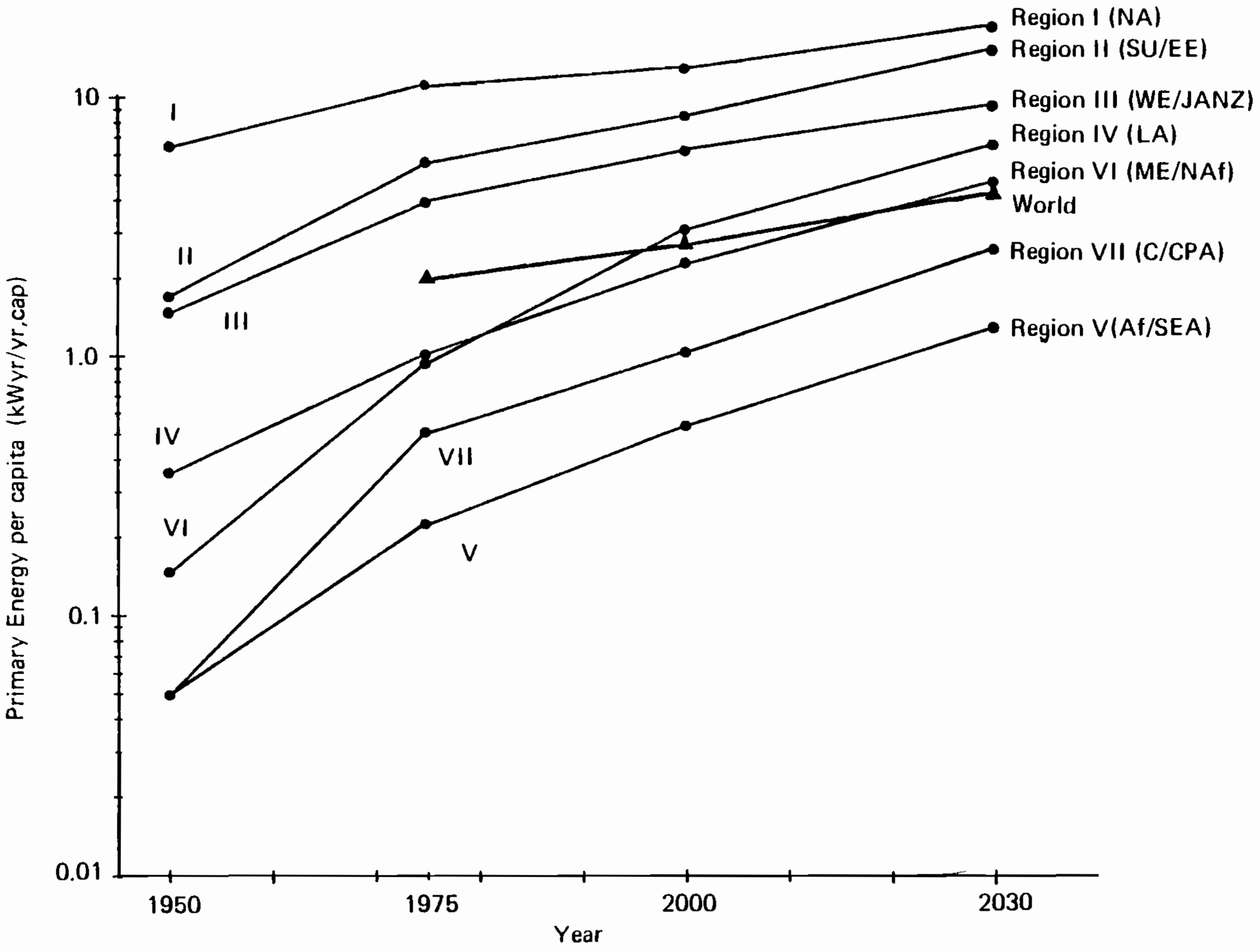
ENERGY USE, POPULATION, AND DENSITIES

Energy Use Per Capita

As noted above, the world was using (commercial) primary energy at the rate of 8.2 TWyr/yr in 1975. For a global population of four billion, this is an average annual rate of 2.1 kWyr/yr per capita. As shown in Figure 16-1, however, the distribution of per capita energy use worldwide is very skewed. Even at the aggregate level of seven regions, the 1975 per capita energy use varies from about 0.2 to 11.2 kWyr/yr per capita.

This distribution changes significantly in the scenario projections to 2030 as illustrated in Figure 15-1. For the High scenario projections, the figure shows the increase in primary energy per capita for each of the seven regions and for the world. On an aggregate regional comparison basis, these per capita figures change from a ratio of almost fifty (region I (NA) relative to

Figure 15-1. Primary energy per capita by region, 1950–2030, High scenario.



region V (Af/SEA)) in 1975 to fifteen in 2030; the ratio is about nineteen in 2030 in the Low scenario. These changes, although modest, come about only with substantial economic cost, as will be seen later in this chapter and in Chapter 19.

The changes in final (commercial) energy use per capita are shown in Table 15-3 for the historical period 1950-1975 and for the projection period for both scenarios. The data indicate very low projected increases in energy use in the developed regions (I, II, and III) and especially in region I (NA) for the Low scenario.

Energy Densities in Two Scenarios

It is interesting to observe the implications of the scenario projections in terms of energy use per unit area on average and in urban areas. The data reported here for 2030 are simply results from the scenario projections; they were not used as inputs or constraints for developing the scenarios.

Estimates of the inhabitable land area and population densities are given in Table 15-4 for each of the seven world regions. The high population density in region VII (C/CPA) stands out especially when compared with the 1975 average urban density for developed regions of approximately 1000 persons/m^2.

This table also shows the average energy use densities for 1975 and for the High scenario projection for 2030. It is expected that the disparity between the energy consumption densities in the developed (I, II, and III) and the developing (IV, V, and VI) regions—a factor of nine difference in 1975—

Table 15-3. Final energy per capita 1975 and growth rates, historical and two scenarios to 2030.

			Growth Rates of Final Energy per Capita (%/yr)			
			High scenario		*Low scenario*	
Region	*Growth Rate (%/yr) 1950–1975*	*Final Energy per Capita (kWyr/yr, cap) 1975*	*1975–2000*	*2000–2030*	*1975–2000*	*2000–2030*
I (NA)	1.3	7.89	0.6	0.8	0.03	0.2
II (SU/EE)	3.9	3.52	1.8	1.5	1.4	0.7
III (WE/JANZ)	3.3	2.84	1.8	0.8	0.8	0.3
IV (LA)	4.0	0.80	3.2	2.2	1.9	1.6
V (Af/SEA)	4.3	0.18	3.5	2.6	2.3	1.7
VI (ME/NAf)	7.4	0.80	4.4	2.3	3.2	1.1
VII (C/CPA)	9.0	0.43	3.1	2.3	1.6	1.3
World	2.4	1.46	1.2	1.2	0.3	0.5

Notes: Total final energy includes nonenergy feedstocks but excludes noncommercial sources of energy (e.g., wood, animal waste). These global per capita growth rates are correct although they may appear inconsistent with the values for the regions. Growth rates of aggregate ratios (e.g., GDP per capita) need not always be within the range of their component parts when both numerator and denominator grow at different rates.

Table 15-4. Land areas, population, and energy densities in world regions.

Region	Inhabitable Land ($10^6 km^2$)	Population Density (cap/km^2)		Energy Density (W/m^2)	
		1975	2030	1975	2030
I (NA)	12.5	19	25	0.21	0.48
II (SU/EE)	15.5	23	31	0.12	0.47
III (WE/JANZ)	9.5	59	81	0.24	0.75
IV (LA)	14.8	22	54	0.02	0.25
V (Af/SEA) VI (ME/NAf)	24.7	63	158	0.02	0.28
VII (C/CPA)	2.7	246	463	0.12	1.20
World	80.3	49	99	0.10	0.44

Notes: Inhabitable land excludes polar regions, deserts, high mountain areas, and most semiarid grass lands and low productivity forests in extreme climates. Energy density figures for 2030 are for the High scenario.

would be narrowed significantly (to a factor of two for both scenarios) if the developing regions increase dramatically their energy use. Note that region VII would have the highest energy consumption density, while still having 2.6 kWyr/yr per capita, a factor of seven less than that of region I (NA). Even the global average energy consumption density of 0.44 W/m^2 by 2030 appears high when compared with the global average forest production of wood at 0.2 W/m^2 (see Chapter 6).

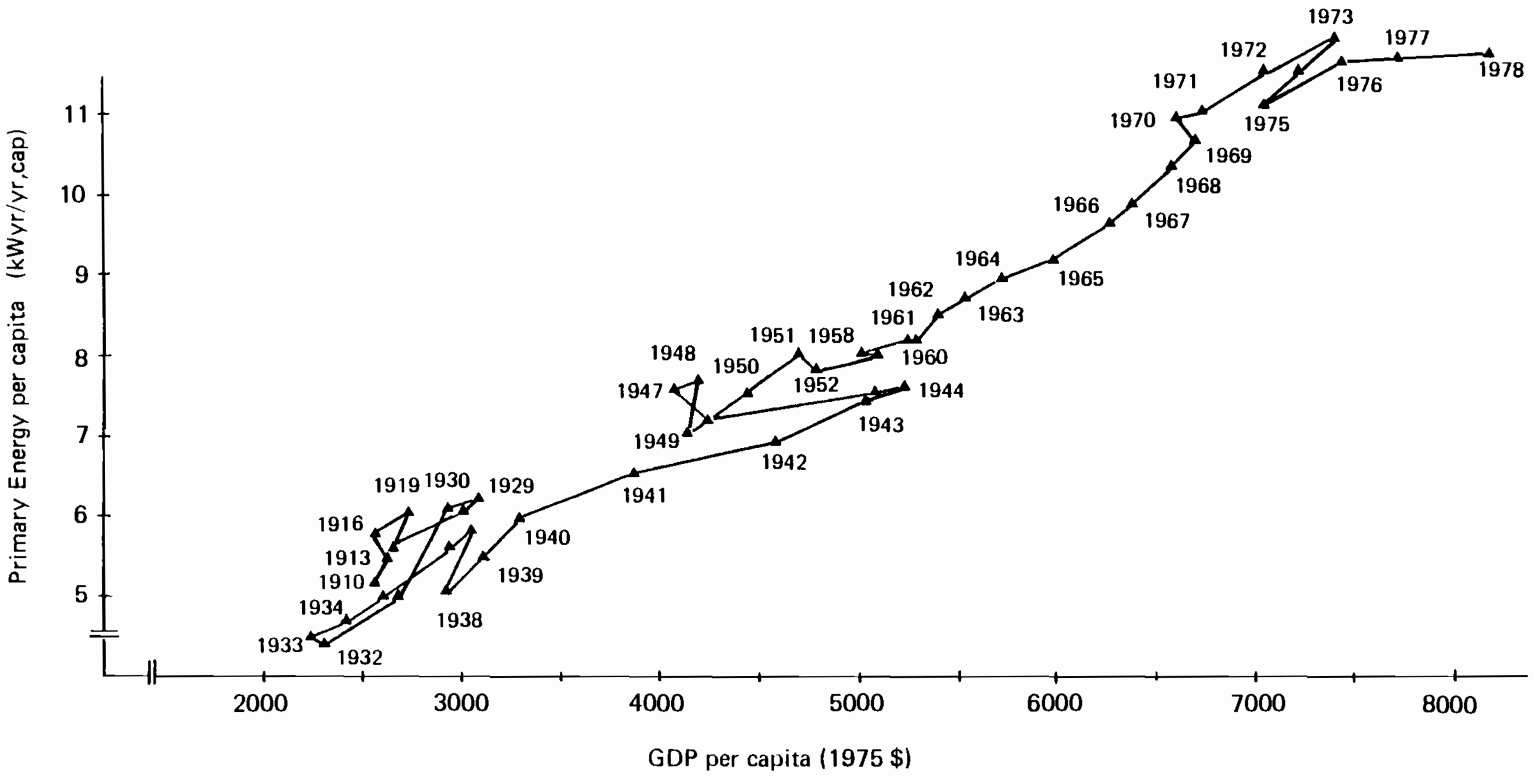
These regional average energy consumption densities mask much of the variation across countries and specifically between urban and rural areas. Not only is the energy consumption per capita different between urban and rural areas, but each region is at a different level of urbanization. The differences in the urban and rural patterns of energy consumption are discussed in detail in Chapter 23.

ENERGY USE AND ECONOMIC ACTIVITY IN THE AGGREGATE

The relationship between energy use and GDP is now examined for recent historical values as well as for the projection period. Later in this section, scenario energy prices will be defined, and the projections will be interpreted in terms of these price assumptions. Again, the purpose of this analysis is for interpreting the scenario projections in economic terms after the projections have been made. The elasticities presented in this chapter result from projections and were not used for input.

A simple way to examine the linkage between energy use and GDP is to relate primary energy use per capita to GDP per capita. As an illustrative example of this relationship over a long historical period, Figure 15-2 presents a graph of primary energy use per capita versus GDP per capita (in constant dollars) for the United States for the period 1910-1978. Even though

Figure 15-2. Primary energy and GDP per capita, United States, 1910-1978. For 1910-1929 and 1951-1959 three-year averages are shown in order to reduce the confusion of point clusters. Sources: Based on data from Alterman (1977) and Bureau of the Census (1978).



the annual variations as shown in this figure include both increases and decreases, the long-term trend is unmistakable. And of course, in the scenario projections to the year 2030, it is the long-term trends that are of interest rather than the annual fluctuations.

In Figure 15-3, the projections for the High and the Low scenarios for region I (NA) are shown in relation to the long-term trend exhibited in Figure 15-2. What is immediately apparent is the change in slope of this graph between the historical period and the scenario projections. This analysis examines the nature of this change in detail for all regions. It is immediately apparent that the scenario projections include large effects of energy conservation and efficiency improvements over and above what has occurred in the past.

This trend of conservation and increasing efficiency of energy use is projected for all regions, but to a lesser extent than for region I (NA), as shown in Figure 15-4. Also evident in the figure is the general trend of less energy intensiveness of economies as they change from relatively underdeveloped—regions V (Af/SEA) and VII (C/CPA) for 1950-1975—to developed.

Figure 15-3. Primary energy and GDP per capita, region I (NA), 1910-2030.

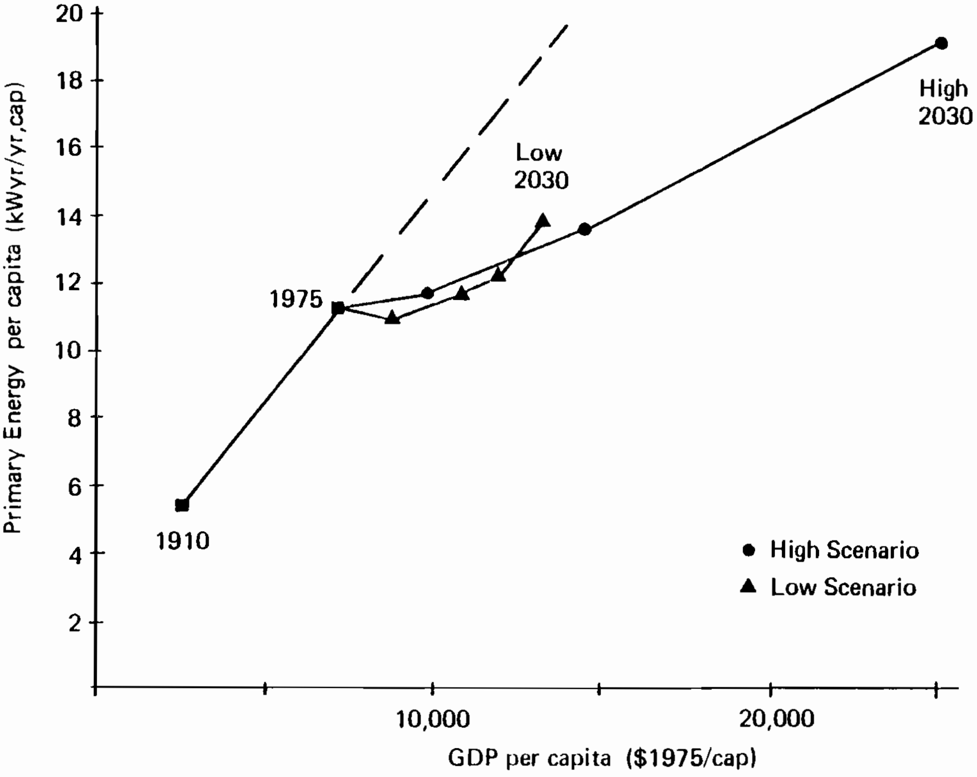
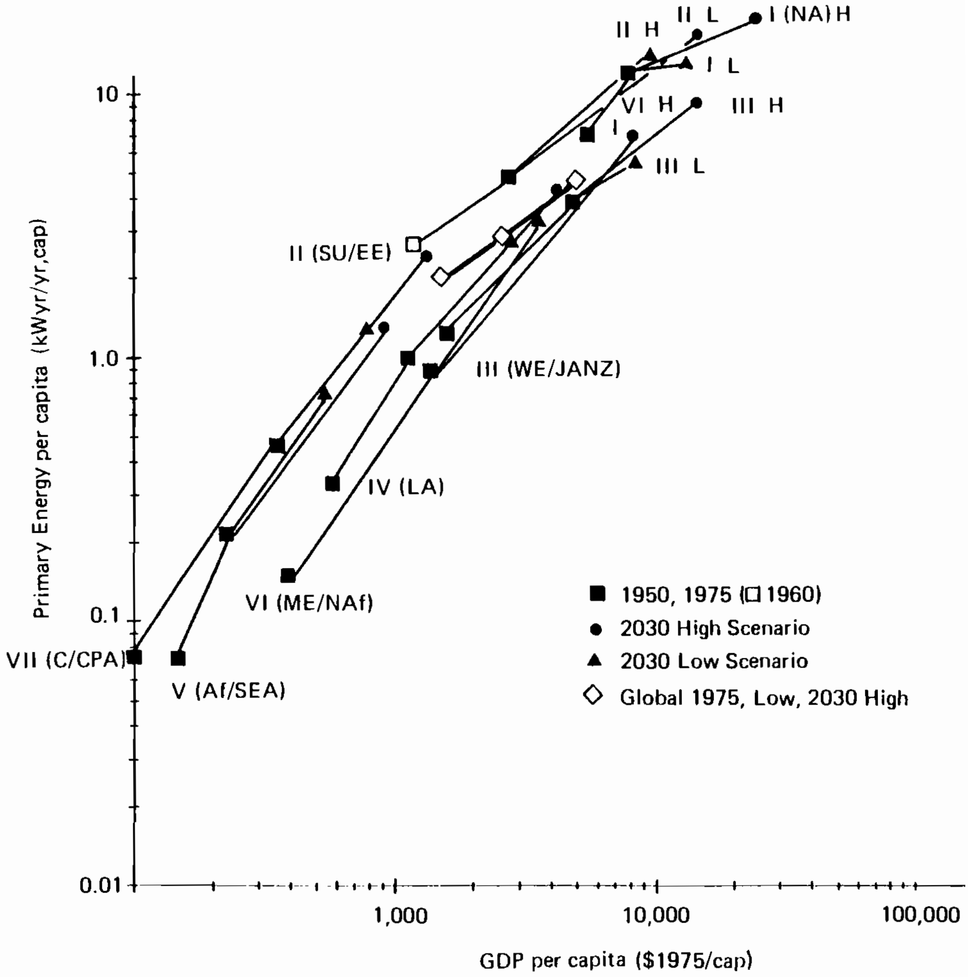


Figure 15-4. Primary energy and GDP per capita, IIASA regions, 1950-2030.



Energy-GDP Elasticities

A convenient way of specifying the degree of coupling between aggregate economic growth and energy demand growth is by means of the energy-GDP elasticity, ϵ.[d] A coefficient value of unity would simply imply that economic growth and energy growth go hand in hand—that is, that a 10 percent growth

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[d] This elasticity, ϵ, is defined by the following relationship:

$$\frac{E(t_2)}{E(t_1)} = \left\{\frac{GDP(t_2)}{GDP(t_1)}\right\}^{\epsilon}$$

Table 15-5. Primary energy-GDP elasticities, ϵ_p, 1950-2030.

	Historical	*High Scenario*		*Low Scenario*	
Region	*1950-1975*	*1975-2000*	*2000-2030*	*1975-2000*	*2000-2030*
I (NA)	1.03	0.42	0.67	0.36	0.89[a]
II (SU/EE)	0.77	0.65	0.67	0.62	0.62
III (WE/JANZ)	0.96	0.70	0.77	0.65	0.73
IV (LA)	1.28	1.04	0.98	1.06	0.97
V (Af/SEA)	1.52	1.15	1.11	1.18	1.19
VI (ME/NAf)	1.20	1.16	0.96	1.23	1.10
VII (C/CPA)	1.57	1.06	1.17	0.98	1.27[a]
World	0.99	0.70	0.90	0.67	0.93

[a] The primary energy-GDP elasticity is unusually high for regions I and VII in the Low scenario. In the later time period in these regions, demand for liquids must be met from coal liquefaction, which has significant conversion losses, thus adding to primary energy use. Since the GDP growth is small in the Low scenario, the elasticity of primary energy use with GDP is increased. If these losses are subtracted from primary energy consumption in 2030, the resulting elasticities are 0.53 and 0.94 for regions I and VII, respectively. The same effect is present in the High scenario for regions I, II, III, and VII, but is less pronounced in the elasticity because GDP growth is higher.

Note: Historical values were computed by linear regression on logarithmic transformation of equation (see note, p. 446) using five yearly data (see Chant 1980). Values for the projection period result from the scenario data.

in GDP would be accompanied by a 10 percent increase in energy usage. A value of zero would imply that energy usage is constant as the economy grows. A value of 0.5 would imply that a fourfold increase in economic activity would be accompanied by only a twofold increase in energy; a doubling of GDP would require about 41 percent more energy, while a 10 percent increase in GDP would require a 4.9 percent increase in energy.

A wide range of values is possible for the energy-GDP elasticity, even values greater than unity or less than zero. A value greater than unity would imply that energy usage increases faster than GDP. This result does not necessarily imply a loss of efficiency but usually refers to a developing economy where the nature of the economic activity is changing; a shift from agriculture to industrial production, or mechanization of agriculture itself, is usually accompanied by large increases in energy usage. On the other hand, negative values of this elasticity during periods of economic growth would imply that energy usage is decreasing. This can happen during periods of strong energy conservation or shortage of supply, perhaps associated with large energy price increases.

The primary energy-GDP elasticities, ϵ_p, resulting from the scenario projections are shown in Table 15-5. The elasticities for the historical period

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where t_1 and t_2 are two given times, E is energy consumption measured in physical units, and *GDP* is gross domestic product measured in real noninflated monetary units. This elasticity can be calculated with respect to primary energy, ϵ_p, or to final energy, ϵ_f. Numerical differences between ϵ_p and ϵ_f can be due to changing energy conversion efficiencies or fuel mixes.

follow the often observed trend of being less than unity for developed economies (regions I, II, and III) and greater than unity for developing economies (regions IV, V, VI, and VII). Regions V (Af/SEA) and VII (C/CPA) exhibit the largest value of ϵ_p for the historical period, but these average values mask an apparent trend from even higher values at the beginning of the period to lower values near the end of this period.

The elasticities, as noted, result from scenario projections of energy demand. They are based less on energy resource considerations than on energy savings potential. Thus, for instance, if region I (NA) has a higher potential for saving energy than region III (WE/JANZ), then the NA elasticities will be lower than those of WE/JANZ, in spite of the fact that energy resources are abundant in NA and (relatively) scarce in WE/JANZ.

The elasticities for the early part of the projection period (1975-2000) are much lower than the historic values, thus indicating the assumed increased efficiencies and conservation of energy use. This trend does not appear to continue throughout the projection period, as indicated by these elasticities for 2000-2030. It is shown below, however, that the trend of improved efficiencies is projected to continue in terms of energy use; but that the increased losses due to coal liquefaction and electrification mask the trend here in terms of primary energy. (Chapter 17 describes the energy supply scenarios by region, including the extent of coal liquefaction and electrification.)

The energy-GDP elasticities for final energy (ϵ_f) can also be calculated. In this case, the elasticity indicates the trends of energy use rather than of energy supply. Table 15-6 presents these elasticities for the historical period (1950-1975) and for four periods during the projection period (1975-2030). The trend of decreasing elasticities as economies develop (both developed and developing economies) is now quite clear. The only significant exception is region I (NA), which has very low values for the initial years of the projection period. This results from assumptions that this region has a great conservation potential that it can and will take advantage of as rapidly as possible. A large part of this conservation before 2000 is due to mandated fuel efficiency improvements in automobiles in the United States and Canada.

The energy-GDP elasticity is the simplest yardstick by which to measure the energy-economy bond. Its application is useful but limited. It highlights gross national or regional differences, shifts in energy supply strategies, and other changes over time but does not explain them. It does not account for energy price changes explicitly; higher prices that lead to lower energy usage yield lower values of ϵ, but there is no measure of the price response. This comes next.

Income and Price Elasticities

There is a multiplicity of factors determining the relationship between energy consumption and economic growth. One factor is technological development, which tends to make energy growth smaller than economic growth. Another factor is the changing texture of economic activity, which for developed

Table 15-6. Final energy-GDP elasticities, ϵ_f, 1950-2030.

A. High Scenario

Region	*Historical* 1950-1975	1975-1985	1985-2000	2000-2015	2015-2030
I (NA)	0.84	0.31	0.43	0.53	0.48
II (SU/EE)	0.68	0.59	0.58	0.52	0.53
III (WE/JANZ)	0.84	0.77	0.65	0.58	0.51
IV (LA)	1.21	1.07	1.01	0.97	0.90
V (Af/SEA)	1.42	1.20	1.08	1.05	1.01
VI (ME/NAf)	1.17	1.12	1.07	0.95	0.81
VII (C/CPA)	1.53	1.10	1.02	1.02	0.96
World	0.87	0.69	0.73	0.78	0.77

B. Low Scenario

Region	*Historical* 1950-1975	1975-1985	1985-2000	2000-2015	2015-2030
I (NA)	0.84	0.24	0.38	0.53	0.46
II (SU/EE)	0.68	0.54	0.57	0.50	0.41
III (WE/JANZ)	0.84	0.67	0.64	0.60	0.49
IV (LA)	1.21	1.10	1.03	0.95	0.88
V (Af/SEA)	1.42	1.19	1.12	1.14	1.06
VI (ME/NAf)	1.17	1.21	1.11	1.01	0.93
VII (C/CPA)	1.53	1.02	0.98	0.99	0.90
World	0.87	0.64	0.73	0.79	0.74

Note: Historical values were computed by linear regression on logarithmic transformation of equation (see note, p. 446) using five yearly data (see Chant 1980). Values for the projection period result from the scenario data.

economies is usually away from energy-intensive industry toward services and for developing economies is away from low-energy-consuming agriculture toward mechanized agriculture and energy-intensive industry. Energy consumption is also affected by energy conservation, which may result from price increases, legislated efficiency improvements, or other public measures.

The relationships among energy use, economic activity, and energy price are complex. These relationships can be abstracted in different ways to aid in understanding. One such abstraction is to consider three categories of ways of reducing energy use—do better, do differently, and do without. The first category, do better, includes improvements in efficiency or technological development—the application of "know-how" to do better. The second category, do differently, suggests that some alternative method of performing an activity (which uses less energy) should be found and that since it excludes the "technical fix" options of the first category, the alternative must involve a substitution of other inputs or resources in place of energy—use more capital and labor and less energy to do it differently. The third category, do without, includes ways of reducing energy use by simply reducing energy-intensive activities or changing lifestyles to get by with less. This may appear simple in concept but in practice can have indirect effects; a conscious decision to forego some activity results in an additional resource (money, time, etc.) that will likely be redirected toward some other activity that may or may not be less energy intensive. The technological development and substitution effects included in categories one and two above are examined in the final section of this chapter for the industry sector. Here, distinguishing between the income effect and the price effect provides another way of understanding the relationships among energy use, economic activity, and energy price.

Changes in energy consumption that are due to changes in GDP when there is no change in the price of energy are called the income effect. Changes in energy consumption due to energy price changes when there is no change in GDP are called the price effect. The separation of energy demand into these two effects is very useful but, of course, in application can be somewhat arbitrary. For example, the mandated motor vehicle efficiency improvement in region I (NA) is not exactly an income or price effect but is an important factor affecting projected energy consumption for this region.

The simplest and most common way of defining these effects quantitatively is by means of elasticities—the energy-income elasticity, γ, and the energy-price elasticity, β.[e] When there are no price changes, the energy-income elasticity, γ, is equivalent to the energy-GDP elasticity, ϵ, presented earlier. First, energy prices are examined.

Energy Prices. It should be immediately clear that the appropriate energy price for relating energy use to price changes is not the international price of crude oil even though this is the price so often quoted when energy price increases are mentioned. If energy price is to help explain the consumption of energy then that price must be the price to the user of that energy, and it must be quoted in real, noninflated terms. In this application, the energy price used is the price for final (delivered) energy, averaged over all forms of final energy.

Before specifying the relative price increases that are used for interpreting

[e] The income elasticity, γ, and price elasticity, β, are defined as follows:

$$\frac{E(t_2)}{E(t_1)} = \left\{\frac{GDP(t_2)}{GDP(t_1)}\right\}^{\gamma} \left\{\frac{P(t_2)}{P(t_1)}\right\}^{\beta}$$

where, in addition to those definitions in footnote d, P is the appropriate price of energy that applies at time t_2 relative to the price at time t_1. See text above for interpretation of "appropriate price." These elasticities may be defined with respect to either primary energy or final energy. In all applications here, γ and β are assumed to be constant over the time period. The price elasticity β is an all-energy elasticity. Individual fuel type elasticities and cross-fuel elasticities are often employed for analyzing energy demand and interfuel substitution. These elasticities are not calculated here. Interfuel substitution is handled within the model analysis and iteration process as described in Chapters 16 and 17.

Table 15-7. Real prices for final (delivered) energy (1975 $ per kWyr).

	Industry Sector	*Transport Sector*	*Residential-Commercial Sector*	*All Sector Aggregate*
Region I (NA)				
1972	30	116	83	70
1975	52	144	108	97
1975-1972	1.73	1.24	1.30	1.35
Region III (WE/JANZ)				
1972	62	254	135	113
1975	92	338	174	159
1975-1972	1.48	1.33	1.29	1.41

Notes: $100 per kWyr is equivalent to $19.40 per barrel of oil equivalent, $3.34 per million Btu, and $0.011 per kWh. These prices are calculated from data contained in Hogan (1979). These data were taken from a data base assembled by Pindyck as described in Pindyck (1978) and updated from several sources by Hogan. Data on current prices were adjusted for inflation using a GNP deflator; currency conversions were based on a purchasing power parity conversion rate. The data reported here for region III (WE/JANZ) are for the aggregation of data for the four largest energy-using countries only: France, FRG, the United Kingdom, and Japan.

the scenario projections, it is useful to look at recent energy price changes. Gathering, reconciling, and aggregating price data for (delivered) final energy products is a tremendous task even for the data of one country. There is a multiplicity of energy products at the user level, and even the same product is sold at vastly different prices to different users.

What can be done is to select important representative energy commodities and gather price data on these according to aggregate user categories. At a minimum, petroleum products used for transportation should be separated because of the large taxes that are usually levied on these products. As well, the user categories of the industry sector and of the residential and commercial sector should be separated because the typically large energy users in industry pay a lower unit price for energy. Prices for different years must be corrected for inflation. Data for different fuel types within these user categories can be aggregated on a calorific quantity basis, but one must recognize that this procedure is not ideal because of different end use efficiencies, environmental effects, ease of use, and the like. The user categories can also be aggregated on the calorific quantity basis with the same caveat. Finally, data for countries within a geographic region can be aggregated on the same basis after choosing an appropriate measure of the equivalences of different national currencies.

This procedure was followed to produce the data of Table 15-7. As shown in the table for region I (NA) in 1972, for example, the delivered energy prices varied significantly for the three user categories, with the transport sector prices[f] ($116/kWyr) being almost four times the industry sector prices

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[f] Prices are quoted in constant (1975) U.S. dollars.

($30/kWyr). For the all sector aggregate price, region III (WE/JANZ) prices were approximately 60 percent higher than region I (NA). Also indicated in the table is that, on the average, 1975 delivered energy prices were only about 40 percent greater (in real terms, of course) than 1972 prices in either region. Clearly, the international price of crude petroleum increased by a much greater factor during this same three-year period, even in real terms, but crude petroleum prices are not the only prices of interest in analyzing the user demand for energy.

The price data of Table 15-7 are simple quantity-weighted averages based on the calorific content of various fuels. A similar weighting of price data from other sources (Doblin 1979) indicates an even smaller price increase between 1972 and 1975 of 27 percent for the United States. Other countries substantiate this trend—France, 19 percent; the Federal Republic of Germany, 22 percent; and the United Kingdom, 26 percent for 1975 as compared to 1972. Even between 1972 and 1978, these sources indicate that U.S. prices had increased by only 33 percent.

Hogan (1979) aggregated fuel types within sectors and across sectors using a Cobb-Douglas function formulation to estimate another average energy price; his procedure assumed that interfuel substitutions would occur to take advantage of different relative fuel price increases. His average price index indicated that 1975 prices would be only 22 percent higher than 1972 prices for the United States and that price increases in other countries would be as follows: France, 11 percent; the FRG, 15 percent; the United Kingdom, 33 percent; and Japan, 31 percent.

The conclusion is that real prices to the user for delivered energy had not increased by more than 40 percent between 1972 and 1975, on average, and possibly less depending on sources, aggregation methods, and currency valuations.

Energy Price Projections. Energy price projections are required for interpreting the scenario projections in terms of income and price elasticities. The price projection required is for final energy delivered to the user and for real price increases relative to 1972 and not relative to the base year 1975, as explained below.

There is a variable lag between the time a price change is made and the time when the effect on the economy is noticed. In some situations the time lag can be practically zero when the activity requiring the energy can be immediately changed or foregone—as, for example, with pleasure travel. In most situations, however, the time lag is very long, up to two or three decades before industrial processes can be redesigned and new equipment can be economically replaced. Even though the price increases between 1972 and 1975 affected the energy consumption of 1975, it is assumed that only a negligible part of the ultimate reaction to these price increases had yet occurred by 1975. Thus, since post-1975 energy use patterns will still be reacting to these earlier price increases, price increases of 1972 to 1975 must be included in the definition of the relative price appropriate for interpreting the scenario projections. The lagged effect of later price increases is accounted for by specifying that the relative price increases for energy are to have taken place by approximately 2010, so that their full effect is represented in the scenario projections for 2030.

The projected energy price increases employed here must be consistent with the energy production cost increases that result from the analysis of energy supply presented in Chapter 17. These production costs are not, however, the sole determinant of user energy prices. Other costs such as transmission, transportation and distribution costs, trade margins, taxes, administrative costs, interest payments, and profit must also be accounted for. The energy production costs examined here include all resource costs, including imported crude oil at world trade prices and all energy conversion costs for refineries, electric power plants, and the like. These production costs estimates are used only as a guideline for projecting final energy price increases.

Energy production and conversion costs are based on the supply scenarios of Chapter 17. For 2030, for example, the total annual cost of supply of all fuel types and electricity was calculated. This total cost was then allocated per unit of final energy that would result from this total production. Thus, for example, the cost of production of electricity was calculated for the amount of secondary energy (gross power station output) required, but this cost was divided by the net amount of final energy (electricity delivered to the user) produced. These production and conversion costs are shown in Table 15-8, along with 1972 costs estimated using the same procedure. Average production and conversion costs would be within the range of \$101 to \$126 per kWyr of final energy for 2030 for both the High and the Low scenarios. These 2030 costs would be between 3.4 and 4.2 times the 1972 costs for regions I (NA) and IV (LA) and between 2.9 and 3 for region III (WE/JANZ) in both scenarios. The apparently low costs for region II (SU/EE) reflect very high shares of relatively inexpensive central sources of heat–district heat and cogeneration plants.

A comparison of final energy prices for 1972 from Table 15-7 with production and conversion costs of energy shows that in 1972 these costs comprised only 43 percent of final energy prices for region I (NA) and 35 percent

Table 15-8. Energy production and conversion costs (1975 US \$ per kWyr of final energy).

Region	*1972*	*High Scenario 2030*	*Low Scenario 2030*
I (NA)	30	126	118
II (SU/EE)	ne	108	103
III (WE/JANZ)	40	119	114
IV (LA)	30	104	102
V (Af/SEA)	ne	105	101

ne–not estimated.

Source: Energy supply scenarios as determined by the MESSAGE model described in Chapter 17.

for region III (WE/JANZ). The difference consists of taxes and other costs. All taxes and other costs are not likely to increase at the same rate as energy production and conversion costs; some of these other costs should not increase at all, while others will increase to varying degrees, and taxes will vary from country to country. It is simply an assumption, adopted here, that these taxes and other costs will little more than double from their 1972 value. Combining these components of costs results in approximately a threefold increase in prices for region I (NA) and a 2.4 times increase for region III (WE/JANZ). The lower price increase for region III is due to the relatively high level of prices already in place in this region in 1972. Since these price levels did not prevail throughout the other regions in 1972, the relative price increase for all other regions is defined to be threefold.

In summary, the implied price evolutions employed in the interpretation of scenario projections in this chapter are as follows:

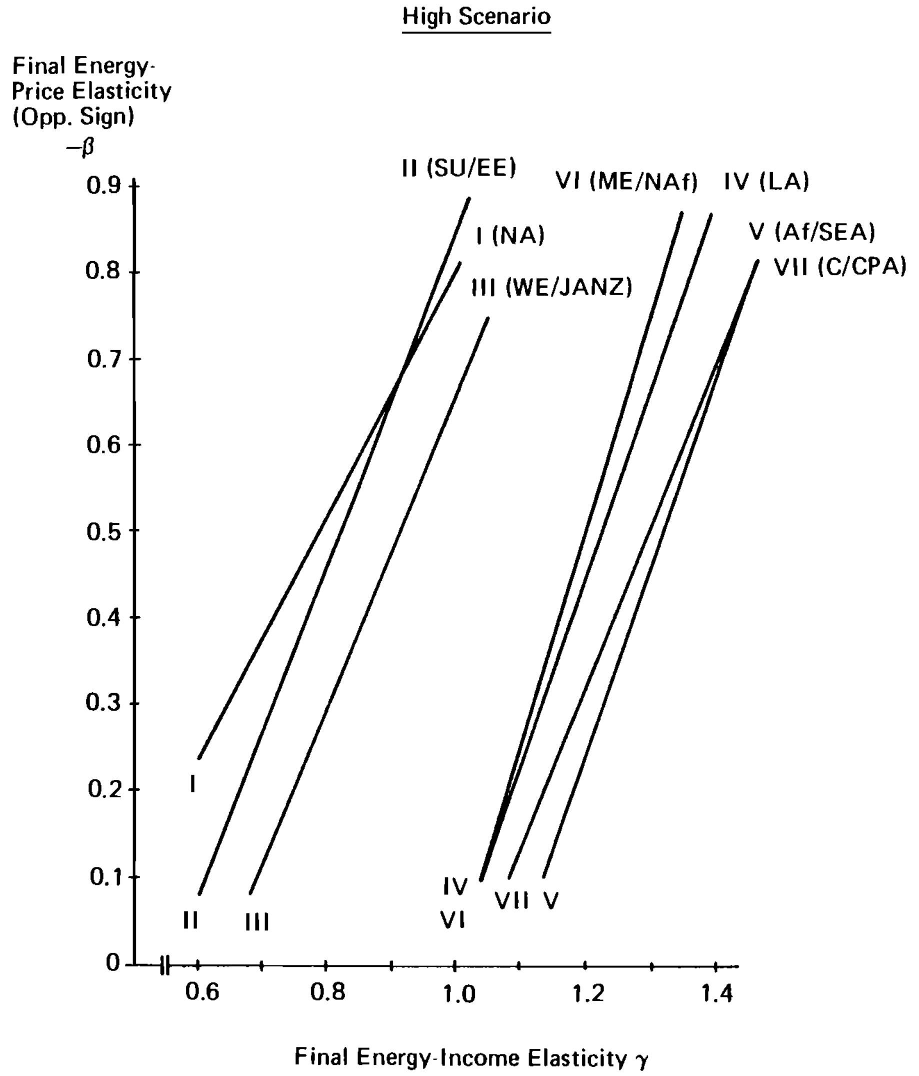
- Energy prices are for final energy (delivered to the user) averaged for all fuels on a calorific content basis.
- Energy prices are for real increases relative to 1972.
- Energy prices are projected to increase by a factor of 2.4 for region III (WE/JANZ) and by a factor of 3 for all other regions.

Elasticities. Income and price elasticities were defined in footnote e. For the historical period (1950–1975), real energy prices did not change significantly; they actually dropped slightly in most countries. Without taking account of these small price changes during this period, the values of the income elasticity, γ, would be the same as those given in Tables 15-5 and 15-6 for the energy-GDP elasticity, ϵ, for primary energy and for final energy, respectively.

For the scenario projection period 1975–2030, energy prices do increase, and therefore both income elasticity, γ, and price elasticity, β, must be considered. If the scenario projections for GDP increases and final energy increases are specified, and if energy price increases are also specified, then the corresponding combinations of γ and β (consistent with the scenario projections) can be calculated. These combinations of γ and β are shown in Figure 15-5 for the High scenario and in Figure 15-6 for the Low scenario. These figures apply to the all sector aggregate of GDP and final energy projections for the period 1975–2030. (The data for GDP are given in Chapter 14 and those for final energy in Table 15-1.) The grouping of the developed regions (I, II, and III) with values of γ less than unity and of the developing regions (IV, V, VI, and VII) with values of γ greater than unity is as expected. A comparison of the two figures for the two scenarios indicates that the High scenario has higher price elasticities or lower income elasticities than the Low scenario for all regions. This result indicates that the High scenario projections represent better assumed efficiency improvements and stronger assumed conservation effects than the Low scenario.

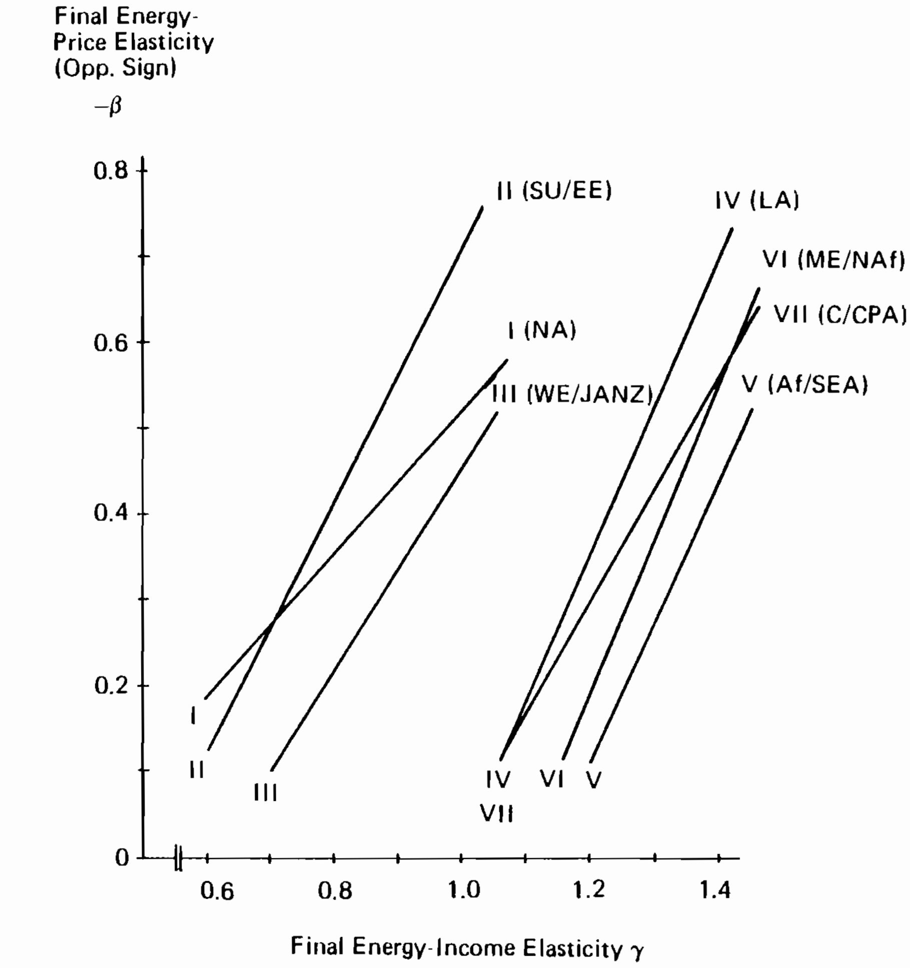
Particular numerical values for γ and β may be selected for any region on the basis of Figures 15-5 and 15-6. For example, if the income elasticity

Figure 15-5. Income and price elasticities for aggregate final energy, High scenario.



were unity (that is, energy use increases in step with GDP increases if there were no price increase), then the price elasticities represented by the scenario projections are -0.81 and -0.52 for region I (NA) for the High and the Low scenarios, respectively. For the historical value of the income elasticity for this region (for final energy it is 0.84), the corresponding price elasticities would be -0.58 and -0.39 for the two scenarios. Table 15-9 presents typical values of both γ and β for all the other regions. As indicated in this table, the price elasticities for aggregate final energy are lower for the developing

Figure 15-6. Income and price elasticities for aggregate final energy, Low scenario.



regions than for the developed regions. This result is not an irrefutable conclusion, because the range of income elasticities shown was chosen arbitrarily and larger price elasticities would result if larger income elasticities were chosen. Based on the historical values of the income elasticities, however, the range of values shown seems reasonable. These findings are also in agreement with many other studies that examine elasticities.

It is useful to perform the same kind of analysis with income and price elasticities that resulted in Figures 15-5 and 15-6 but for different categories of energy use. As mentioned in the opening paragraph of this chapter, energy serves two purposes—as a factor of production (an intermediate input in the economic system) and as an end product for use by consumers to make their homes comfortable and to provide mobility—a final demand for the eco-

Table 15-9. Final energy-income and energy-price elasticities.

	High Scenario		Low Scenario	
Region	*Income elasticity* γ	*Price elasticity* β	*Income elasticity* γ	*Price elasticity* β
I (NA)	(0.8, 1.0)	(-0.52, -0.81)	(0.8, 1.0)	(-0.35, -0.52)
II (SU/EE)	(0.8, 1.0)	(-0.46, -0.85)	(0.8, 1.0)	(-0.42, -0.71)
III (WE/JANZ)	(0.8, 1.0)	(-0.30, -0.66)	(0.8, 1.0)	(-0.22, -0.45)
IV (LA)	(1.1, 1.2)	(-0.23, -0.44)	(1.1, 1.2)	(-0.18, -0.35)
V (Af/SEA)	(1.2, 1.3)	(-0.24, -0.45)	(1.2, 1.3)	(-0.11, -0.27)
VI (ME/NAf)	(1.1, 1.2)	(-0.24, -0.49)	(1.1, 1.2)	(-0.02, -0.20)
VII (C/CPA)	(1.2, 1.3)	(-0.32, -0.50)	(1.2, 1.3)	(-0.30, -0.43)

Note: Final energy price elasticities are all sector aggregates for the period 1975–2030, calculated according to the equation (see footnote e) to be consistent with GDP and final energy scenario projections and with the assumed range of values for the income elasticities shown. The historical values for 1950–1975 for γ are given in Tables 15-5 and 15-6 under the assumption that real prices did not change during that period. These values are, respectively, 0.84, 0.68, and 0.84 for regions I, II, and III and 1.21, 1.42, 1.17, and 1.53 for regions IV, V, VI, and VII. The high values for the developing regions would not be particularly appropriate for the projection period; the range shown in this table would be more appropriate. Note also that the price elasticities of the High scenario are larger than those for the Low scenario, because it was implied that a higher innovation rate thus favoring more energy conservation would go along with the higher growth rates of the High scenario.

nomic system. (The two terms final energy and final demand should not be confused.) Energy used for these two purposes can be identified from the detailed projections described in Chapter 16. Having done so, the elasticities of each category of energy use can be examined with the same model as defined in footnote e.

Two components of the final demand category of energy use can be distinguished—energy used in households and energy used for passenger transportation. All other final energy is defined as belonging to the category of intermediate input energy. An examination (Chant 1980) of these three components separately shows that, as for the case of the aggregate of all energy use, the High scenario projections exhibit higher price elasticities (β) and lower income elasticities (γ) than the Low scenario projections. Passenger transport energy also has higher βs and lower γs than household energy but only for region I (NA). For all other regions the opposite is true. This result indicates the very high efficiency improvements and conservation potential that were realized in these projections for region I. More importantly, perhaps, is the assumed saturation effect on passenger transportation, which is most pronounced in this region.

A comparison of the two categories of energy use (household plus passenger transport energy and intermediate input energy) shows that the elasticities for the regions are very different for the final demand category but reasonably close together for the intermediate input category of energy use. Also, in the High scenario, the developed regions have higher βs and lower γs for the final demand category than for the intermediate input category,

Table 15-10. Comparison of elasticities. The result indicated is for the final demand energy use category as compared to the intermediate input energy use category within each region. The final demand energy use category is final energy used in households and for passenger transportation. The intermediate input category includes all other final energy use. Combinations of γ and β that were consistent with scenario projections for GDP, energy use, and price increase were plotted as in Figures 15-5 and 15-6. The result "higher β, lower γ" indicates that the straight line representing combinations of γ and β for the final demand category was higher and to the left of the line for the intermediate input category. These results are described in more detail in Chant (1980).

Regions	*High Scenario*	*Low Scenario*
Developed (I, II and III)	Higher βs Lower γs (very pronounced)	Higher βs Lower γs (less pronounced)
Developing (IV, V and VI)	Same Elasticities	Lower βs Higher γs

whereas for the developing regions the two categories are almost identical. In the Low scenario, the effect for the developed regions is less dominant, but for the developing regions the final demand category has lower βs and higher γs than the intermediate input category. (See Table 15-10 for a summary of these results.)

An interpretation of these results is that, for the developed regions, GDP growth would be accompanied by relatively lower growth (more conservation) in the final demand for energy than in the requirements for intermediate input energy. Conversely, for the developing regions, and especially in the Low scenario, GDP growth would be accompanied by relatively higher growth in the final demand for energy (which is strongly linked to population) than for intermediate input energy.

Payments for Energy

Price increases were projected here to be threefold relative to 1972 prices (2.4 times for region III). Energy consumption would increase substantially in both scenarios, although the increase is slowed (relative to GDP increases) because of improved efficiencies and conservation. A simple calculation can be performed that indicates how much more total energy payments would increase than would GDP in these projections. Table 15-11 shows the results of this calculation. For each region, this table gives the relative increase of GDP and final energy (projected 2030 value relative to 1975 base year value) and the price increase assumption. For example, the combination of a threefold increase in energy price and the projected increase in final energy usage

Table 15-11. Projected increases in payments for energy as fraction of GDP.

A. High Scenario

Region	*GDP*	*Final Energy*	*Final Energy Price*	*Payments for Energy-GDP*[a]
I (NA)	4.75	1.96	3.0	1.24
II (SU/EE)	8.23	3.25	3.0	1.18
III (WE/JANZ)	4.90	2.75	2.4	1.35
IV (LA)	10.50	10.36	3.0	2.96
V (Af/SEA)	10.26	12.56	3.0	3.67
VI (ME/NAf)	15.36	15.45	3.0	3.02
VII (C/CPA)	7.66	8.13	3.0	3.18

B. Low Scenario

Region	*GDP*	*Final Energy*	*Final Energy Price*	*Payments for Energy-GDP*[a]
I (NA)	2.50	1.41	3.0	1.69
II (SU/EE)	5.07	2.31	3.0	1.37
III (WE/JANZ)	2.79	1.88	2.4	1.62
IV (LA)	6.56	6.49	3.0	2.97
V (Af/SEA)	5.87	7.42	3.0	3.79
VI (ME/NAf)	6.90	8.19	3.0	3.56
VII (C/CPA)	4.20	4.04	3.0	2.89

[a] Projected energy payments as a fraction of GDP in 2030 relative to energy payments as a fraction of GDP in 1975 using 1972 energy prices. For example, if energy consumption doubles and price triples, then energy payments increase sixfold. But if GDP also increases fourfold, then this "payments for energy-GDP" index would be 6/4 = 1.50.

Notes: Values given are for the year 2030 as a multiple of base year value. GDP and final energy are given as projected 2030 values relative to 1975 values. Price increase is for final energy (delivered to the user) relative to 1972 price levels.

by the factor 1.96 in region I (NA) in the High scenario would imply a 5.88 increase in energy payments. During the same period, however, GDP would increase only by a factor 4.75, so that energy payments as a fraction of GDP would increase to 1.24 times its base year value—a 24 percent increase. Payments for energy in the developed regions are a relatively larger fraction of GDP in the Low than in the High scenario, primarily because of stronger conservation and efficiency improvements assumed in the High scenario. The developing regions would have much higher increases in relative payments for energy in both scenarios.

The calculation just performed was for energy payments by users of final energy. As noted above, the production and conversion costs of providing this energy would increase more substantially than the final energy price (more than fourfold for region I and about threefold for region III). More importantly from the energy supply and economic impact point of view, however, is that the energy supply system is projected to become increasingly capital intensive; therefore, fourfold production cost increases translate into even larger increases for investment in the energy sector. The detailed analysis in Chapter 19 shows that these investments would almost double their base year fraction of GDP for the developed regions and more than triple it for the developing regions. The relatively small projected increases in total payments for energy (relative to GDP) for the developed regions should not, therefore, be taken as comforting. Not only would large increases in investment be required in the future, but these projected increases would be a reversal of the trend that pertained for 1950–1975. In the past payments would have dropped to 0.83–0.85 (for regions I and III) relative to GDP if prices had been constant in real terms. But they were not—they dropped. The large increases for the developing regions appear staggering. They point to the need for studying the world trade prospects and potential balance of payments problems.

ENERGY USE IN INDUSTRY

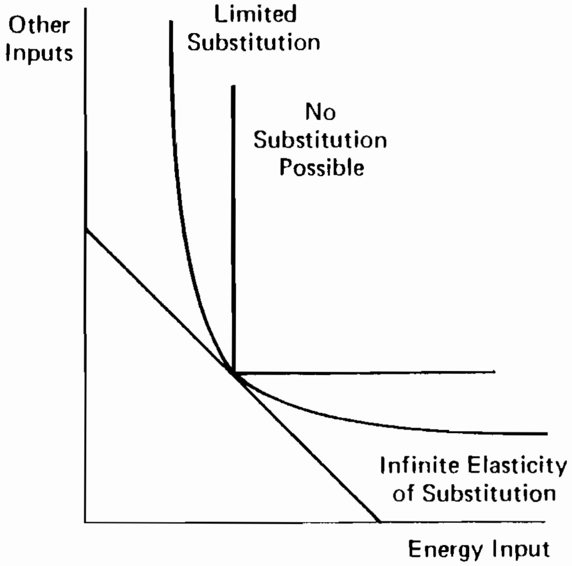
Three ways of reducing energy consumption have been defined—do better, do differently, and do without. In this section, two factors primarily responsible for the effects included in the first two categories are examined—technological development and substitution. Technological development (or efficiency improvements) allows processes to "do better" or to "do more with less." Substitution as used here refers to the substitution of other non-energy inputs of production in place of energy inputs and not to interfuel substitutions. If less energy use is achievable either by changing processes or by changing combinations of labor, capital, and other material inputs, then it is energy conservation by "doing differently." In this section these effects are examined in the scenario projections for the industry sector only.

Production Function Approach

A production function approach is used here to analyze the substitution effect in industry. That is, the options available to industry, when it is deciding which production process to use and how much labor and other inputs to use, are described by a smooth curve indicating what combinations of such inputs produce a given output. This concept is illustrated in Figure 15-7.

The production function approach is useful since certain relationships concerning prices can be derived. If it is assumed that industry produces at whatever level it chooses but at minimum cost, then theoretically, the relative amounts of inputs it uses are determined by the relative prices of these inputs. The amount of substitution that results from a change in relative price of inputs is measured in this approach by the elasticity of substitution, σ. This elasticity is defined as the ratio of the percentage change in use of inputs (measured as a proportion) due to a percentage change in the relative

Figure 15-7. Idealized factor substitution curves. Each curve defines combinations of energy and other inputs that produce constant output.



prices of the inputs.[g] The shape of the curve in Figure 15-7 determines σ. For small price changes, the relationship between energy use and energy price using this approach shows that the elasticity of substitution, σ, is almost equal (in magnitude) to the energy-price elasticity, β, defined earlier.

Technological Development

Historical analysis indicates that industry has been producing more for less on the average as technology improved. If this factor is ignored, then energy requirements for industry in the scenario projections (which are lower per unit output) will appear to reflect a higher price effect or substitution effect than is really the case. In fact, it is partly this technological development "more for less" effect that results in energy-GDP elasticities being less than unity for developed economies (as has already been seen).

An illustration of historical technological development is given in Figure 1-6, where the energy efficiency of prime movers is shown over a 300-year

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[g] Mathematically, the elasticity of substitution, σ, is defined by the following differential:

$$\sigma = \frac{d(E/Z)}{E/Z} / \frac{d(P_Z/P_E)}{P_Z/P_E}$$

where E represents the energy input with price P_E and Z represents other (nonenergy) inputs with price P_Z.

period. The nature of this kind of plot is described in Chapter 8; it describes an S-shaped curve for efficiency as a function of time. The rate of improvement of efficiency ranges from 0.8 to 1.5 percent per year up to the 50 percent efficiency point, and then the rate of improvement begins to decrease. Not all technological development trends follow this pattern, nor do they all improve at the same rate. Examination of data for the United States on these trends, especially with respect to energy use, indicates that on the average, technological development has been contributing between 0.5 and 1 percent per year to the decrease in energy use per dollar of value added.

Technological development is represented in the production function analysis by an exponential growth factor with coefficient, δ.[h] It is important to note that this treatment of technological development emphasizes efficiency improvements only and that other factors are included in addition when defining labor productivity.

Interpretation of Scenario Data

This analysis of technological development and substitution has been applied to the industry sector of the scenario projections. The relevant data from the projections are presented in Table 15-12, where industrial output Y and energy input E are given for the year 2030 relative to 1975. An indication of the "more for less" trend that was included in the projections is that industrial output increases up to twice as much as do requirements for energy. The separation of this trend into technological development and substitution is accomplished by means of the production function model as shown below.

In this application of this model, the scenario projection data of Table 15-12 and the energy price projections described in an earlier section are taken as given. The values of the technological development coefficient, δ, and of the elasticity of substitution, σ, both of which are consistent with the scenario data, are then calculated. The equation relating output, energy use, energy price, and the two parameters δ and σ is given in footnote h. Since there is only one equation and two unknown parameters, only combinations

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[h] In this analysis, the often-used constant elasticity of substitution production function with neutral technological development on energy and nonenergy (prime) inputs is applied. That is, output Y is produced from energy input E and other inputs Z according to

$$Y = e^{\delta t}\left[aE^{-\frac{1-\sigma}{\sigma}} + bZ^{-\frac{1-\sigma}{\sigma}}\right]^{-\frac{\sigma}{\sigma-1}}$$

where σ is the elasticity of substitution, δ is the technological development coefficient (indicating exponential growth with time, t), and a and b are constants. The quantities of Y, E, and Z are measured relative to their base year (1975) value. The equilibrium price of E, p_E, must be equal to its marginal productivity defined by the derivative of Y, which yields the relationship

$$E = a^{\sigma} e^{(\sigma-1)\delta t}\, Y p_E^{-\sigma}$$

where the price of output product Y is assumed to be unity. The equilibrium price of energy in the base year (t=0) is a. Energy price increases are defined relative to this base year price.

Table 15-12. Projected industry sector output and energy requirements for six regions.

	High Scenario		*Low Scenario*	
Region	*Industrial output*	*Final energy input*	*Industrial output*	*Final energy input*
I (NA)	4.28	2.37	2.57	1.64
II (SU/EE)	6.53	2.88	4.27	2.09
III (WE/JANZ)	4.22	2.71	2.56	1.75
IV (LA)	13.76	9.13	7.80	5.26
V (Af/SEA)	15.58	11.46	8.09	5.70
VI (ME/NAf)	39.78	28.27	17.52	13.27

Notes: Projected values in 2030 relative to 1975 values. Industrial output is value added in mining, manufacturing, and construction, excluding the energy sector (and excluding mining in region VI), plus payments for energy. Payments for energy were calculated multiplying final energy use in industry by the average final energy price for industry (see Table 15-7 for base year (1972) values). Region I prices were used for all regions except region III; prices for 2030 were taken to be 3 times for all regions except region III (2.4 times). Final energy data exclude feedstocks. Details are given in Chant (1980).

of δ and σ that are consistent with the scenario data can be determined. These combinations are shown graphically in Figure 15-8.

In this figure, regions II (SU/EE) and I (NA) in the High scenario stand out as having either higher technological development or higher elasticity of substitution. The industry sectors of the developing regions V (Af/SEA) and VI (ME/NAf) exhibit almost identical trends in terms of this model and are projected to be the least likely to benefit from the "more for less" trend.

This kind of production function analysis of the substitution effect between energy and nonenergy inputs is often performed without including the technological development factor. The interpretation of the scenario projection data in this case is very simple; it is the case with $\delta=0$.[i] As indicated in Figure 15-8, the elasticities of substitution with $\delta=0$ are very high for region II (SU/EE) (0.65, 0.75), are between 0.41 and 0.54 for regions I (NA) and III (WE/JANZ), and are between 0.27 and 0.38 for the developing regions.

These aggregate analyses are useful for comparing broad regions, for interpreting scenario projections, and for comparing the scenarios with other similar energy studies. It must not be forgotten, however, that these aggregate effects are the total of many and complex efficiency, technology, lifestyle, regulatory, and standards changes as well as other factors that are somewhat misrepresented when lumped together. How these energy projections were made based on economic and population projections as well as other assumptions is the subject of the following chapter.

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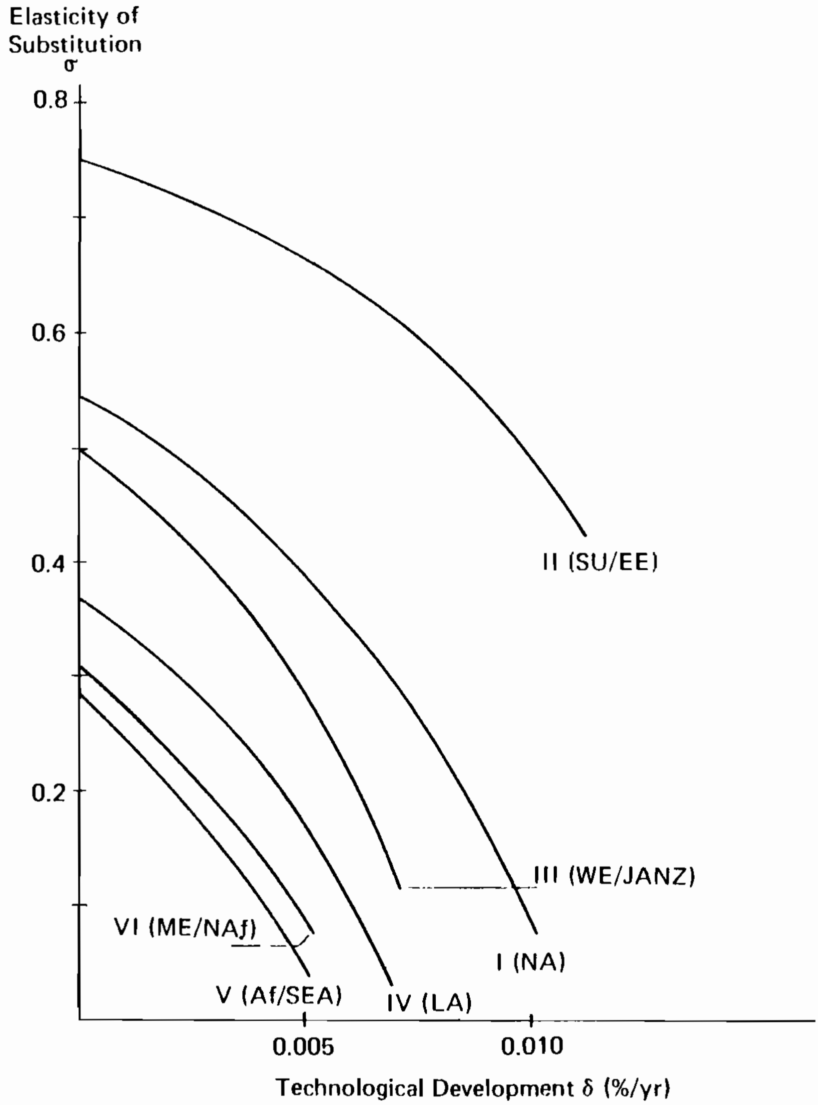
[i] It is interesting to note that this model with $\delta=0$ and the earlier model with γ and β for $\gamma=1$ yield exactly the same values for σ and β (with opposite sign). Unity income elasticity ($\gamma=1$) is, in these aggregate models, equivalent to no technological development ($\delta=0$).

Figure 15-8. Technological development and substitution in industry in the High scenario.



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16 ENERGY CONSUMPTION AND CONSERVATION

Governments and energy policymakers have acknowledged the importance of understanding the components of energy use and of using energy more efficiently wherever possible. Clearly, it is beneficial if the same productive process or service can be accomplished with relatively less energy inputs (all other things being equal). With continually rising fuel costs and their resultant economic burdens, saving energy is more than important—it is essential.

Yet energy consumption, present and future, rests midst some fundamental and strategic questions. Is "use less" a resource-poor country's sole defense against potential energy shortages and embargos? Or are countries better served by accelerating their own energy production? How large is the real potential of reducing energy consumption? During what time span is it achievable and at what costs (and benefits)?

The answers, unfortunately, are not simple and direct, because energy demand (as the end use of energy is commonly called) is not a simple and direct subject. The use of energy by industries, by motorists, by homeowners, depends on a multitude of factors—not least among which are economic development and population growth, as discussed in the previous chapter. Among the other factors influencing energy consumption are climate, technological progress, government regulations and taxes, pricing policies, lifestyle decisions, cultural distinctions and preferences, education and public perceptions. Energy demand is always complex and is often confusing. It is not likely to become less complex, even in the relatively long-term future.

Much research has already been done by many. Important contributions have come from a diverse and rapidly increasing number of individuals and groups—the American Physical Society Conference on Efficient Use of Energy; the energy demand work done within the United States National Research Council-sponsored Committee on Nuclear and Alternative Energy Systems (CONAES) study; the national assessments done as part of the International Energy Agency (IEA) activities; the landmark Dutch "Energy Conservation: Ways and Means" study; the work of the Workshop on Alternative Energy Strategies (WAES); and a score of other studies completed and underway at universities, research institutions, and government agencies around the world. (A representative list of these and other broad-ranging energy demand and conservation studies appears at the end of this chapter.)

This chapter is about energy consumption present and future, about potential improvements in the efficiencies of energy use, and about the relationship of energy demand and detailed economic activities. It is about using and saving energy in importantly different parts of the world. Total energy demand is viewed here on the long term and on a regional basis and in light of expected energy supplies. Detailed assessments of a range of plausible energy demand futures—a High and a Low energy scenario—are made for six of the seven world regions. Through sets of assumptions about lifestyle, economic activities, and technical efficiencies, considerable energy savings were incorporated in the scenarios.

These studies are meant to be a conceptualization of energy demand prospects over a fifty-year horizon: they are neither forecasts nor predictions. While they may accurately be labeled projections, their real value is more in the concepts illuminated rather than in the numbers themselves.

The analyses reported in this chapter were aided greatly by the use of the MEDEE-2 model.[a] This model, one in the set of IIASA energy models described in Chapter 13, offers a means of collecting and processing large numbers of assumptions and calculating resultant energy use. MEDEE-2 results are presented in this chapter for regions I through VI. For region VII (C/CPA), about which very little is known, a simpler model, SIMCRED[b] was used.

The approach adopted here for making energy demand projections using the MEDEE-2 model is a relatively detailed one. Once these detailed projections are made, they can be aggregated into demand categories such as transportation, household, agriculture, and industry. These broad categories, as well as the total, can then be analyzed and interpreted in terms of various elasticities including energy price elasticities (Chapter 15). Any unreasonable result in terms of elasticities is then a signal for reexamining the related combination of detailed assumptions and projections in the MEDEE-2 frame-

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[a] The MEDEE-2 model considered here was adapted at IIASA by B. Lapillonne and is described in Chapter 13 and in Lapillonne (1978).

[b] SIMCRED (Simulation Model based on Cross Country Regressions for Energy Demand) was developed by J.K. Parikh, at IIASA. A description of this model can be found in Parikh (1980).

work. Thus, the approach here is detailed energy scenario development for energy-influencing macroeconomic, lifestyle, and technological factors, followed by aggregate elasticity analysis.

An alternative approach would be to make energy demand projections on the basis of elasticities alone. In this approach (at whatever level of disaggregation is desired), energy demand is related to economic and energy price variables by means of elasticities (based on historical data or by assumption); energy demand estimates then result from projections of these economic and price variables. This approach is attractive, especially at the most aggregate level, because reasonable projections can be made with very little effort. The shortcoming is clear, however: no insight is gained on how and where energy conservation and improvement of efficiencies may occur. At a more disaggregated level, the elasticity approach offers no escape from detailed data analysis and from having to make detailed assumptions where data are insufficient for setting parameter values. Even at the detailed level, no insight is gained as to physical parameter changes that must occur—changes that are very helpful for judging whether scenario projections are reasonable.

There is no answer to the question as to which alternative yields more trustworthy projections—this depends on the frame of reference of the persons making the projections. The approach adopted here makes use of both alternatives—one primarily for generating projections (the detailed accounting framework of this chapter) and the other for interpreting these projections (the calculations in Chapter 15).

SOME DEFINITIONS

This chapter concentrates on estimating final energy consumption; the usual accounting schemes deal only with primary energy. The distinction is important. The various energy forms and levels have already been defined in Part I and are illustrated there in Figure 1-1. Here, some additional comments are in order.

Primary energy[c] (at the lower left of Figure 1-1) represents the energy content of extracted raw fuels—for example, crude oil or natural gas at the wellhead; coal at the mine mouth. Some primary fuels need to be refined or converted to secondary energy (in oil refineries or power plants) with typically rather large conversion losses (at least 60 percent losses in the case of coal converted to electricity), while others can be transported and used directly as secondary energy. Secondary energy, after transmission and distribution through major networks (e.g., oil or gas pipelines, delivery trucks, high and low voltage lines), becomes final energy. Electricity at the output, or busbar, of a power station is secondary energy; electricity at the home

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[c] Primary energy also includes fossil fuel equivalents of, for example, nuclear and hydropower conversion to electricity and the energy obtained from new sources such as solar, geothermal, wind, ocean thermal gradients, charcoal or wood fuels from forests, planned wood plantations, biogas, and so forth.

wallplug is final energy. Final energy is energy delivered to final consumers—oil delivered to burners in the basement or to industrial boilers.

Final energy is what the consumer buys. What one actually benefits from is useful energy—the heat that warms living rooms, for example. Produced photons, heated air, and kinetic energy are useful energy. All of the conversion losses, from primary through to at least final energy (and sometimes, if possible, through to useful energy), are counted in the analyses here and are shown in the detailed presentation or results in these pages and in supporting documents.

As there is a law of energy conservation, the balance is easy to calculate for each and every stage shown in Figure 1-1. Ultimately, primary energy becomes waste heat through one or another channels of energy transfer—photons become absorbed, heated air dissipates, kinetic energy is used up in friction. In short, energy is not really "consumed" at all: energy "demand" is an inexact notion. What is demanded instead is energy services. Energy services are provided when, for example, photons illumine book pages, warm air heats living rooms, kinetic energy keeps automobiles moving. The well-lit pages, the comfortable rooms, and the moving vehicles are the services demanded—services that, not being energy, do not (broadly speaking) obey laws of conservation.

ENERGY SERVICES

To take a trivial but instructive example of energy services, imagine a potter. He has a potter's wheel, a motor for driving the wheel, spatulas—and his skill. As he progresses, his daily output of pottery increases, he produces less scrap, his skill improves. The amount of sustained influx of kinetic energy per output of pottery has decreased; useful energy has been partly substituted by skill. Encouraged, our potter buys a more sophisticated potter's wheel. His daily output increases further and in turn the amount of sustained influx of kinetic energy per output of pottery has decreased. The potter therefore demonstrates that energy services can be substituted by services of capital stock and skill.

A homeowner can do the same. With greater investment in, for example, insulation (capital) and careful building design (know-how), he can reduce his energy services requirements—and his monthly heating bill. Ultimately, energy conservation is obtaining more energy service from less energy input—even if more capital, and/or labor, and/or know-how is being used.

In Chapter 21, on energy, negentropy, and endowments, the fundamental reasoning behind these considerations will be elaborated.

Table 16-1. Global commercial energy use in 1975, base year (GWyr/yr).

	Coal	*Oil*	*Gas*	*Electricity*	*District Heat*	*Hydro*[a]	*Nu-clear*[a]	*Total*
Transportation	45	1272	0	16	0	0	0	1333
Industry[b]	729	722	620	359	170	0	0	2600
Household-Service	285	547	382	249	48	0	0	1511
Feedstocks[c]	0	298	0	0	0	0	0	298
Final energy	1059	2839	1002	624	218	0	0	5742
Transportation and distribution losses	38	0	97	91	10	0	0	236
Secondary energy	1097	2839	1099	715	228	0	0	5978
Inputs to electricity[d] and distributed heat	1069	534	359	[-734]	[-277]	497	119	1567
Other losses[e]	91	455	49	19	49	0	0	663
Primary energy	2257	3828	1507	0	0	497	119	8208

[a] Hydro- and nuclear-generated electricity are given in terms of fossil primary energy input equivalent.

[b] Industry includes agriculture, construction, mining, and manufacturing.

[c] Feedstocks include nonenergy uses of fuels. (Natural gas used to make fertilizers is included in "industry.")

[d] The inputs to electricity generation are primary equivalents of the sources; these figures include primary sources used in cogeneration facilities. (The -734 figure under "electricity" represents the secondary [busbar] electricity generated from the several primary sources.)

[e] "Other losses" include all primary to secondary losses (e.g., primary transport, oil refining); they also include bunkers (210 GWyr/yr of oil in 1975)—energy used in international shipments of fuel.

Sources: Based on data from United Nations (1977a); United Nations (1978); OECD (1976); World Energy Conference (1978); Economic Commission for Europe (1976); Smil (1976); CIA (1975); Kambara (1974); Vigdorchik (1976); Beschinsky and Kogan (1976); Petro Studies Co. (1978).

ENERGY DISTRIBUTION IN 1975 AND A RATIONALE FOR PROJECTIONS

In 1975, the world was consuming (commercial) primary energy at an average rate of 8.2 TWyr/yr, which is equivalent to some 8.5 billion (10^9) tons of coal per year or to some 110 million (10^6) barrels of oil per day (mbd).[d]

In terms of secondary energy, the world in 1975 used about 6 TWyr/yr, as seen in Table 16-1, while total final energy use was 5.7 TWyr/yr. Although these global totals tell us something about how much of which kind of energy was used, they reveal little about where—in which economic sector or

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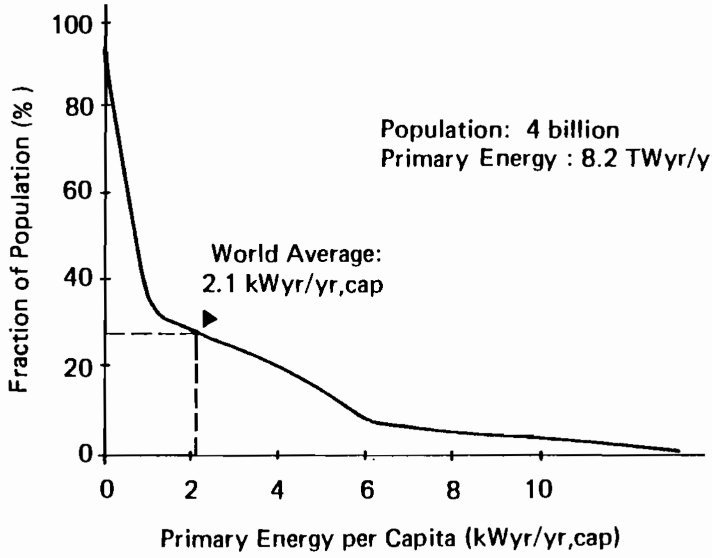
[d] For more precise conversion of energy units, see Appendix 1B.

Figure 16-1. Global per capita commercial primary energy consumption, 1975. Values show fraction of population whose primary commercial energy consumption is smaller than the corresponding value on the horizontal axis.



in which country—energy was used. This latter information is exceedingly important for projecting energy demand.

Present per capita energy use around the world is very unevenly distributed. In 1975, the global average per capita consumption of commercial primary energy was 2.1 kWyr/yr—or a total of 8.2 TWyr/yr for a global population of four billion people. However, about 60 percent of the world's population exist with less than one-half of that amount, and only about 7 percent of the people in the world consume energy at rates greater than 7 kWyr/yr, cap. Figure 16-1 graphs these inequities; the United States and Canada (and Luxembourg) provide the data for the right-hand side of the diagram.[e]

The maldistribution of energy use has deep implications for future energy consumption. Responsible technological planning and energy scenario building should attempt to even this heavily skewed distribution. At what level it should become even is an open question. One simple possibility, of course, is for energy use to stabilize at the present global average of 2.1 kWyr/yr, cap. This is the value today in Greece, Spain, and Singapore, for example.

Developing countries will continue to require energy growth, substantial

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[e] Of course, there are many reasons why some countries (e.g., those that export large quantities of energy-intensive products) have higher per capita energy consumption than others. It is not the purpose here to cast value judgments on consumption levels. Surely, the distribution of Figure 16-1 generally illustrates inequities, waste, and inadequate energy provisions in most of the world.

energy growth, in order to achieve industrialization and human betterment goals. There seems little doubt about this. One fact supporting this assessment is the high and relatively constant level of energy consumption per unit of area in cities in both the developed and the developing countries (see Chapter 23 for a discussion of this subject). This, coupled with projections for dramatically increasing urbanization in most of the developing countries, leads to clear indications of substantial and inevitable energy growth in these countries. The challenge is to provide the requisite energy efficiently and effectively—to facilitate development in the developing regions while avoiding transfer of any of the wasteful energy excesses of some developed regions.

These issues have a great bearing on the globe's energy future. Because of it, one must consider the present position of developing countries with care.

ENERGY CONSUMPTION IN DEVELOPING REGIONS[f]

Some Basics[g]

The search for effective and speedy means of meeting human needs and hopes is accentuated in the developing countries by their present plight—the great distance between practice and potential, realities and aspirations. The challenges to development in the developing regions are substantial; they reflect individual and societal distresses that call for fresh thinking and innovative solutions. Distinctive characteristics of economic structure, cultural patterns, and political goals in the developing regions cannot be ignored. The implications for energy requirements, particularly over the long term, are large and serious.

Here, only a few of the distinctive characteristics of the developing regions are outlined. In economic terms, the regions have (typically) low per capita income levels, high consumption and low investment rates, relatively large agriculture sectors, (usually) large and life-giving imports and foreign aid, and supply-constrained (rather than demand-driven) growth patterns. Most of the developing countries seem to be heading toward steady industrialization and rapid urbanization, although there may be some slackening of the latter trend in some places. In energy terms, national total and per capita energy consumption levels are very low; the share of oil among commercial energy uses is often high; and noncommercial energy plays an important baseline role, particularly in rural areas and, to a certain extent, in households in urban areas.

These are generalizations, to be sure. But they convey some impressions and some learning. They imply, almost certainly, the considerable likelihood

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[f] "Developing regions" here refers to regions IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA). Occasionally excluded is region VI (when only nonoil-exporting countries are meant) or region VII (China is often a special case). These occasions will be clear by statement or implication.

[g] A detailed description of these observations may be found in the work of Parikh (1980).

of major increases in energy demand in the future. And they may indicate that the developing regions could have a higher flexibility in choosing among future energy supply and industrial options than the developing regions. Some of the specific data that lay behind these observations are reported in Table 16-2 for two of the developing regions—IV(LA) and V (Af/SEA).

Low Energy Consumption. The exceedingly low level of commercial energy consumption in many developing countries is a difficult fact for many to grasp. For contrast, North America recently (1975) had 11 kWyr/yr, cap; the USSR and Eastern Europe, about 5 kWyr/yr,cap; Western Europe about 4 kWyr/yr,cap. In the developing regions (IV-LA, V-Af/SEA, VI-ME/NAf, and VII-C/CPA) in 1975 consumption was 1.1, 0.2, 1, and 0.5 kWyr/yr,cap, respectively. Consider some typical examples: in 1975 Brazil

Table 16-2. Energy in two developing regions, 1965 and 1975.

	1975	
	Total	*Rural Fraction*
Population (10^6)		
Region IV (LA)	319	0.40
Region V (Af/SEA)	1422	0.78
	Total	*Share of Agriculture*
GDP (10^9 \$)		
Region IV (LA)	340	0.12
Region V (Af/SEA)	340	0.36
	1965	*1975*
Total primary energy (including noncommercial) (TWyr/yr)		
Region IV (LA)	0.278	0.447
Region V (Af/SEA)	0.442	0.672
Share of oil		
Region IV (LA)	0.46	0.51
Region V (Af/SEA)	0.15	0.24
Share of noncommercial energy[a]		
Region IV (LA), of which	0.35	0.24
Wood	0.28	0.18
Agricultural wastes	0.07	0.06
Region V (Af/SEA), of which	0.61	0.51
Wood	0.41	0.34
Agricultural Wastes	0.20	0.17

[a] Noncommercial energy is expressed here in terms of its calorific heat content and not as a replacement equivalent of fossil fuels. The efficiencies of use of noncommercial and commercial fuels are quite different (see text).

Sources: For GDP and share of agriculture see United Nations (1977b) and World Bank (1977). For rural fraction see United Nations (1976b). For commercial energy see United Nations (1976a, 1977a). Estimates of noncommercial energy are based on data from FAO (1976, 1977a); Parikh (1980).

had 0.7 kWyr/yr,cap; India, 0.2 kWyr/yr,cap; and about 30 African and Asian countries–including Bangladesh, Burma, Ethiopia, Nigeria, Uganda–used primary energy at the rate of less than 0.1 kWyr/yr,cap.

High Oil Share. Current oil prices are high, as the whole world knows. But they have been low, and oil is easy to transport. Even without expensive high voltage lines or underground pipelines, oil in tincans can reach even the remotest of villages. As a result, the oil shares of total primary commercial energy in 1975 were 67 percent in Latin America and 49 percent in Africa and South Asia. Many countries–Peru, Thailand, and Kenya among them–have 80 and 90 percent or more (of commercial primary energy) oil shares. In regions I (NA) and III (WE/JANZ) the shares were 44 percent and 56 percent, respectively; in the oil-rich Soviet Union it was 39 percent. But oil must be imported to many developing countries, and this strains hard currency reserves that are also needed in no small measure for imports of food, equipment, and spare parts. The oil payments outflow in many developing countries is serious; in some countries 30 percent and even more of export earnings go to oil purchases.

Rural Electrification Backlog. Vast rural areas in many developing countries are without electricity. Only 15 percent of the rural population in Latin America and Asia have electricity; less than 4 percent of Africa's 80 percent rural population does. At the same time, the degree of electrification, and in particular its consumption density in urban areas in these countries, is comparable to that in the urban areas in developed countries.

Noncommercial Energy. The role of noncommercial energy in rural areas in the developing countries is difficult to measure. In 1975, these sources provided probably about 24 percent of total energy in Latin America (region IV) and as much as 51 percent in region V (Af/SEA). But these shares have been declining–from 35 percent and 61 percent, respectively, in 1965. Obviously, this trend is important for estimates of future consumption of comcial fuels.[h]

Wood continues to play a major noncommercial energy role in the developing regions, and its use has been growing in Africa and Asia at over 4 percent per year for the past two decades (see Table 16-3). About 70 percent of noncommercial energy use today is met by fuelwood–village women trudging several kilometers each day in gathering and carrying. The resulting long-term deforestation effects have led to recognition of a possibly imminent "fuelwood crisis." The problems of energy use in the developing regions are not small; they may not be purely local, either. For example, the harvest of noncommercial fuels usually works to aggravate environmental problems

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[h] Noncommercial energy's main role is in the household, and its present end use efficiency is typically 10 to 20 percent of that of fossil fuel. As a result, the current share of noncommercial fuels in useful energy is much lower–less than 10 percent in region IV (LA) and less than 20 percent in region V (Af/SEA).

Table 16-3. Consumption of fuelwood, 1951-1975.[a]

Region	*1951 (GWyr/yr)*	*1961 (GWyr/yr)*	*1975 (GWyr/yr)*	*Growth Rate (%/yr)*
IV—Latin America	59	70	84	1.5
V—Africa (except Northern Africa and South Africa)	35	75	101	4.5
South and Southeast Asia	47	93	128	4.3

[a] 2.7 m^3 of wood = 1 kWyr

Source: FAO (1977a, 1966, 1962).

such as deforestation and soil erosion, and pollutants and smoke from these fuels are serious health hazards. The tasks for the future are both large and complicated. But they are critically important ones for the well-being of most (if not all) of earth's inhabitants.

Long-term Projections for Developing Regions

These observations and interpretations about present-day developing regions have led to methodologies and assumptions for projecting energy growth in these regions. In the results presented here, use has been made of mathematical computer models and the expertise of scientists at IIASA from developing countries. The detailed inputs to and results of projections for the developing regions are reported in this and the next chapter, along with the inputs and results for other regions. Here, some of the major findings for the developing regions are summarized.

In 1975, the developing regions—regions IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA)—accounted for 15.7 percent of total global primary (commercial) energy. By 2030, under the assumptions of the High and the Low scenarios, they would represent 38 to 43 percent of this global total. Clearly, much of the global growth in energy consumption and many of the new energy markets are in the developing regions. By 2030, per capita levels of consumption in the developing regions would have grown substantially, but in most instances they would not have reached 1975 West European (4 kWyr/yr,cap) levels. Only region IV, Latin America, and region VI, the Middle East and Northern Africa, could be nearing, by 2030 (especially in the High scenario), a status that could be called "developed."

The important role of noncommercial sources at present in developing economies cannot be overlooked. Noncommercial energy use in regions IV and V is estimated to drop from 30 and 58 percent, respectively, of total final energy demand in 1975 to about 5 and 10-15 percent by 2030 in the two scenarios.Yet even these numbers are somewhat overstated. If noncommercial energy is counted in useful terms, the same percentages are about 6 and 17 percent for 1975 and would be about 1 and 2-4 percent in 2030, in spite of an assumed 60 to 100 percent improvement in its end-use efficiency. The very low conversion efficiencies of noncommercial sources into useful energy exaggerates their magnitude if counted on a primary or, even more so, on a final equivalent basis. This is an important distinction. It is assumed that by the year 2030, regions IV, V, and VI would continue to use about as much noncommercial energy as they did in 1975, but this would be a continually diminishing fraction of total energy use.[i]

These observations on the prospects for the developing regions provide background for the discussion of energy use worldwide, in region-by-region comparable detail.

A SUMMARY OF ENERGY DEMAND RESULTS[j]

The results summarized here are based on the High and Low scenarios defined in Chapter 15. Many exogenous assumptions, judgments, and data are required to produce the energy demand estimates presented here. These inputs will be described in subsequent sections of this chapter.

If the High and Low scenarios span a plausible range of future possibilities, then (as already noted in Chapter 15) energy demand growth would slow down overall, especially if compared with recent historical trends. The scenario assumptions lead to growth rates of global primary energy demand declining from an average of nearly 4.8 percent per year over the past twenty-five years to an average of 1.9 to 2.8 percent per year in the next fifty years. Table 15-2 recorded the totals—primary energy consumption of roughly 36 TWyr/yr in the High scenario and 22 TWyr/yr in the Low scenario by 2030.

Based on the assumptions of the High scenario by 2030, global primary energy consumption would be about 4.5 kWyr/yr,cap—the present level in France, Poland, and the United Kingdom. With the Low scenario, the global 2030 average would be about 2.8 kWyr/yr,cap, the present value in Italy and Ireland.

But the inequities in energy consumption among regions abate only slightly by 2030 under the conditions of these scenarios. Regions are distinctly different; for example, both the High and the Low scenarios allow somewhat higher (although hardly an excess of) per capita energy growth for the developing regions than for the developed regions, recognizing the saturation effects and slower growth in the latter. Although the High scenario offers considerably increased economic development for the developing regions (see Chapter 14), it could be argued that even this amount falls short of their worthy goals and aspirations. The shape of the energy future hinges on the successful development of conventional, uncon-

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[i] This does not mean that uses of wood or agricultural wastes, for example, should be put to an end. In addition to continued noncommercial supplies, the supply analyses (Chapter 17) describe the possibilities of using produced and harvested wood or plantation crops, or the conversion of farm wastes into methane, as commercial energy sources.

[j] For a complete description of base year information, assumptions concerning projections, and results see Khan and Hölzl (1980).

Table 16-4. Per capita final energy consumption, two scenarios 1975 to 2030 (kWyr/yr, cap).

Region	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
I (NA)	7.89	9.25	11.63	7.95	8.37
II (SU/EE)	3.52	5.47	8.57	4.98	6.15
III (WE/JANZ)	2.84	4.46	5.70	3.52	3.90
IV (LA)	0.80	1.75	3.31	1.28	2.08
V (Af/SEA)	0.18	0.42	0.89	0.32	0.53
VI (ME/NAf)	0.80	2.34	4.64	1.76	2.46
VII (C/CPA)	0.43	0.93	1.87	0.64	0.93
World	1.46	1.96	2.86	1.58	1.83

Note: The figures are average rates of final energy use, averaged over the population and the year. The figures for regions I through VI result from the many assumptions and calculations for each of the scenarios, using the MEDEE-2 model; the figures for region VII are based on SIMCRED model runs.

ventional, and alternative energy resources at acceptable costs in many parts of the world. Certainly much of the potential for growth in the centrally planned economies of region II (SU/EE) depends on the successful development of the vast and resource-rich areas of Soviet Asia.

Per capita final energy consumption figures (Table 16–4) show relatively slow growth in this indicator in the developed regions and the more rapid growth in the developing regions—moderated by high population growth rates. Whether these reflect acceptable levels of improvement in developing regions remains to be seen.

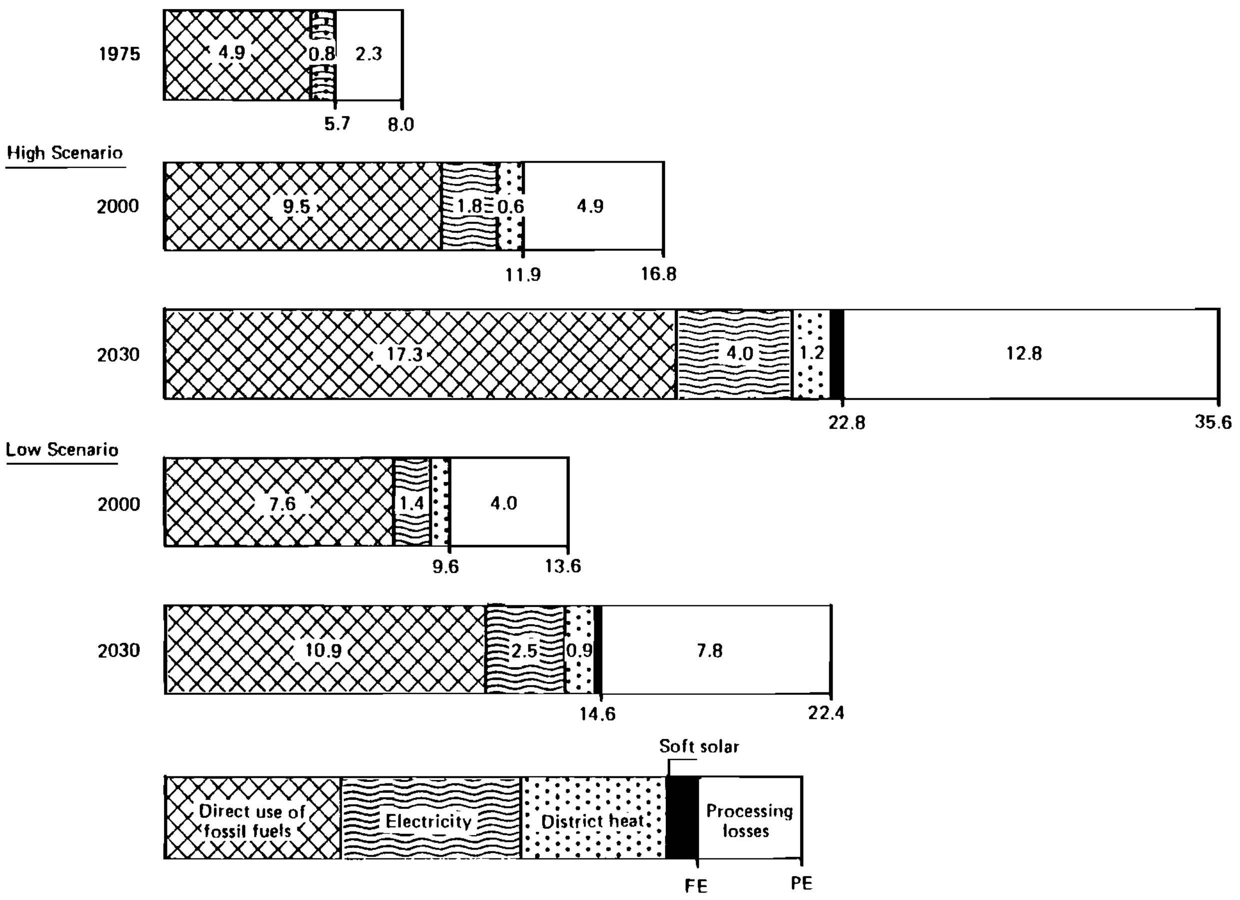
Figure 16-2 summarizes the projections of global final and primary energy use over the coming decades on the basis of the High and Low scenarios. Note the relatively rapid growth in electricity use and, attendantly, in processing and conversion losses. These trends result from assumptions of increasing electrification (although almost solely for special purposes) and from declining relative availability of liquid fuels. The assumptions underlying the final energy projections are given in detail in subsequent sections of this chapter.

ELECTRIFICATION ASSUMPTIONS

The degree of electrification in each of the world regions results from a set of scenario assumptions affecting the relative use of electricity and other fuels for various sectoral activities. These scenario assumptions follow the relative price changes of electricity and competing fuels that result from successive iterations through the modeling loop of Chapter 13.

Electrification is seen in the analyses here to be demand driven in the near term, with significant supply limitations imposing constraints over the

Figure 16-2. Global energy demand projections, 1975–2030. FE = total final energy use; PE = total primary energy use. Units: TWyr/yr.



medium and the long term. Over time, the trend of increasing penetration of electricity into end use markets slows down significantly, especially in developed regions.

In summary, the electrification assumptions are as follows:

- Electricity use of "essential electric" purposes such as motive power in industry, aluminium production, lighting in buildings, home appliances, and computers would grow in the scenarios at a rate comparable to growth in sectoral activities.
- Electricity would modestly enter the heat market in buildings for space heating, water heating, and cooling. For example, it is assumed that by 2030 roughly 17 percent of home heating could be provided by electricity in regions I (NA) plus III (WE/JANZ) (from 8 percent in 1975) and about 7 percent in the developing regions (VI-LA plus V-Af/SEA plus VI-ME/NAf) in 2030 from just 1 percent today.
- Electricity would also penetrate the industrial heat market to a certain extent; to do so, it would compete not only with fossil fuels but, increasingly, with solar and cogenerated heat. By 2030, 10 percent of industrial process and space heat is assumed to be provided by electricity in each of regions I, IV, and VI, 4 to 5 percent in regions III and V, and 5 to 10 percent in region II.
- Electricity use for transportation is assumed to increase in all regions because of increasing electrification of railways and urban mass transit systems in metropolitan areas and also because of a likely shift from gasoline cars to electric cars in urban travel. The share of electricity in transportation energy would thus increase to 1 to 2 percent of all transportation energy use in 2030 in regions I, IV, V, and VI from virtually zero today. In regions II and III, the shares may be as high as 9 and 4 percent, respectively, by 2030.

An additional comment on transportation energy is in order here. In region I (NA), no electrification is assumed for freight trains; for passenger trains, 20 percent of passenger km are with electric trains, compared to 1 percent in 1975, and 50 percent of mass transit is assumed to be electric. However, because of the insignificant share of rail and urban mass transit in this region, electricity used for transportation is and would remain low. In region III (WE/JANZ), on the other hand, 9 percent of the freight service (30 percent of rail freight) is performed on electric trains, and this share is projected to increase to 15 percent by 2030 (50 percent of rail freight). Similar shares can be observed for intercity passenger transport, and urban mass transit plays a significant role in this region. Because of the higher end use efficiencies of electric modes of transportation relative to modes using motor fuel, the electricity share appears to be low even for this region, despite the large share in service. Figure 16-3 and Table 16-5 provide some of the details about electrification in the scenarios.

Electrification rates could substantially exceed the ones assumed here if heat pumps penetrate appropriate markets surprisingly rapidly or if elec-

Figure 16-3. Electricity in two scenarios by region, 1975-2030.

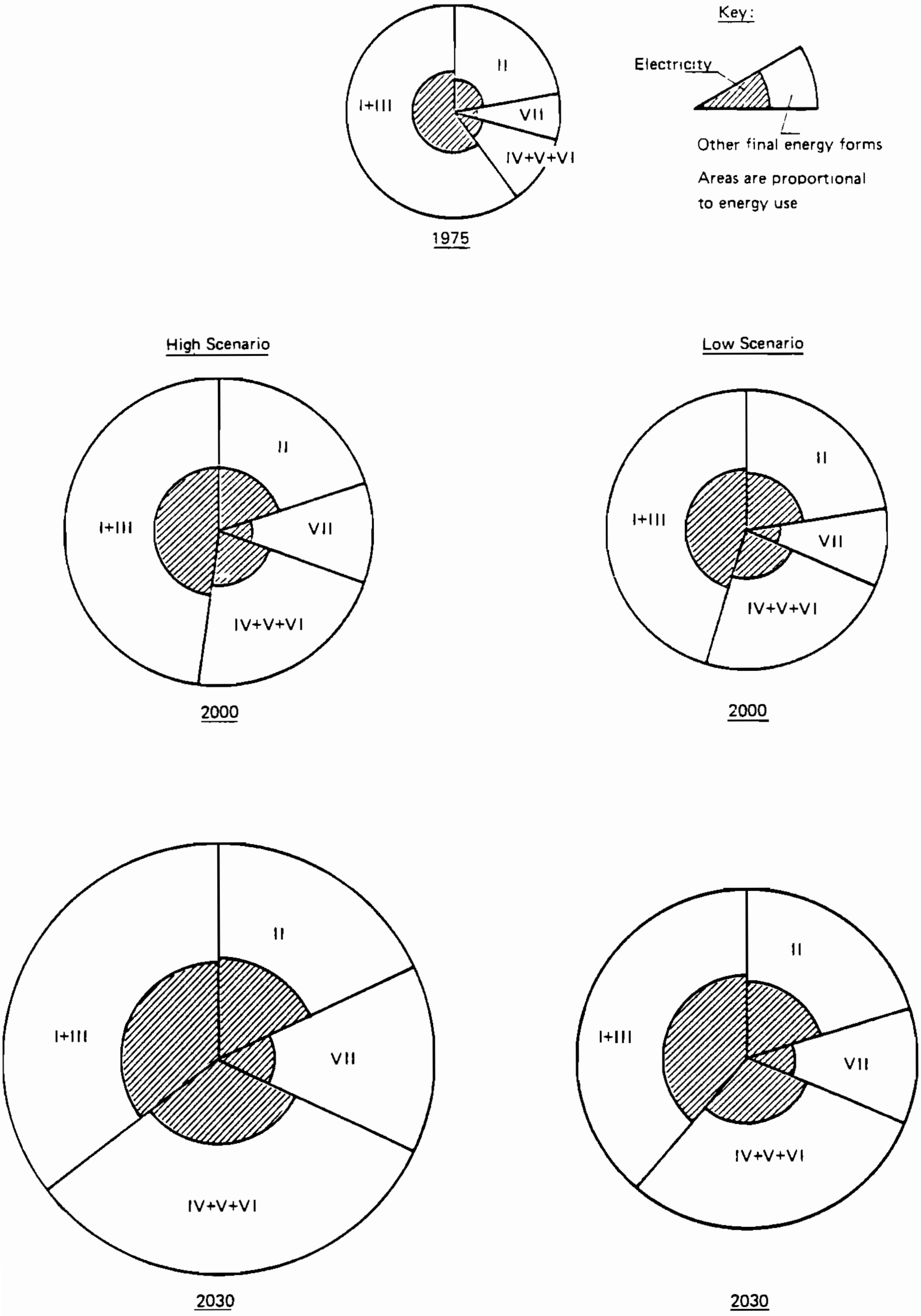


Table 16-5. Household use of electricity, 1975 and scenario assumptions (10^3 kWh/household).

Region	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
I (NA) total electricity	9.4	13.0	15.0	11.9	12.9
(% thermal uses)[a]	(59)	(52)	(47)	(56)	(52)
II (SU/EE) total electricity	1.2	3.9	6.5	3.0	4.3
(% thermal uses)	(25)	(26)	(23)	(29)	(30)
III (WE/JANZ) total electricity	3.1	6.0	9.1	5.3	7.1
(% thermal uses)	(38)	(39)	(34)	(38)	(36)
IV (LA) total electricity	0.7	1.9	4.2	1.4	2.7
(% thermal uses)	(3)	(11)	(20)	(13)	(21)
V (Af/SEA) total electricity	0.05	0.2	0.5	0.1	0.3
(% thermal uses)	(1)	(4)	(8)	(3)	(11)
VI (ME/NAf) total electricity	0.2	1.2	4.3	0.9	1.8
(% thermal uses)	(9)	(22)	(23)	(19)	(33)

[a] Thermal uses include air conditioning.

Notes: Only for region I (NA) were sufficient statistics available; for other regions estimates come from partial data and/or data for selected countries. Consumption of electricity per household for specific uses (lighting, electrical appliances) is a direct assumption; consumption for thermal uses results from separate assumptions on useful energy consumption for space heating, water heating, cooking, and air conditioning and from assumed penetration of electricity into these markets.

tricity proves to be cheaper than substitute fuels. The latter is not felt to be likely in many regions in this study, although in region II (SU/EE), a substantial body of opinion today sees nuclear power costs actually declining in the future. If this were to occur, electricity penetration would be higher than indicated in Figure 16-3 and Table 16-5.

Electricity today accounts for between 10 and 13 percent of final energy in the developed regions (I, II, and III), while only 6.5 percent of final energy is electricity in the developing regions (IV, V, VI, and VII), ranging from about 10 percent for region IV to less than 4 percent for region VII.

These assumptions produce an increase in electricity use globally to 2030 of 2.6 to 3.4 percent per year in the Low and High scenarios, respectively—from 2 to 3 percent per year in regions I and III, to 3 to 4 percent per year in region II, 4 to 6 percent per year in regions IV and V, and 6 to 8 percent per year in region VI. These growth rates are about one-half of the current rates in most of the world. Electricity is saturating in its uses in many developed countries. Electricity growth is still higher than overall energy growth—a factor of about 1.4 higher globally, compared to factors typically 2 times higher in recent decades.

"Essential" uses of electricity make up a fairly significant fraction of total final energy use in all regions. By 2030, the scenarios lead to some 20 to 30 percent (or more) of total final energy in buildings being devoted to electricity for appliances, lighting, cooling, and air conditioning. In industrial sectors, the shares of electricity for lighting, motor drive, electrolysis, and electric furnaces are typically 15 to 20 percent by 2030. The increasing shares in the scenarios reflect the relatively greater savings possible for other energy uses.

Assuming average 70 percent load factors of power plants and 15 percent losses in transmission and distribution (the 15 percent figure represents the average of all losses from power station busbar to home wallplug), the installed capacity required to generate the electricity of Figure 16–3 becomes 3550 to 4390 GW(e) in 2000 and from 6320 to 9845 GW(e) in 2030.[k] (The 1975 total world installed electric capacity was nearly 1600 GW(e).) Can the world build such capacity? What are the available sources for such generation? These questions are dealt with in the overall supply estimates and major supply "alternatives" reported in Chapters 17 and 18.

ENERGY CONSUMPTION IN SECTORS: ASSUMPTIONS AND RESULTS

The Sectoral Shares: GDP, Demographics, and Energy

The analytical approach embodied in MEDEE-2 calls for a detailed specification of the overall economic growth projections—in particular, a sectoral breakdown of GDP. This detailing is necessary in order to incorporate some important energy-influencing pieces of information, including anticipated changes in the investment and consumption rates in GDP and in the mix of manufacturing activities; expected changes in demographics (urbanization, family size, labor force participation); likely evolutions of certain socioeconomic activities (transportation systems planning, use of energy-consuming equipment, etc.); and perceived changes in lifestyles.

The disaggregation of the GDP projections of Chapter 14 into more meaningful sectors is not an easy task. There is no universally accepted method for projecting the evolution of various socioeconomic activities and related technological parameters over a period of several decades. There is also an acute shortage of disaggregated relevant data; sufficiently detailed data on energy consumption are available only for a few countries (mostly developed), and even then, such data have been compiled for only a few years. The scenario assumptions here were developed on the basis of judgments guided by past trends, interregional and intercountry comparisons (wherever appropriate), estimated relationships reflecting the interdependence between various economic and social activities, and estimated prospects of future technological developments.

In short, the process is one of estimating large numbers of detailed parameters, all (or most) influenced directly by the total GDP projections. These scenario assumptions and the resulting sectoral and subsectoral energy demand projections are not deterministic, but simply guidelines for understanding the nature of future energy demand.

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[k] The installed capacity figures result from the supply analyses described in Chapter 17. The figures quoted for load factors and losses in transmission and distribution are average on typical figures; more precise numbers are given in Chapter 17.

As a first step, GDP in each region is disaggregated into three broad sectors—agriculture, industry (manufacturing, mining, construction, and energy), and service. Table 16-6 records the assumptions made for six of the world regions. These changes in economic structure over the next fifty years are assumptions. They are based on past data, observed trends, and national expectations. The changes are generally greatest in the developing regions, which are, in these terms, developing—shifting GDP more and more (relatively) from agriculture to industry. In developed regions, the expected shift is toward more services.

Disaggregation of the demographics projections of Chapter 14 is necessary in order to consider the final consumption of energy demand in a sufficiently detailed way. The assumptions of Table 16-7 illustrate the expected trends—increased urbanization throughout the world; slightly increasing economically active population fractions, especially in the developed regions; and reductions in family sizes in all regions. (Such estimates are important—for example, changes in average energy use per capita can vary considerably with changes in average family size.)

With these inputs, final energy consumption is calculated in detail in MEDEE-2. Aggregating these results into three broad groups (household-service, industries, and transportation) yields the figures in Table 16-8. Regional differences in sectoral use of energy are apparent. These differences seem to persist in spite of the fact that economic and demographic structures in some of the regions have been assumed to undergo considerable changes over the next fifty years.

Table 16-8 illustrates that the share of final energy used in buildings is, throughout, much higher in the developed regions (I, II, and III) than in the developing regions (IV, V, and VI), as one would expect. In addition to low space heating requirements in the developing regions, this is also because of the considerable dependence of these regions on noncommercial fuels for domestic use. Also, building energy use is low in these projections because of saturation effects, which can be seen in almost all the world regions.

Transportation activities in the developing regions make up a relatively high share of final energy in 1975, and the trend, in general, shows a slight increase in both scenarios. This is because of a considerable increase in freight transportation, projected to grow with industrial output and because of expected increase in personal travel and a reduction of average load factors. Among the developed regions, the relative shares of transportation and industrial activities are markedly different in regions I (NA) and III (WE/JANZ) and region II (SU/EE), mirroring the differing emphases on industrial activity and personal transportation in the two types of economies.

Transportation Energy

Energy used in moving people and goods around is high everywhere—from about 18 percent of total final energy consumption in 1975 in region II (SU/EE), to 30 percent in regions I (NA) and V (Af/SEA), to about 40 per-

Table 16-6. GDP sectoral shares assumptions (percentage of GDP).

	1975			High Scenario 2030			Low Scenario 2030		
Region	*Agriculture*	*Industry*[a]	*Service*	*Agriculture*	*Industry*[a]	*Service*	*Agriculture*	*Industry*[a]	*Service*
I (NA)	2.8	32.4	64.8	1.5	29.0	69.5	2.0	32.2	65.8
II (SU/EE)	10.7	50.3	39.0	4.0	41.0	55.0	7.0	43.0	50.0
III (WE/JANZ)	5.8	45.7	48.5	2.5	39.5	58.0	3.0	42.0	55.0
IV (LA)	12.2	35.5	52.3	4.6	47.0	48.4	6.5	43.0	50.5
V (Af/SEA)	36.1	25.5	38.4	16.2	38.2	45.6	23.2	34.8	42.0
VI (ME/NAf)	7.0	66.0	27.0	2.3	46.7	51.0	4.0	54.4	41.6

[a] Industry includes manufacturing, mining, construction, and energy sectors.

Sources of data for the base year (1975): regions I, II, and III—United Nations (1977c); regions IV, V, and VI—United Nations (1977b); and data on various region VI countries supplied by the Arab Fund for Economic and Social Development, Kuwait.

Table 16-7. Demographic assumptions.

Region	1975			2000			2030		
	Persons per household	*Population in large cities*[a] *(%)*	*Economically active population*[b] *(%)*	*Persons per household*	*Population in large cities*[a] *(%)*	*Economically active population*[b] *(%)*	*Persons per household*	*Population in large cities*[a] *(%)*	*Economically active population*[b] *(%)*
I (NA)	2.98	36	44	2.48	37	44-48	2.24	38	44-51
II (SU/EE)	3.70	58	39	3.00	70	42-45	2.70	80	45-51
III (WE/JANZ)	3.00	49	45	2.72	52	49-50	2.56	55	50-52
IV (LA)	5.10	37	32	4.80	53	37	4.15	69	41
V (Af/SEA)	5.24	13	38	4.80	23	44	4.15	44	49
VI (ME/NAf)	5.25	29	27	4.90	45	31	4.35	65	36

[a] Large cities refer to urban agglomerations as classified in official statistics in region II; in regions I and III with more than 50,000 persons; and in regions IV, V, and VI with more than 100,000 persons.

[b] Economically active population is total labor force as a share of total population.

Sources of base year data (and some projections) United Nations (1976b, 1974); FAO (1977b); Paxton (1976); CMEA (1976); U.S. Department of Commerce (1976); Statistics Canada (1975); and Keyfitz (1977).

Table 16-8. Shares of sectors in final energy demand (percent of final energy).

	1975			*High Scenario 2030*			*Low Scenario 2030*		
Region	*Transportation*	*Industry*[a]	*Buildings*[b]	*Transportation*	*Industry*[a]	*Buildings*[b]	*Transportation*	*Industry*[a]	*Buildings*[b]
I (NA)	29	40	31	28	52	20	26	50	24
II (SU/EE)	18	59	23	19	64	17	19	63	18
III (WE/JANZ)	20	51	29	25	52	23	23	49	28
IV (LA)	41	47	12	44	46	10	44	43	13
V (Af/SEA)	30	59	11	29	62	9	32	55	13
VI (ME/NAf)	39	47	14	37	52	11	36	50	14

[a] Industry includes agriculture, manufacturing, mining, and construction.

[b] Buildings in the household and service sectors.

cent in regions IV(LA) and VI (ME/NAf). For the world the figure is 24 percent. Of course the ways in which this energy is used (the mix of transport modes—automobiles, buses, trains, trucks, planes—and the fuels used) vary considerably from country to country. But the end result is usually a large share of energy use in transport, and it is growing.

In the United States, for example, transportation consumes directly about 30 percent of total final energy. If one counts all the indirect uses—energy used to make automobiles, energy used to make steel to make automobiles, energy used in road construction, and so forth—the figure is well over 40 percent.

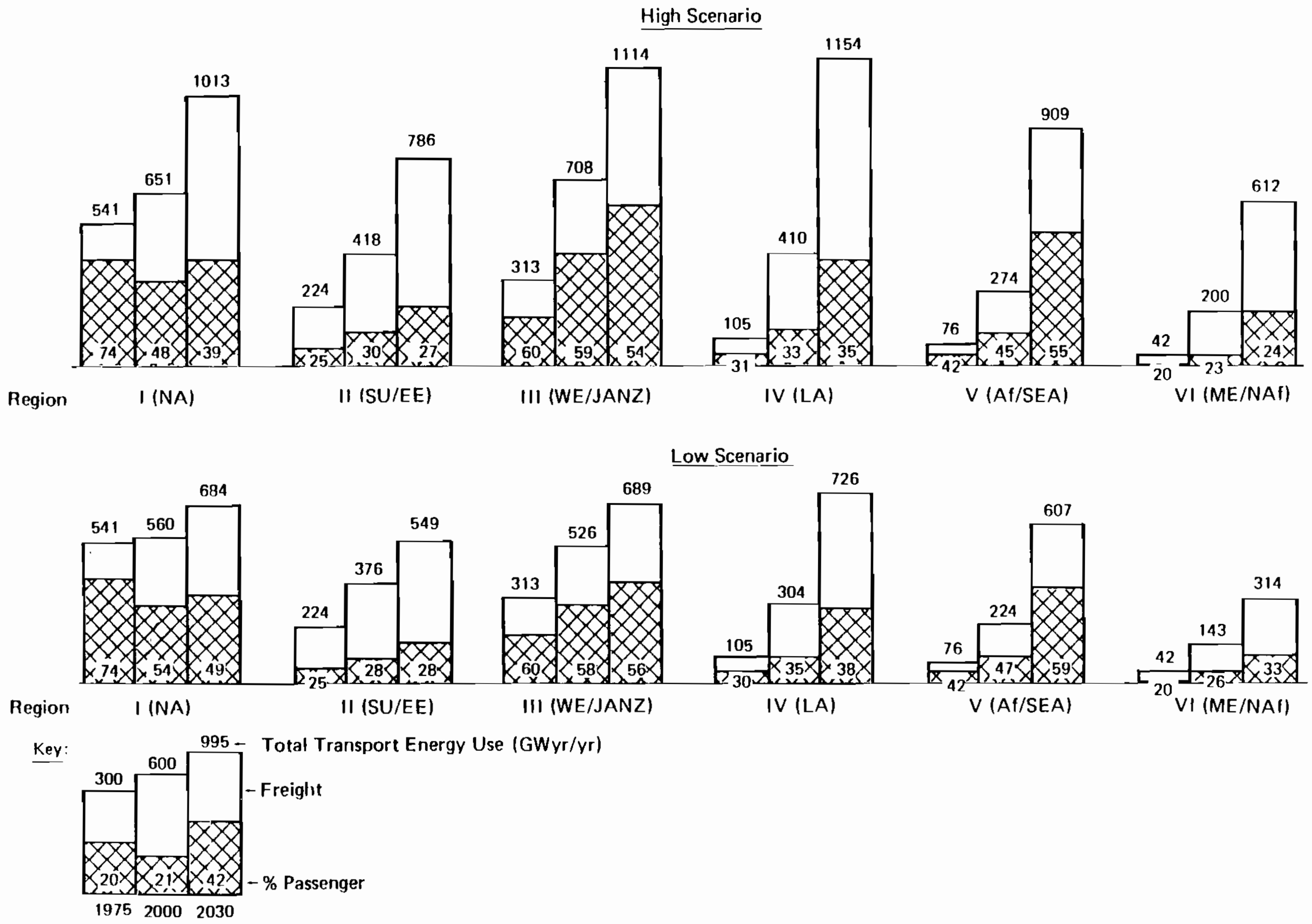
The analysis reported here foresees some changes in this picture—relatively slower growth in personal travel in the developed regions (except for air travel), moderately increased use of public transportation for urban travel (a consequence of cities' growing congestion), and greater economies of gasoline consumption. These assumed changes are due to relative price increases, changes in public perceptions about energy availabilities (which may or may not be accompanied quickly by price changes), and government mandates.

The results are strikingly different in different parts of the world, as illustrated in Figure 16-4. Region I (NA) evidences the smallest relative increase in transportation energy use, although the high mobility, great distances, and large (but slowly shrinking) automobiles of the United States and Canada keep the absolute level of energy use high. In region III (WE/JANZ), mobility continues to increase steadily in these projections among all modes of transport.

In region II (SU/EE), transportation energy use is currently low compared to that in both regions I (NA) and III (WE/JANZ), despite large distances. The main factors for this contrast are the large share of rail in both freight and passenger transportation and the emphasis on urban mass transit in region II. Although a certain increase in automobile ownership and attendant increase in energy use for personal transportation is envisaged in this region, the total increase is not so marked because in freight transportation no significant shift toward trucks is expected. In developing regions IV (LA), V (Af/SEA), and VI (ME/NAf), growth in transport energy demand is significantly higher, owing to greater freight transport accompanying growth in industrial and agricultural output and to the fact that personal travel is far from the saturation mark.

Consider the relative levels of transport activity around the world in 1975: total passenger travel (intercity plus urban) in North America was some 4100 billion (10^9) passenger kilometers (population 237 million); in region II it was 1700 billion passenger kilometers (population 363 million); in region III over 5000 billion passenger kilometers (population 560 million). The total activity for developing regions IV, V, and VI together was only 3000 billion passenger kilometers for 1874 million people. But this seems sure to change. Passenger travel in the developed regions is expected to be nearing saturation levels; further increases in personal travel will probably be relatively modest. (There are limits—of income and time—to how much one can travel.) This effect is especially pronounced in region I. Regions I and III together show

Figure 16-4. Transportation final energy-use projections.



only a 1.2 to 1.6 percent per year growth in total passenger travel according to the MEDEE-2 runs for the two scenarios to 2030, while the developing regions IV, V, and VI together increase their personal travel amount by from 3.9 to 4.4 percent per year. The region II growth rate is projected at 1.9 to 2.4 percent per year.

The types or modes of travel also matter—as do relative load factors. Table 16-9 summarizes, for the High scenario, the results of an array of assumptions for urban and intercity mobility, relative growth of different transport modes, and expected changes in load factors around the world. It is apparent in Table 16-9 that passenger travel in NA is assumed to shift away from automobiles and toward planes in the scenarios. Still, by 2030 the automobile would account for 73 percent of total passenger kilometers, confined to 50 percent or less in other regions. In general, the developed regions are projected to continue observed tendencies toward relatively more air and (except NA) automobile travel, while the developing regions reflect expected shifts toward automobile (noticeably) and trains (less noticeably) and away from today's large fraction of bus travel (roughly 60 percent in the developing regions compared to less than 20 percent in the developed regions).

Automobiles. Automobiles consume prodigious amounts of energy. More precisely, they consume prodigious amounts of petroleum—a particularly important distinction.

In North America, total automobile travel (intercity and urban) is assumed to grow from 3800 billion passenger kilometers in 1975 (which is equivalent to four automobile trips coast to coast across the United States per person per year) to about 6000 billion passenger kilometers by 2030. This average growth rate of just 0.8 percent per year indicates a leveling off in the so far continuously increasing automobile use in the North American region. The region III (WE/JANZ) growth in total automobile travel, by contrast, is assumed to be 1.6 to 2.4 percent per year, while in region II (SU/EE) it is assumed to be 2.1 to 2.7 percent per year. In the developing regions IV (LA), V (Af/SEA), and VI (ME/NAf), the corresponding rates are between 4 and 6 percent per year—even though the assumptions restrict urban automobile travel, because of city traffic congestion, to 35-50 percent of all urban passenger travel.

Assumptions for automobile ownership and usage vary widely among regions, as recorded in Table 16-10. Automobile ownership is thought to be nearing limits in North America, as is the distance traveled per automobile. Region IV (LA) is assumed to approach the present statistics of region III by 2030, whereas the figure for region V in 2030 may be comparable to region IV today. The relatively high growth in regions IV, V, and VI of automobile ownership in the scenarios results from assumed higher growth in GDP per capita and anticipated increases in urbanization.

Region II (SU/EE) has low automobile ownership and high distance traveled per automobile—figures more common to the developing regions. The scenario projections for this region maintain that autmobile ownership

Table 16-9. Projected passenger travel (intercity and urban) and assumed distribution, High scenario.

	1975					2000					2030				
	Activity level (10^{12} pass km)	Modal split (%)				Activity level (10^{12} pass km)	Modal split (%)				Activity level (10^{12} pass km)	Modal split (%)			
Region		Plane	Car	Train[a]	Bus		Plane	Car	Train[a]	Bus		Plane	Car	Train[a]	Bus
I (NA)	4.1	4	93	1	2	6.2	12	83	2	3	8.2	20	73	3	4
II (SU/EE)	1.7	11	26	51	12	4.0	13	29	45	13	6.4	15	30	41	14
III (WE/JANZ)	5.2	3	37	37	23	9.2	9	44	27	20	13.8	12	50	20	18
IV (LA)	1.3	1	37	5	57	4.3	3	45	5	47	10.7	4	49	9	38
V (Af/SEA)	1.5	1	25	14	60	5.2	2	32	11	55	16.4	2	39	10	49
VI (ME/NAf)	0.3	1	29	5	65	1.6	2	34	9	55	5.6	4	38	15	43

[a] Train includes urban electric mass transit.

Sources of data for 1975: United Nations (1977c); International Road Federation (1973, 1976); *The Middle East and North Africa, 1974–1975* (1976); CMEA (1976).

Table 16-10. Assumptions for automobile ownership and usage in six world regions.

	Base Year	*High Scenario*		*Low Scenario*	
	1975	*2000*	*2030*	*2000*	*2030*
A. Auto Ownership (auto/1000 pop)					
Region:					
I (NA)	500	526	526	526	526
II (SU/EE)	25	63	100	50	67
III (WE/JANZ)	192	305	450	240	313
IV (LA)	39	100	230	72	144
V (Af/SEA)	4	11	38	9	22
VI (ME/NAf)	17	59	177	42	79
B. Intercity and Urban Distance Traveled (10^3 km/auto/yr)					
Region:					
I (NA)	15.9	16.1	16.5	15.9	15.9
II (SU/EE)	18.5	17.1	17.6	16.2	16.5
III (WE/JANZ)	9.2	10.2	10.3	10.1	9.9
IV (LA)	13.2	13.8	13.1	15.4	15.0
V (Af/SEA)	25.2	21.3	19.3	24.4	26.0
VI (ME/NAf)	16.4	16.6	18.1	19.3	24.4

Sources of data for 1975: United Nations (1977c); International Road Federation (1976); U.S. Department of Commerce (1976).

would continue to be low, reaching only one-half of the present WE/JANZ (region III) level by 2030. This reflects the explicit desire in region II to develop public transport facilities, to minimize the need for private automobile use, and thus to minimize liquid fuels requirements (see also the discussion in Chapter 17).

Energy use in vehicles can be reduced significantly by increasing load factors (average number of passengers per trip or passenger kilometers divided by vehicle kilometers) and by improving the vehicle's energy-using efficiency. Load factors for automobiles are assumed to hold about constant in the scenario cases in the developed regions, but are reduced somewhat in the developing regions as automobiles become more common and family sizes shrink. However, the largest factor by far in reducing potential per kilometer energy use in automobiles is efficiency improvement. The lion's share of this potential is found, not surprisingly, in North America.

In the United States in 1975 automobiles were, on average, burning about 17 litres per 100 kilometers traveled (about 14 miles per United States gallon). By the year 2000, average efficiency of all automobiles on the road in North America is projected to improve by about 55 percent—to 7.8 l/100 km (or 30 miles per gallon). This impressive performance is the result of legislation[1] passed in the U.S. Congress mandating an average fuel efficiency

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[1] The Energy Policy and Conservation Act of December 1975.

for all new automobiles in 1985 of 27.5 mpg (8.6 ℓ/100 km). By 2000, virtually no automobiles older than the 1985 model year will be on the road —thus the figure of 30 mpg assumed here in 2000. This substantial improvement in automobile fuel performance in the early years of the fifty-year time horizon of this study has no precedent in the United States and could still be open to reasonable question. By 2030, automobiles traveling in North America are projected to operate at an average fuel efficiency (about 6.8 l/100 km or 35 mpg), substantially exceeding that in region III (WE/JANZ) today about 10 l/100 km or 24 mpg). This efficiency improvement signals smaller automobiles (a lifestyle change of a sort for many drivers) and better design of engine and body (including any mix of new technologies or construction materials that one would like; these numbers are meant to be the aggregate of such possibilities). Fuel efficiency improvement in other regions are not projected to be as great as in region I; a range of 30 to 45 percent improvement in the next fifty years is expected in region II (SU/EE), 30 to 35 percent in regions III (WE/JANZ) and VI (ME/NAf), and about 15 percent in regions IV (LA) and V (Af/SEA).

Electric cars offer a potential for reduction of motor fuel use in automobiles. Electric cars, assumed to be three times as efficient as internal combustion engine automobiles, nevertheless would consume about the same total primary energy as conventional cars—if, of course, the electricity would come from central station sources. It is assumed here that by 2030 about 20 percent of urban automobile travel in the developed regions (I, II, and III) and perhaps 5 percent of urban car travel in developing regions (IV and VI) might be accounted for by electric cars.

As a result of these and other assumptions, automobile energy use declines sharply in region I and shows a modest decline (as a share of total transportation energy use) in regions II and III. Regions IV, V, and VI contrast sharply with these results, increasing in total automobile energy use markedly, largely because of the low level of use today.

Table 16-11 shows these projections for automobile energy use in the scenarios. The quantities are large, as can be seen. The gasoline consumption in automobiles in 2030 in regions I through VI would amount to about 0.9 to 1.1 TWyr/yr of oil. One must ask the extent to which alternative transport modes could replace the car and with what energy consequences.

Mass Transit. For intercity trips, North Americans travel relatively less by automobile in these projections over fifty years than they do today. One reason is an assumed modest shift away from automobiles and toward mass transit for intercity travel. In other regions, the shift assumed is actually toward automobiles for intercity travel, but trains continue to play a very significant role in regions II (SU/EE), III (WE/JANZ), V (Af/SEA), and VI (ME/NAf)—by 2030, 35 to 40 percent in region II, 20 to 35 percent in region III, 16 percent in region V, and 20 percent in region VI, from 53, 42, 26, and 10 percent, respectively, in 1975. In region I (and IV), intercity train travel is assumed to remain low—1 percent (6 percent) of all intercity travel in 1975 to about 2 percent (3 percent) in 2030.

Travelers take to the air in greatly increasing numbers in both the High

Table 16-11. Energy use by automobiles in six world regions.

Region	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
I (NA)					
Energy used by cars (GWyr/yr)	364	205	194	203	201
As share of total transportation energy (%)	(67)	(32)	(19)	(36)	(29)
II (SU/EE)					
Energy used by cars (GWyr/yr)	26	45	63	42	50
As share of total transportation energy (%)	(11)	(11)	(8)	(11)	(9)
III (WE/JANZ)					
Energy used by cars (GWyr/yr)	111	214	249	168	179
As share of total transportation energy (%)	(35)	(30)	(22)	(32)	(26)
IV (LA)					
Energy used by cars (GWyr/yr)	20	82	238	67	179
As share of total transportation energy (%)	(19)	(20)	(21)	(22)	(25)
V (Af/SEA)					
Energy used by cars (GWyr/yr)	17	67	277	60	216
As share of total transportation energy (%)	(22)	(25)	(30)	(27)	(36)
VI (ME/NAf)					
Energy used by cars (GWyr/yr)	6	27	108	22	67
As share of total transportation energy (%)	(13)	(13)	(18)	(16)	(21)

and the Low scenario projections for the developed market economies. The rate of growth would also be high for developing regions, but from a much smaller starting amount. In region IV (LA), intercity air travel would grow from 2.6 percent in 1975 to 6–8 percent by 2030; in regions V (Af/SEA) and VI (ME/NAf), the increase would be from 1.5 percent in 1975 to 3–7 percent by 2030 in the scenarios. In region I (NA), airplane flights would account for as much as 30 percent of all intercity travel in 2030 (from 7 percent today), while region III (WE/JANZ) would increase plane travel from 3.5 percent today to as much as 18 percent of all intercity travel by 2030 in the scenarios. In region II (SU/EE), air travel may account for as much as 27 percent of all intercity movements by 2030, from 20 percent today.

Load factors for trains and planes (and buses) are assumed in most cases to be approximately constant or to increase only marginally in regions I and III. This is hardly the case for the developing regions. There, overcrowding on buses and trains is the norm, not the exception. High population growth, coupled with the high mobility preferences accompanying income increases, keep the load factors high in regions IV and V—although a gradual relaxation of the present overcrowding is assumed to occur in parallel with increasing per capita income and a slowing down of population growth. Load factors of 20 and 25 passenger kilometers per vehicle kilometer for buses and about 150 for trains are common for regions I and III. In regions IV, V, and VI, the bus load factors of typically forty to fifty today would drop to twenty to forty by 2030 in the scenarios, while train load factors would fall from five hundred to two to four hundred. (Of course, varying "vehicle" size among and even within regions increases the difficulties of drawing comparisons.)

The bus and train load factors in region II are also assumed to drop by a factor of two over the next fifty years and become comparable to those in regions I and III.

Freight transport is assumed to grow significantly in all world regions roughly in parallel with the activity levels in the agriculture, mining, and manufacturing sectors. It is a big business: some 5 trillion (10^{12}) ton-kilometers of freight in 1975 would reach some 11 trillion ton-kilometers in the Low scenario and some 19 trillion ton-kilometers in the High scenario for the developed regions I and III by 2030; energy use increases by a factor of 2.4 to 3.9 over the fifty-year period. Freight transportation activity is much lower in regions IV, V, and VI. These regions together had only about 2 trillion ton-kilometers of freight movement in 1975; an increase of six to ten times that level is projected by 2030. Gradual shifts toward increasing freight transportation on trains in regions IV and VI and with trucks in region V are assumed. No significant change is assumed in the present distribution of freight transportation modes in the developed regions I, II, and III.

Energy in Buildings

Homes use fuels and electricity for heating, lighting, air conditioning (sometimes), cooking and the like. Commercial and public buildings—the service sector—use energy for about the same purposes, as well as electricity for special needs such as medical equipment, office machines, computers, and elevators. The total amounts of all these building operation energy uses are not small.

In 1975, in region I (NA) and III (WE/JANZ), there were 266 million homes, 45 percent of them centrally heated houses and apartments. There were three persons per household on average. In the scenarios, housing construction is assumed to be tied to population growth (which is low), while allowing for further reductions in the assumed average number of persons per household by 2030—to 2.24 in region I and to 2.56 in region III. Almost all new residential dwellings are assumed to be centrally heated; many of them are also air conditioned. In these two regions, by 2030, about 90 percent of dwellings would be centrally heated, from 45 percent today. Air conditioning would be available for 30 to 40 percent of dwellings, from 12 percent in 1975.

In regions IV (LA), V (Af/SEA), and VI (ME/NAf) taken together, the number of residential dwellings reaches about 1130 million by 2030, from 360 million in 1975, with the number of persons per household dropping from 5.22 to 4.16. Space heating requirements being relatively small in these mostly warm regions, only about 25 percent of dwellings require space heat. By 2030, some 17 to 19 percent are assumed to use space heat, from 11 percent in 1975.

Service sector floor area increases fairly briskly in regions I and III, reflecting the high growth of the total service sector in these regions. By 2030, from 1.7 to 2.1 times as much building area is in use and to be energy serviced, as in 1975 in these two regions; in region II (SU/EE), the increase is even larger, from 3.2- to 4.4-fold. Two main factors—higher population growth and improvement in the working conditions of service sector employees—cause the growth in service sector activity in the developing regions to be even greater than in the developed regions. Service sector floor area in the developing regions is about 6.0 to 7.5 times (by 2030) that in 1975.

Tables 16-12 and 16-13 report some of the energy consumption figures associated with the economic activity levels just cited. Readily apparent in both of these tables is that by far the largest energy-gorging device in buildings in the developed regions is the space itself. Space heating (and to a lesser extent air conditioning) overwhelms other needs in residences; in service sector buildings, electrical appliance consumption of energy is also very high. In regions I and III, about 60 percent of useful energy in buildings goes to heating the inside air; in the scenario projections here this number decreases to 40 to 50 percent as various energy-saving measures are introduced.

Improved insulation in old and new homes can reap substantial reductions in energy use. The assumptions in the scenarios of insulation improvements in new buildings plus retrofit of pre-1975 dwellings significantly reduce the heat losses in dwellings in regions I, II, and III. Retrofitting of the pre-1975 housing stock is assumed to reduce their heat losses by 20 to 30 percent over the next fifty years. According to the assumptions used here, by 2030 the average heat losses of all post-1975 dwellings would be only 50 percent of those in 1975. Further gains are difficult beyond certain initial savings. Rising prices and an assumed increasing public awareness of energy uncertainties (as well as a fair measure of government-instituted standards) lead to these results.

Electricity use for appliances has grown by great leaps and bounds in recent years, usually much faster than rises in real income. Increased disposable income has to date seemed to go in rather large shares to such "extras" as dishwashers, color televisions, and clothes dryers. In region I, and to some extent in regions II and III, some flattening of this growth curve is postulated—appliance ownership saturates, and their energy efficiencies, in response to rising prices, improve.

Relative increases in electricity consumption for household appliances (see Table 16-12) are much higher by 2030 in the developing regions—being three to five times 1975 levels in region IV, five to ten times in region V, and six to seventeen times in region VI—mainly because the present levels are so low. Most houses that use electricity at all in these regions today use it only for lighting and a bare minimum of other activities.

Another factor that is expected to play an important role in the future energy requirements of buildings in both developed and developing regions is air conditioning. Until now the extensive use of air conditioning has been limited to region I; scenario assumptions here project by 2030 considerable use of air conditioning in several other world regions as well (see Table 16-13).

At present the useful thermal energy requirements in the household/

Table 16-12. Projected useful energy requirements in households (10^3 kWh per dwelling per year).

	1975				High Scenario 2030				Low Scenario 2030			
Region	*Cooking*	*Space and water heating*	*Air condi-tioning*	*Miscellaneous electrical appliances*	*Cooking*	*Space and water heating*	*Air condi-tioning*	*Miscellaneous electrical appliances*	*Cook-ing*	*Space and water heating*	*Air condi-tioning*	*Miscellaneous electrical appliances*
I (NA)	1.2	25.3	1.0	3.9	1.2	18.2	2.0	8.0	1.2	18.2	1.7	6.3
II (SU/EE)	1.2	11.9	0	0.9	1.2	14.4	0.2	5.0	1.2	13.6	0.2	3.0
III (WE/JANZ)	1.3	9.5	0	2.0	1.3	12.8	0.5	6.0	1.3	11.4	0.4	4.5
IV (LA)	1.9	1.0	0	0.7	2.1	2.9	0.4	3.4	2.1	2.3	0.2	2.2
V (Af/SEA)	1.2	0.1	0	0.05	1.4	0.2	0.02	0.5	1.4	0.1	0.01	0.3
VI (ME/NAf)	1.9	0.8	0.01	0.2	2.1	3.8	0.7	3.3	2.1	3.1	0.4	1.2

Notes: Useful energy is expressed as electricity equivalent. Figures here are averages for all dwellings within a region.

Table 16-13. Useful energy projections for service sector.

	1975				High Scenario 2030				Low Scenario 2030			
		kWh/m²				*kWh/m²*				*kWh/m²*		
Region	*Service sector working area ($10^9 m^2$)*	*Space and water heating*	*Air condi-tioning*	*Miscellaneous electrical appliances*	*Service sector working area ($10^9 m^2$)*	*Space and water heating*	*Air condi-tioning*	*Miscellaneous electrical appliances*	*Service sector working area ($10^9 m^2$)*	*Space and water heating*	*Air condi-tioning*	*Miscellaneous electrical appliances*
I (NA)	2.72	270	22	120	5.00	227	33	150	3.79	225	28	136
II (SU/EE)	1.50	256	0	40	6.65	186	12	100	4.75	186	8	80
III (WE/JANZ)	3.00	110	2	40	7.26	96	8	104	5.99	95	6	89
IV (LA)	0.60	12	2	25	3.20	19	16	65	3.41	22	14	66
V (Af/SEA)	1.25	1	0	15	9.40	2	2	38	6.90	2	1	33
VI (ME/NAf)	0.18	20	2	15	2.54	52	20	100	1.84	52	12	85

Note: Useful energy is expressed as electricity equivalent.

service sector are met essentially by fossil fuels and electricity in the developed regions and by fossil fuels and noncommercial energy in the developing regions. The scenario assumptions pertaining to future use of noncommercial fuels, efficiency improvements in the use of all fuels, and penetration of electricity, soft solar, district heat, and heat pumps lead to the final energy demand patterns shown in Table 16-14. There, the large reliance on district heat in region II is apparent (see Chapter 17). Also, the higher fossil, and lower electric, shares in the developing regions than in the developed regions reflect the end use patterns typical in buildings in these two kinds of regions. It has been assumed that by 2030 heat pumps would be used to the extent of 40 to 50 percent in regions I, II, and III and of 12 percent in regions IV and VI and that there would be efficiency improvements of 10 to 25 percent in the use of fossil fuels in different world regions.

Energy Use in Industrial Activities

Industrial energy use is currently a major portion of the total consumption in all world regions; the scenario assumptions do not lead to major departures from that. Energy as a factor of production, as an "input" to productive output, is an indispensable commodity—qualitatively different from the energy used by households or that consumed in transportation activities. Yet despite its firm footing in virtually all of the world's economies, industrial energy demand trends and possibilities span an impressively wide range. Before highlighting some specifics in the industrial energy projections for the scenarios, it may be helpful to define the particular breakdown of this large and highly heterogeneous activity as it is specified in the MEDEE-2 model.

By "industry" four broad sectors are meant—agriculture, construction,

Table 16-14. Shares of energy sources in the household-service sector heat market (percent of total useful thermal energy).

	High Scenario									
	2000					*2030*				
Region	*NCE*	*FF*	*EL*	*DH*	*SS*	*NCE*	*FF*	*EL*	*DH*	*SS*
I (NA)	0	68	24	0	8	0	56	31	0	13
II (SU/EE)	4	44	6	43	3	3	22	10	60	5
III (WE/JANZ)	0	73	15	6	6	0	55	21	13	11
IV (LA)	18	72	3	1	6	14	57	9	8	12
V (Af/SEA)	37	63	0	0	0	26	70	2	0	2
VI (ME/NAf)	3	94	2	0	1	2	86	5	2	5

Notes: NCE = noncommercial energy sources; FF = fossil fuels (for regions IV, V, and VI this column includes the fossil fuel equivalent of charcoal/wood and biogas to be supplied as commercial fuel); EL = electricity; DH = district heat; SS = soft solar. In 1975, noncommercial energy share is estimated to be 7, 39, 68, and 9 percent in regions II, IV, V, and VI, respectively. The Low scenario shares are quite similar to these in the High scenario.

mining, and manufacturing. Energy use in these sectors is projected as the product of their value added and their energy intensiveness (energy use per unit of value added). For manufacturing, calculations are done for four subsectors—basic materials (e.g., primary metals, building materials, basic chemicals); machinery and equipment; nondurable goods (food, textiles, clothes); and miscellaneous.

The energy intensiveness is specified for three main types of energy use—specific uses of motor fuel, specific uses of electricity, and thermal uses for which the energy can be provided by various energy forms. The first two coefficients are specified in terms of final energy; the third one is in terms of useful energy. Specific uses of electricity are, for example, lighting, motive power, and electrolysis. Thermal uses are steam generation, furnace firing, and space and water heating. (Ideally, the distribution of useful energy consumption among these types of thermal uses is specified for each sector. If these data are not available, an average distribution for all sectors must be specified.) The distribution among these categories is necessary in order to estimate the potential industrial markets for district heat, solar energy, heat pumps, and electricity and to make meaningful assumptions about the penetration of these energy sources into the useful energy market. The fraction of this market that is not covered by electricity, district heat, solar energy, or heat pumps would be met by conventional fossil fuels.

In order to calculate final energy, one has to specify average end use efficiencies of fossil fuels relative to those of electricity, either for the three types of thermal uses separately or for an average for all thermal uses. The overall final energy intensiveness can then be obtained from a consideration of the following:

1. The distribution of value added among the economic sectors distinguished in the model (agriculture, construction, mining, the four manufacturing sectors, and the rest);
2. The energy intensiveness coefficients of each sector mentioned above;
3. The penetration of energy sources such as electricity, district heat, heat pumps, and solar energy into their appropriate useful thermal energy markets; and
4. The average process efficiencies of the technologies used (e.g., the average efficiency of fossil-fired furnaces, of fossil-fired boilers).

Of these, the first factor captures differences in economic structures; the last three factors are meant to reflect technological patterns as they relate to energy use. The energy intensiveness coefficients are also influenced by the mix of activities in each sector.

Manufacturing. Manufacturing activities account for a lion's share of the industrial energy consumption. In 1975, the share of manufacturing activities, including coke usage in the steel industry and feedstock inputs to petrochemical industries, out of total industrial energy consumption was 90 to 97 percent for regions I to V, in spite of considerable differences in the composition of their economic structure. In region VI (ME/NAf) this share was relatively smaller—about 62 percent—owing to the exceptionally low level of manufacturing activity and the dominance of oil and gas production in the industrial sector of this region. The scenario assumptions of changes in economic structure, composition of manufacturing activities, and technological coefficients result in projections for the years 2000 and 2030 for which the share of manufacturing in the industrial energy consumption varies between 76 and 90 percent in all world regions.

In the following paragraphs some salient features of the scenario assumptions affecting the energy consumption in the manufacturing sector in different world regions are outlined. As mentioned earlier these scenario assumptions are based on judgments, past trends, interregional and intercountry comparisons, and estimated prospects of technological developments and conservation measures.

The projected changes in the overall economic structures of region I to VI embodied in the scenarios were outlined in Table 16-6. Table 16-15 describes the assumed shifts in the composition of manufacturing activities for the High scenario. The projected changes for the Low scenario are in the same general direction but occur relatively more slowly.

The requirements of energy for a given mix of manufacturing activities can be reduced as follows: by incorporating better machinery and processes (which reduces the energy intensiveness of these activities); by increasing the share of electricity, district heat, and soft solar energy in meeting the demand for thermal processes (which reduces conversion losses); by making increased use of cogeneration and heat pumps (which reduces the requirements of final energy); and by improving the efficiency of fossil fuels for conversion to process heat (which also reduces conversion losses). Tables 16-16 and 16-17 outline assumptions of plausible changes in different regions of the world over the next fifty years. The data for 1975 (column 1, Table 16-16) show considerable differences in average useful energy intensiveness of manufacturing activities in various world regions. These differences are due in part to different mixes of component activities and in part to differences in processes, technologies, and the extent of automation. (For most of the regions the data are relatively scarce, and estimates used here have been based on available information for representative countries.

One sees in these projections in general a greater reduction of energy intensiveness in the developed regions than in the developing regions. These reductions are particularly large in regions II (SU/EE) and I (NA) but not so large in region III (WE/JANZ), where manufacturing activities have already undergone considerable modernization. A part of these reductions is, of course, because of structural changes in the manufacturing activities. The largest structural changes in the manufacturing sector are assumed for the developing regions, where both the most energy-intensive basic material industries and the least energy-intensive machinery and equipment industries grow relatively faster than the nondurable goods industries. This has a

Table 16-15. Assumed distribution of manufacturing activities, High scenario.

	1975				*2000*				*2030*			
Region	*Total Mfg*[a]	*Basic Mtls*[b]	*Mach & Equip*[c]	*Cons Goods*[d]	*Total Mfg*[a]	*Basic Mtls*[b]	*Mach & Equip*[c]	*Cons Goods*[d]	*Total Mfg*[a]	*Basic Mtls*[b]	*Mach & Equip*[c]	*Cons Goods*[d]
I (NA)	24.5	25	43	32	22.3	23	47	30	20.7	21	52	27
II (SU/EE)	38.2	23	48	29	33.7	23	52	25	29.0	23	57	20
III (WE/JANZ)	33.6	33	42	25	31.3	31	46	23	28.1	28	51	21
IV (LA)	24.8	31	26	43	30.4	36	35	29	33.0	35	42	23
V (Af/SEA)	16.6	26	18	56	22.3	32	24	44	25.8	37	30	33
VI (ME/NAf)	7.8	20	10	70	24.2	35	15	50	27.3	35	40	25

[a] Total manufacturing (percent of total GDP).

[b] Manufacturing of basic materials (percent of total manufacturing value added).

[c] Manufacturing of machinery and equipment (percent of total manufacturing value added).

[d] Manufacturing of (nondurable) consumer goods (percent of total manufacturing value added).

Note: In regions I, II, and III, basic materials also include mining of nonenergy products but exclude manufacturing of petroleum and coal products.

Sources: United Nations (1977b, 1977d, 1977c).

Table 16-16. Projected reduction in average useful energy intensiveness of manufacturing industries, High scenario.

Region	*Useful Energy Intensiveness (kWh/$ VA)* 1975	*Useful Energy Intensiveness (kWh/$ VA)* 2030	*Percent Reduction In 2030 Relative to 1975*	*Percent of Which Due to Structural Change*[a]
I (NA)	8.66	6.06	30	8
II (SU/EE)	10.86	6.12	44	1
III (WE/JANZ)	4.20	3.21	24	4
IV (LA)	5.81	4.51	22	4
V (Af/SEA)	11.06	9.29	16	-3
VI (ME/NAf)	7.68	4.96	35	-8

[a] Structural changes are the result of assumed changes in manufacturing activities.

Notes: Useful energy is expressed as equivalent electricity requirement. Data are for manufacturing industries, excluding coke and petrochemical feedstock use.

balancing effect on the overall energy intensiveness of manufacturing.

For the projections of the penetration of various more efficient energy forms, as well as cogeneration and heat pumps in the industrial heat market (see Table 16-17), regional differences in settlement patterns, past practices, current technological trends, geographical conditions, and so forth have been kept in mind. In spite of these technological changes, more than 80 percent of the industrial process heat requirements in all regions except region II (SU/EE) would still have to be met by fossil fuels in 2030 in the High scenario. Improvements of the order of 20 percent in the average efficiency of fossil fuel use are assumed to be possible over the next fifty years.

Table 16-17. Assumed penetration of electricity, district heat, cogeneration, heat pump, and soft solar in their potential industrial heat markets in 2030, High scenario (percent of potential industrial heat markets).[a]

Region	*Electricity*	*District Heat*	*Cogeneration*	*Heat Pump*	*Soft Solar* Low temperature	*Soft Solar* High temperature
I (NA)	0.10	0	0.50	0.50	0.15	0.05
II (SU/EE)	0.10	0.85[b]	0	0	0.10	0.03
III (WE/JANZ)	0.05	0.15	0.60[b]	0.50	0.15	0.05
IV (LA)	0.10	0.12	0.20	0.20	0.30	0.10
V (Af/SEA)	0.04	0.05	0.15	0.10	0.30	0.10
VI (ME/NAf)	0.10	0.12	0.25	0.20	0.30	0.10

[a] Potential industrial heat markets: electricity—all process heat; district heat—steam and hot water; cogeneration—low temperature steam and hot water; heat pump—steam and hot water demand met by electricity; and soft solar—steam and hot water.

[b] In region II district heat and in region III on site cogeneration were already supplying 69 and 30 percent of their respective potential markets in 1975.

The overall effect of these technological developments, better practices, and structural changes would be to reduce the average final energy intensiveness of manufacturing activities (excluding use of coke in steel industry and feedstocks) by about 35 to 55 percent in different world regions, as shown in Table 16-18 for the High scenario. The effects of structural changes are somewhat smaller on final energy than on useful energy as the overall conversion efficiencies from final to useful energy are assumed to improve by 20 to 30 percent because of technological changes.

At present, the use of coke in the steel industry amounts to 2 to 11 percent of final energy requirements of manufacturing activities in various world regions. The consumption of coke per ton of pig iron produced varies considerably from country to country. Estimated regional averages for 1975 are between 500 kg in region III (WE/JANZ) and 1000 kg in region VI (ME/NAf). The lowest consumption has been achieved by the Japanese steel industry, where the consumption decreased to about 390 kg per ton of pig iron in 1972. However, following the oil crisis, the consumption of coke in Japan increased again as fuel oil use decreased; the consumption in 1975 was 441 kg per ton of pig iron. Despite this short-term reversal in the trend of the Japanese steel industry, it is assumed here that reductions down to about 400 kg per ton of pig iron would become feasible in various world regions because of future technological improvements.

Table 16-19 summarizes the present and projected levels of final energy consumption in manufacturing and also shows the growth of electricity in manufacturing energy use in various world regions in the two scenarios. A large share of total final energy would to to manufacturing for all world regions in the scenarios. The trends generally show stable or declining shares (except for regions I-NA and VI-ME/NAf).

Agriculture. Agriculture in the developing regions, based largely on traditional farming practices, is currently far less energy intensive than that in the developed regions. According to the economic projections of the scenarios here (see Table 16-6), the agricultural GDP in regions IV, V, and VI is ex-

Table 16-18. Average final energy intensiveness of manufacturing activities (excluding feedstocks and coke).

Region	*Energy Intensiveness High Scenario (kWh/$VA)* 1975	2030	*Relative Decrease (%)*	*Reduction Due to Structural Change (%)*
I (NA)	12.3	7.0	43	6
II (SU/EE)	13.9	6.4	54	1
III (WE/JANZ)	5.7	3.6	37	4
IV (LA)	8.6	5.5	36	3
V (Af/SEA)	19.6	12.6	36	-2
VI (ME/NAf)	12.2	6.1	50	-7

Table 16-19. Energy consumption in manufacturing.

Region	Base Year 1975	High Scenario		Low Scenario	
		2000	2030	2000	2030
I (NA)					
Manufacturing energy use[a] (GWyr/yr)	700	1189	1701	984	1186
Percent of final energy[b]	(37)	(45)	(46)	(44)	(45)
Electricity[c] (GWyr/yr)	91	214	362	172	233
II (SU/EE)					
Manufacturing energy use (GWyr/yr)	699	1350	2369	1216	1623
Percent of final energy	(55)	(57)	(58)	(56)	(55)
Electricity (GWyr/yr)	83	237	564	196	336
III (WE/JANZ)					
Manufacturing energy use (GWyr/yr)	731	1385	2011	1052	1298
Percent of final energy	(46)	(46)	(46)	(44)	(43)
Electricity (GWyr/yr)	113	267	477	197	277
IV (LA)					
Manufacturing energy use (GWyr/yr)	106	438	1102	293	628
Percent of final energy	(42)	(44)	(42)	(40)	(38)
Electricity (GWyr/yr)	15	72	235	49	133
V (Af/SEA)					
Manufacturing energy use (GWyr/yr)	144	585	1615	395	774
Percent of final energy	(57)	(55)	(51)	(49)	(41)
Electricity (GWyr/yr)	16	88	336	59	156
VI (ME/NAf)					
Manufacturing energy use (GWyr/yr)	31	262	733	203	346
Percent of final energy	(29)	(45)	(45)	(47)	(40)
Electricity (GWyr/yr)	4	53	180	41	85

[a] Manufacturing energy use is final energy of all types (including coke and feedstocks) used in the manufacturing sector.

[b] Percent of final energy is manufacturing energy as a percent of commercial final energy.

[c] Electricity is electricity used in the manufacturing sector.

pected to increase by a factor of 3.7 to 4.5 over the next fifty years; the expected increase would be 2.2 to 2.5 times in regions I, II, and III. The implications of these projections in energy terms can be seen in the parameters of Table 16-20.

Consider arable land in the developing regions. There is not much potential for expanding arable land area in regions IV, V, and VI, where the present per capita availability of arable land is about 0.34 ha compared to 0.62 ha in developed regions I, II, and III. If no significant new area is brought under cultivation, the per capita arable land availability would decrease over the next fifty years to 0.14 ha in the developing regions and to 0.46 ha in the developed regions.

These limits on arable land expansion imply that essential agricultural productivity improvements must come from increases in the use of fertilizers, irrigation, and farm mechanization. But surface water is in short supply, and precipitation is not adequate in most areas. Increasing use would therefore have to be made of underground water.

Table 16-20. Agricultural patterns in different world regions in 1975.

Region	*Arable Land per Capita (ha/cap)*	*Irrigation (% of arable land)*	*Mechanical Appliances (per 1000 ha)*	*Fertilizer Use (kg/ha)*
I (NA)	1.07	7	22	80
II (SU/EE)	0.77	7	15	96
III (WE/JANZ)	0.34	9	45	117
IV (LA)	0.45	9	7	32
V (Af/SEA)	0.32	14	1	14
VI (ME/NAf)	0.33	25	4	27
VII (C/CPA)	0.15	61	2	50

Note: All data refer to arable land including land under permanent crops. Mechanical appliances included here are tractors and harvester-threshers. Fertilizer use refers to consumption in terms of N_2, P_2O_5, and K_2O.

Sources: FAO (1977b); United Nations (1977c).

Taking these factors into account, the energy intensiveness of agriculture (including mechanization and irrigation, but not including energy used to produce fertilizers) in regions IV, V, and VI is assumed to increase by a factor of ten over the next fifty years. Thus, by 2030 the average energy intensiveness in these regions would be about the same (2.8 kWh per dollar value added) as the present average value for the developed regions. The final energy used in agriculture would increase for the High and the Low scenarios by about 45 and 37 times the 1975 level in the developing regions and by just 2.4 and 2 times in the developed regions. The share of agricultural activities in industrial energy consumption in 2030 is thus found to lie in the range of 3 to 5 percent in all regions except region V (Af/SEA), where it amounts to 10 percent for the High scenario and 15 percent for the Low scenario. (The shares in all regions in 1975 were in the range of 1 to 4 percent.)

Energy needed for fertilizer production is counted in these analyses in the basic materials manufacturing sector and in feedstocks production. For regions IV and V, those sectors are projected to increase in output by 2030 to about ten to twenty times their 1975 levels. These increases should easily encompass the energy demand for chemical fertilizer, which may increase by a factor of five to ten in the same period.

FUELS DEMAND

Careful, intelligent, and selective use of fuels can be a highly effective means of energy conservation. It is not, after all, energy per se that is in short supply so much as it is particular types of energy, or fuels, that must be wisely marshaled.

In 1975, 47 percent of the world's 8.2 TWyr/yr (commercial) primary energy need was slaked by oil and another 18 percent by natural gas. These fuels have in recent decades increasingly dominated energy markets. Oil movements are of staggering proportions: oil moved around in ships that carry as much as 400,000 tons of oil—ships whose size rivals the world's largest skyscrapers. Oil is big business. And the picture is not likely to change dramatically in the foreseeable future.

Uses of Liquid Fuels

Liquid fuel is premium fuel. It is essential as a motor fuel and as a raw material for certain industrial processes. Its convenience of transport and, until quite recently, easy availability have expanded its common uses to include heat raising and electricity generation.

But crude oil resources are not infinite; oil prices are rising in response to the perceived limitations on expansion of oil production. The supply analyses of Chapter 17 support this nearly consensus view. The data of Table 16-21 are the result of several iterations of liquid fuel demands and supplies.

Table 16-21. Final energy demands for liquid fuels, 1975-2030.

Region	*Base Year 1975*	*High Scenario 2000*	*High Scenario 2030*	*Low Scenario 2000*	*Low Scenario 2030*
I (NA)					
Liquids[a] (TWyr/yr)	0.951	1.14	1.67	0.99	1.13
Percent motor fuel + feedstock[b]	(74)	(86)	(94)	(84)	(91)
II (SU/EE)					
Liquids (TWyr/yr)	0.438	0.70	1.31	0.64	0.89
Percent motor fuel + feedstock	(65)	(90)	(100)	(88)	(100)
III (WE/JANZ)					
Liquids (TWyr/yr)	0.979	1.65	2.06	1.32	1.44
Percent motor fuel + feedstock	(52)	(69)	(86)	(64)	(76)
IV (LA)					
Liquids (TWyr/yr)	0.190	0.68	1.68	0.49	1.05
Percent motor fuel + feedstock	(69)	(79)	(90)	(79)	(89)
V (Af/SEA)					
Liquids (TWyr/yr)	0.138	0.53	1.57	0.42	1.02
Percent motor fuel + feedstock	(58)	(74)	(91)	(74)	(88)
VI (ME/NAf)					
Liquids (TWyr/yr)	0.070	0.31	0.88	0.23	0.47
Percent motor fuel + feedstock	(74)	(85)	(94)	(85)	(91)
World[c]					
Liquids (TWyr/yr)	2.85	5.46	10.36	4.37	6.69
Percent motor fuel + feedstock	(64)	(79)	(92)	(77)	(88)

[a] Liquids means total final energy demand for liquid fuels.

[b] Percent motor fuel and feedstock means "nonsubstitutable" liquids demand for motor fuel (in transportation, agriculture, mining, and manufacturing) as well as petrochemical feedstock uses requiring liquids.

[c] World includes region VII (C/CPA), assumed here simply to be the average of other developing regions.

In the High and Low scenarios, liquid fuels more and more come to be used primarily—almost exclusively in some regions—for premium uses—as motor fuel and as feedstocks for petrochemical products. Oil for other purposes, described region by region in the following sections, is increasingly replaced by other fuels under the conditions of the scenarios. In rough global average terms (making some gross assumptions for region VII), about 64 percent of liquids and fuels went to premium uses in 1975, increasing to some 88 to 92 percent by 2030 in the scenarios.

The shifts of liquid fuels away from nonessential uses is accomplished judgmentally in these studies, in response to the relative price rises of liquid fuels. After each round of the iterative procedure, fuels and electricity prices are compared, and a redistribution (within limits) of secondary energy demands among fuel types is made. The liquid fuels prices that induce the shifts are reported in the next chapter: as a benchmark, international oil prices would be about $21 per barrel (1975 dollars) by 1990 in the High scenario and about $19 per barrel by 1990 in the Low scenario.

In spite of this shift away from nonessential uses of oil, demands for liquid fuels continue to grow under the assumptions of the scenarios—from 1.6 to 2.4 percent per year worldwide, 1975 to 2030. And it is the prospect of continued growth in demand for liquid fuels, coupled with the realization of its finite supply, that raises the specter of a future energy famine. It might be true: Chapter 17 looks squarely at global supply-demand balances of fuels. Here, we seek only an understanding of the opportunities and constraints for altering the mix of fuels demanded in final energy—an understanding that can help in managing an uncertain energy future.

Interchangeable Fossil Fuels: Charcoal and Biogas

Some fuels for some purposes are essentially noninterchangeable—electricity for lighting, liquid hydrocarbons for automobiles, coking coal (to a certain extent) for steel making. With the detailed "bottom up" demand calculation procedures followed here, these and other fairly certain (even over fifty years) uses of specific fuels can be accounted for.

And one can go one step further. One can evaluate the possible growth of electricity into places (such as home heating) where other fuels could substitute, and one can evaluate the potential growth of new sources such as solar energy for heat and hot water. This has been done with an eye to relative prices, fuel availabilities, and other scenario assumptions that affect fuel supplies. The growth of electricity and district heat or combined heat and power generation derived in this way have already been described. The solar growth description follows in the next section.

What is left (mostly) is interchangeable fossil fuels—or "substitutable" fossil fuels, as they are frequently called here. These are fuels allocated to heat (industrial, and household and service sector) requirements that are not supplied by electricity, district heat, combined cycle, or solar systems. In addition to coal, oil, and gas, they are assumed to include the commercial supply of charcoal and wood from forests and plantations and biogas from anaerobic fermentation of agricultural and animal wastes. The latter, in the case of some developing regions, may be able to meet a significant fraction of the heat demand of industries and the household/service sector if an aggressive policy is pursued for their exploitation.

Substitutable fossil fuels defined in this way were meeting essentially 82 percent of heat demands in 1975—being 48 percent of total final energy in regions I (NA), II (SU/EE), and III (WE/JANZ) together and 45 percent of final commercial energy in developing regions IV (LA), V (Af/SEA), and VI (ME/NAf). (The remaining 18 percent of 1975 heat demand was met by electricity and district heat—region II only—and noncommercial fuels—developing regions primarily.) By 2030, substitutable fuels would be as low as 27 to 29 percent under the conditions of the scenarios. This is largely because of electricity, solar, district heat, and cogeneration penetrations into the heat market and because of improvements in insulation levels that further reduce space heating needs.

The allocation of substitutable fuels among the competing sources—oil, gas, coal, and renewable energy sources—is an issue worthy of considerably more attention and rigorous treatment than this study has been able to provide. But some simplifying assumptions can be made and were made broadly consistent within the scenarios with relative prices of these competing fuels.

The start is with the figures calculated in MEDEE-2 for substitutable fossil fuels in two sectors—industry and household/service—from 1975 to 2030, for each of the scenarios and for each of the regions. Then, after observing the dynamics of relative prices from the supply-demand balance calculations (Chapter 17), the fuel mix of substitutable fossil fuels over time are adjusted in these sectors to be consistent with the relative prices. In the developing regions, the potentials for maximum penetration of local renewable sources is also considered. Table 16-22 records a selection of these fuel-shifting assumptions for four regions of the world for the High scenario.

Developed Regions. In region I (NA), coal is sufficiently in abundance so that its use in industry directly can and should increase. Its abundance is reflected in its low relative price. Therefore, it is assumed here that the share of substitutable fossil uses in industry increases from 12 percent in 1975 to about 25 to 30 percent by 2030. (These assumptions, based on MEDEE-2 outputs, are used to create inputs in appropriate form for the energy supply system MESSAGE model of Chapter 17.) Oil is assumed to be used less and less for heat purposes in both the industrial and household/service sectors. That is liquid fuels, by assumption, are held for essential motor fuel and feedstock purposes. (As a result, liquid fuels used as part of substitutable fossil fuels in household/service and industry would drop from 251 GWyr/yr in 1975 to 99 to 105 GWyr/yr in 2030.) Gas use rises as a replacement for liquid fuels: its price, reflecting its relative (compared to oil) abundance, grows less slowly than the oil price.

In region II (SU/EE), a dramatic shift is seen away from reliance on oil for heat to extensive use of gas (and, to a lesser extent, of coal) and com-

Table 16-22. Assumptions for changes in substitutable fossil fuels, High scenario.

	Region I (NA)		*Region II (SU/EE)*		*Region III (WE/JANZ)*		*Region V (Af/SEA)*	
Substitutable Fossil Fuels[a]	*1975*	*2030*	*1975*	*2030*	*1975*	*2030*	*1975*	*2030*
Industry (GWyr/yr)	481	910	309	414	413	791	110	915
Liquids (%)	14	7	20	0	53	20	36	10
Gas (%)	74	68	32	75	35	60	9	40
Coal (%)	12	25	48	25	12	20	55	50[b]
Household/service (GWyr/yr)	440	314	225	163	388	451	24	200
Liquids (%)	42	13	36	0	65	28	78	25
Gas (%)	56	85	14	70	23	70	7	27[c]
Coal (%)	2	2	50	30	12	2	15	48[d]

[a] Substitutable fossil fuels are fuels allocated to heat requirements (industrial, household-service sectors) that are not supplied by electricity, district heat, combined cycle, or solar systems.

[b] Includes 18 percent coal and 32 percent charcoal.

[c] Includes 7 percent natural gas and 20 percent biogas.

[d] All charcoal, 0 percent coal.

bined cycle and district heat systems. Oil would simply not be used for heating in the Soviet Union in the long term and probably very little or not at all in Eastern Europe as well. As a result, gas is assumed to take the major share of substitutable fossil uses in both industry and household/service sectors (about 75 percent by 2030 in the High scenario, from 25 percent in 1975). Coal used for such purposes may actually decline (from current relatively high levels) in the face of this increased gas use and the desire to use coal for central station electric and combined heat and power plants.

Region III (WE/JANZ) has not been blessed with a bounty of fuel resources. As a result, there are fewer clear signals to use in allocating substitutable fossil demands among fuels. Here, a modest growth in direct coal use in industry is assumed—to 20 percent of industrial substitutable fossil demands in 2030 in the High scenario, from 12 percent in 1975. Coal is relatively plentiful in this region (at least compared to other fuels) and could be exploited. The gas share is projected to grow markedly in response to supply availabilities and the hope of offshore finds and imports from region II, both at nonexcessive prices. Gas would then contribute 502 to 791 GWyr/yr to final energy demand in 2030, compared to 234 GWyr/yr in 1975. As in most other regions, liquid fuels in region III are shifted out of substitutable uses and saved for motor fuel and feedstocks. Thus, oil's share of total substitutable fossil fuel would drop from 59 percent in 1975 to 23 to 36 percent in 2030.

Developing Regions. It is assumed that, in view of the scarcity of fossil fuels and their rising production costs and import prices, the developing regions IV (LA) and V (Af/SEA) would pursue an aggressive policy to save on fossil fuels by making extensive use of renewable resources. A part of substitutable fossil demand in each region may be replaced by the organized commercial supply of charcoal and wood, agricultural wastes, and biogas, without disrupting the normal evolution of various activities in the industrial and household/service sectors. The analysis of the maximum renewable contribution (Table 16-23) takes into account the evolution of settlement patterns (urbanization, distribution of city sizes) and the likely distribution of various energy-consuming activities among rural areas (villages), towns (urban agglomerations with less than 100,000 inhabitants), and large cities in each region.

Keeping in view the differences of traditional practices and social habits of people in regions IV and V and also taking into account the potential of biomass resources in the two regions (see Chapter 17), the extensive use of biogas plants has been considered as a viable option only for rural areas in region V, but not for those in region IV. On the basis of the assumptions in Table 16-23 and the level of use of noncommercial fuels assumed, it is expected that biogas generation in region V may substitute for as much as 15 GWyr/yr of fossil fuel by 2000 and 35 to 40 GWyr/yr by 2030. The substitutable fossil fuel demand to be met by commercial supplies of charcoal and wood and biogas would be 100 to 121 GWyr/yr by 2000 and 273 to 424

Table 16-23. Assumed penetrations of renewable sources of energy, regions IV (LA) and V (Af/SEA).

Demand Sector	*Nature of Demand*	*Projected Penetration of Renewables*[a] *(fraction of useful heat demands)* *2000*		*2030*
		Region IV	*Region V*	*Regions IV and V*
Households				
Cities	Cooking, space and water heating	0.40	0.45	0.60
Towns[b]	Cooking, space and water heating	0.60	0.70	0.80
Villages[c]	Cooking, space and water heating	0.75	0.85	0.90
Service sector				
Cities	Space and water heating	0.20		0.40
Towns	Space and water heating	0.30		0.60
Manufacturing				
	Low temperature steam/hot water	0.40		0.80
	High temperature steam	0.30		0.60
	Furnace heat	0.06		0.12

[a] Projected penetrations assume aggressive policies and include the use of noncommercial fuels in households.

[b] Towns are urban agglomerations with less than 100,000 inhabitants.

[c] Villages include all rural households.

Source: Khan (1980).

GWyr/yr by 2030 in region V; in region IV it would be 55 to 69 GWyr/yr by 2000 and 166 to 247 GWyr/yr by 2030.

After allowing for the estimated shares of charcoal/wood and biogas, as discussed above, the remaining substitutable fossil fuel demands in each of the developing regions are distributed over time between coal, oil, and gas in the light of the relative price dynamics of these fuels resulting from the supply-demand balance calculations of Chapter 17. This is done in various regions in the following way.

Region IV (LA) does not have abundant coal resources but could be self-sufficient in oil and gas. Coal supplied a mere 7 percent of substitutable fossil fuels in 1975 and is projected to drop to 1 to 2 percent (all in industry) by 2030. Oil made up the largest fraction (at 62 percent) in 1975. Its share may drop, although high total demands would keep oil a major supplier of heat. Commercial sources of wood (charcoal) may well be able to meet substantial portions of substitutable fossil needs. It is projected that by 2030 charcoal may offer as much as 247 GWyr/yr to a total substitutable fossil demand of up to 578 GWyr/yr (see Chapter 17).

Region V (Af/SEA) resembles region III in that domestic oil is scarce and expensive, yet region V does have major resources of coal (compared to its demand level) and, to a lesser extent, gas. With supply pressure on liquid fuels, the liquids share of total (secondary) substitutable fossil fuels has been assumed to drop from some 43 percent in 1975 to just 13 to 19 percent in 2030—although this represents a growth of from 58 to as much as 141 GWyr/yr by 2030. Coal and, more importantly, charcoal expand to cover nearly 50 percent of substitutable fossil fuel needs by 2030. Gas is sufficiently available to contribute further to industrial heat needs, whereas biogas may play an important role in meeting the bulk of commercial energy requirements of rural households.

Table 16-22 records some of these observations for the High scenario. Differences for the Low scenario mostly reflect the not so great supply pressure on liquid fuels in this instance and hence the relatively less pronounced assumed shifts away from liquid fuels. Still, the similarities in assumptions for the two scenarios are greater than the differences.

"Soft" Solar

Fifty-year energy projections need to recognize the potentials of new technologies. Solar technologies have a role to play in the long term—ultimately perhaps the lead role. Here, attention is given to the possible penetration, buildup, and use of single-building rooftop solar collectors for producing heat for rooms and water. (This is so-called "soft" solar, discussed briefly in Chapter 6.) Other solar technologies for large-scale production of electricity and fuels, untested and uncertain new technologies, and indirect uses of the sun are treated in Chapter 5. Their possible role in the primary energy supply mix of the future will be discussed in Chapter 17.

In regions I and III it is assumed (quite optimistically, it seems fair to say) that 50 percent of all new (post-1975) single family centrally heated homes and low rise service sector buildings would install solar heating systems. (The assumption is 30 percent for region II.) These would be systems that are 50 to 70 percent solar—that is, requiring backup (oil, electric, gas) for 30 to 50 percent of the time. Further, it is assumed that by 2030 nearly 40 percent of all households would be using solar water-heating systems. The result of these assumptions in region I is that by 2030 some 14 percent of residential space heating and 28 percent of water heating would be provided by solar systems; service sector space and water heating would be 6 to 7 percent solar. The same numbers in region III are 7, 28, and 6 percent, respectively. In both regions, solar systems provide 3 percent of total industrial process heat (5 percent of steam generation) and 10 percent of industrial space heat by 2030. All of these numbers are, in aggregate, virtually zero today.

The aggressive buildup rate assumptions for soft solar in the developed regions are meant to explore a reasonable upper bound for their contribution to the energy mix. With the additional, hard to measure expected contributions of passive solar building design, local solar contributions would indeed be significant fifty years from now. But their ultimate contribution seems to be constrained by the market size—the demands for space and water heat in detached or low rise buildings are not excessive. Further, large-scale applications of solar technologies for cooling, for industrial process heat, and for electricity generation are discussed in Chapter 5 and 6, but are integrated into these scenarios in only a very aggregate way. Chapter 17 summarizes the results.

It is instructive to look at the plausible role that the soft solar space- and water-heating technologies can play in the developing world, where sunshine is relatively more abundant. About 82 percent of the useful heat demand in the household/service sector in regions IV, V, and VI in 1975 is estimated to be due to cooking needs. The share of space and water heating in the heat demand of the household/service sector in the three regions increases from about 18 percent in 1975 to 36 to 41 percent by 2030. As the space- and water-heating demands per dwelling are much lower in regions IV, V, and VI than in regions I and III, the soft solar space- and water-heating systems are expected to penetrate later and relatively more slowly in the developing countries. Still, in regions IV and V, gradually by 2030 up to 50 percent of the new construction of single family, centrally heated dwellings and of low rise service sector buildings needing space heating are assumed to turn to solar systems, which would require backup by fossil fuel for about 20 percent of the time. Further, it is projected that by 2030 as much as 30 percent of the total hot water demand in regions IV and V would be met by solar devices. The penetrations of soft solar in the household/service sector of region VI are assumed to be only about half of these numbers.

With these assumptions one finds that solar heating would support 14 percent of the household/service sector's space- and water-heating demand in regions IV, V, and VI by 2030 in the scenarios. The penetration of soft solar in the industrial demand for process heat in these regions is projected to increase by 2030 to 30 percent of low temperature steam and hot water demand and 10 percent of high temperature steam demand—assuming a 20 percent fossil fuel backup of the installed systems. The share of soft solar in the industrial heat demand of these three regions is thus estimated to be about 4 percent by 2030. The total contribution of soft solar in the final energy demand of regions IV, V, and VI comes out to be 78 and 46 GWyr/yr in 2030 for the High and Low scenarios, respectively, which amounts to just 1 percent of the corresponding final energy.

The Exploitation of Conservation in the Two Scenarios

The extent of energy efficiency improvement embodied in the two scenarios can be seen in Figures 16-5 and 16-6, where final energy per unit of GDP is plotted against GDP per capita for regions I through VI. It is seen that the ratio of final energy demand to GDP continues to decrease for the developed regions (I, II, and III) in line with the historical trends. On the other hand, the ratio continues to increase, at least initially, for all the developing regions, again in line with the historical trends, but later on it flattens off and even starts decreasing for regions IV and VI. These different trends in

Figure 16-5. Energy intensiveness in different world regions, High scenario.

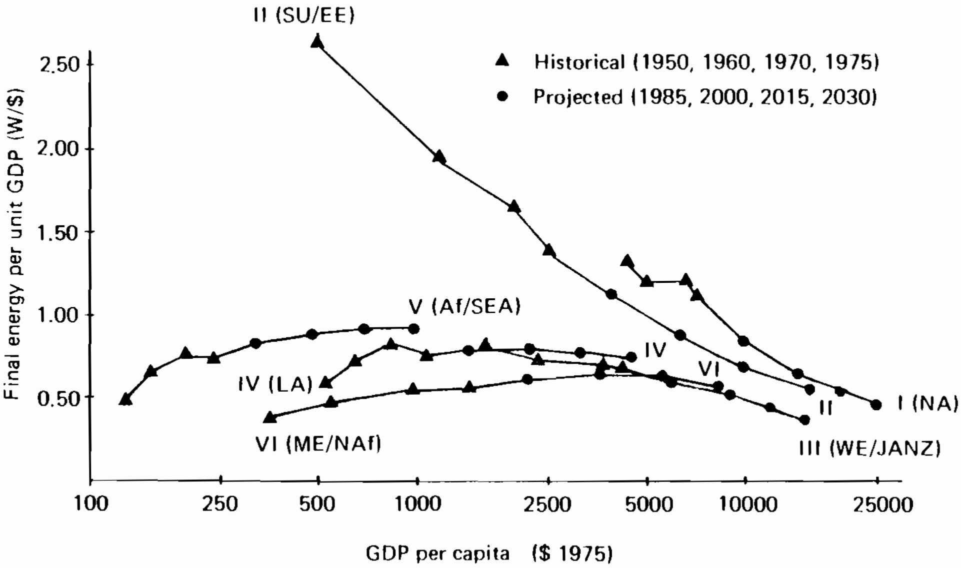
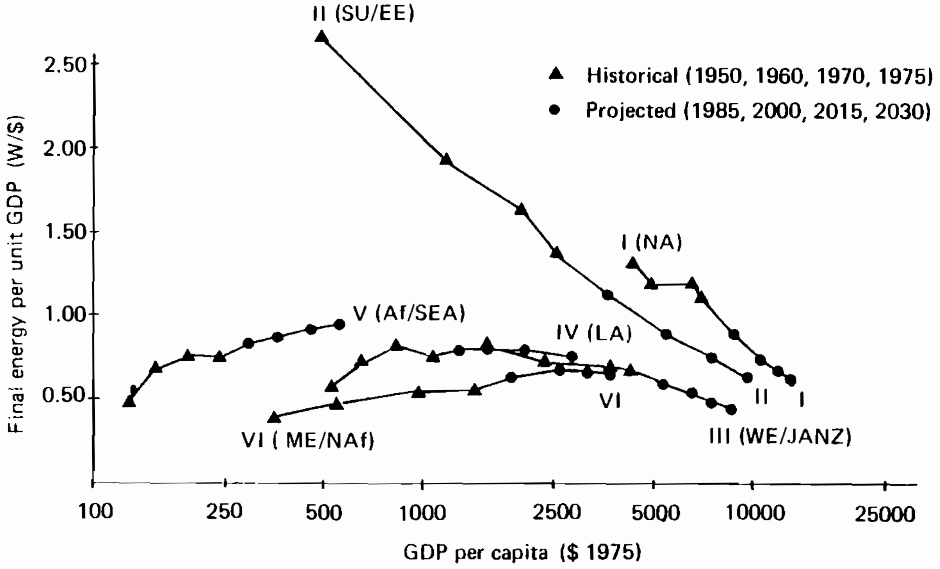


Figure 16-6. Energy intensiveness in different world regions, Low scenario.



the developed and the developing regions are characteristic of economies that have already reached a high level of industrialization but are still in the process of building up their industrial infrastructure.

Globally speaking, the curves of Figures 16-5 and 16-6 imply a reduction of final energy per dollar GDP from 0.91 in 1975 to values of 0.53 and 0.62 in 2030 for the High and the Low scenarios, respectively. If only the developed regions I, II, and III are considered, the improvement is even more impressive: final energy per dollar GDP decreases from 0.95 in 1975 to 0.45 and 0.55 over a period of fifty-five years. By far the largest improvement is seen in region II (SU/EE), where the overall conservation resulting from various scenario assumptions amounts to 61 and 54 percent. The corresponding figures for region I are 59 and 44 percent and for region III, 45 and 33 percent. These improvements, seen in the light of real price increases of 3 and 2.4 times the prices in the recent past (see Chapter 15), appear quite pronounced—but not unrealistic. Some measures of this trend, in detail, have been reported in this chapter. Indicators such as automobile efficiency, average transport load factors, home insulation, structural changes in industry, and others have been cited to illustrate the extent of the energy-using improvements assumed.

Another measure of the efficiency improvements assumed for the scenarios can come from calculating the final energy that would result by 2030 if the historical 1950–1975 final energy-to-GDP elasticity were to be applied for 1975 to 2030. Table 16-24 shows the differences between final energy calculated in this way and the final energy projections of the High and Low scenarios. Savings of roughly 20 to 50 percent occur in each region. The demand reduction steps behind these figures represent an important "supply" source of 7.3 to 18.3 TWyr/yr globally by 2030.

These amounts are certainly substantial. They underscore the aggressive

Table 16-24. Final energy in the two scenarios compared to final energy calculated with historical elasticities (2030).

Region	*High Scenario (GWyr/yr)*	*With Historical ϵ_f^a (GWyr/yr)*	*Difference^b (Percent)*	*Low Scenario (GWyr/yr)*	*With Historical ϵ_f^a (GWyr/yr)*	*Difference^b (Percent)*
I (NA)	3665	6921	47	2636	4036	35
II (SU/EE)	4114	5355	23	2952	3850	23
III (WE/JANZ)	4375	6037	28	2987	3761	21
IV (LA)	2640	4385	40	1656	2481	33
V (Af/SEA)	3173	6900	54	1876	3121	40
VI (ME/NAf)	1638	2590	37	868	1015	16
VII (C/CPA)	3196	8849	64	1589	3536	55
World	22,801	41,037	44	14,564	21,800	33

[a] Calculated using historical (1950–1975) final energy-to-GDP elasticity (ϵ_f) for each region.

[b] Calculated as final energy using historical ϵ_f minus IIASA scenario projection divided by final energy using historical ϵ_f.

conservation measures assumed in the scenarios. They reflect the belief that vigorous actions to increase energy efficiency and to improve energy productivity are necessities in any energy strategy—short, medium, or long term. Without such improvements, the supply scenarios in the next chapter would surely prove to be infeasible.

Energy savings certainly will attractively and economically compete with many alternative energy supply additions; the detailed assumptions on efficiencies and "lifestyles" here were intended broadly to reflect this. At the same time, changes in energy use sectors can come along slowly—it takes on the order of a decade to retool a major industry and on the order of a century to replace a nation's housing stock. These several considerations lead, in these studies, to the estimates as reported in this chapter.

Still, one wonders if an additional potential exists—a potential for cutting back growth in energy demand to the point that supply difficulties (such as those revealed in the next chapter) are almost totally mitigated. A number of voices claim that such potential exists and is realizable. The studies at IIASA have not been designed to assess the validity of such assertions. But the approach followed at IIASA can possibly illuminate the implications of major demand reductions.

Recognizing such possibilities, a very low energy scenario is assessed using this same MEDEE-2 tool. This scenario is meant to explore the implications of actions designed to achieve zero, or even negative, overall energy growth in developed regions. In Chapter 18, the analysis of this very low energy scenario is described. First, however, the energy supply possibilities for the High and Low scenarios of this chapter are presented in the next chapter.

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17 ENERGY SUPPLY AND CONVERSION

How can sufficient energy be supplied over the next five decades to meet the continuing needs of growing economies? While the answer is by no means obvious, the issue is sufficiently important to be worthy of careful analysis. As demonstrated in Chapters 15 and 16, requirements for energy are high and will become higher, forcing prices to rise. Energy supply and conversion systems to meet the needs must offer some measure of convenience and acceptably low cost, and they must not jeopardize environmental security. The aim of this chapter is to explore a feasible range of such systems in some detail.

Because energy supply and conversion systems are complex and interregionally interdependent, mechanistic approaches to their study do not suffice. The description in Chapter 13 of the quantitative, analytical approach used here illustrates the iterative, interactive character of the tools and methods that produced the results summarized in these pages. Interactions among energy needs, preferences, relative prices, resource availabilities, production constraints, and costs are treated so that, after some examination and reexamination, a reasonably consistent energy supply and conversion system should result. The goal is synthesis—the integration of the many components of demand and supply into a coherent energy system.

An important tool in this process is a dynamic linear programming model of the energy supply and conversion system, a model called MESSAGE. The detailed results of applying this model region by region—within assumed constraints—appear throughout this chapter. (The model is described in Chapter 13.)

The system being modeled in these studies is a heterogeneous one in which energy demand, supplies, and international flows are coordinated via a complexity of market prices, government regulations and interventions, and physical constraints. No international central planning bureau exists (for better or for worse), and none is modeled.

In this context, it is important to remember that, while the computer models in use provide the important benefits of speed of computation, internal consistency, and organization of assumptions, they do not drive the fundamental logic of the analysis nor the interpretation of the results. Human judgments and assumptions play a large role in these studies; mental models are, in any case, prerequisites to computer models.

In this chapter, the two scenarios (High and Low) of Chapter 14 are examined. These scenarios do not postulate the buildup and use of the endowment-creating technologies as described in Part II of this book. That is, the possible production of a synthetic liquid fuel, such as methanol, through the use of heat from nuclear breeders or from centralized solar collection systems is not considered here. The implementation of these technologies (thought to be more expensive than the ones used here) seems sufficiently uncertain and possibly delayed into the very long term so that they are treated only in the next chapter.

Table 17-1 summarizes some of the central definitional characteristics of the High and Low scenarios, as well as some summary results of the analysis. The two scenarios have different economic growth assumptions and thereby different energy demand requirements. They have different supply profiles

Table 17-1. Two global supply scenarios: definitions of main parameters.

	High Scenario	*Low Scenario*
Assuming, by 2030:		
Population		
factor increase	2	2
total (10^6)	7976	7976
Gross World product[a]		
factor increase	6.4	3.6
growth	declining rate	
average growth, (%/yr) 1975-2030	3.4	2.4
Final energy Demand[b]		
factor increase	4.0	2.5
2030 annual rate (TWyr/yr)	22.8	14.6
Results in, by 2030		
Primary energy		
factor increase	4.3	2.7
2030 annual rate (TWyr/yr)	35.65	22.39
average per capita (kWyr/yr)	4.5	2.8

[a] See Table 14-4.
[b] See Table 15-1.

(resulting from MESSAGE runs) and thus different energy price assumptions. But they both (simplistically, perhaps) carry the same resource availabilities, unit cost estimates, and maximum buildup rate assumptions. These several assumptions have important bearing on the results summarized here and are presented in more detail in the pages that follow.

This chapter begins by summarizing the main assumptions and results of the energy supply system analyses. The next three sections contain what can, for these supply analyses, be taken as assumptions. Then, the potentials and limitations on future oil production are examined, because oil turns out to be the most demanded primary resource, and its supply is constrained. The next three sections lead to a summary of oil supply results, region by region. The results for gas and coal supply and demand and for electricity generation follow. Then, the potentials of local renewable sources in developing regions are sketched. Calculation of cumulative fossil fuel use leads to questions of carbon dioxide concentrations and, ultimately, of resource depletion.

GLOBAL PRIMARY ENERGY[a]

The bottom line of any traditional energy accounting is the total primary energy use. Within that total, the various energy sources must be identified. When these sources are set down beside the demand figures already described (Chapter 16), the nature of the globe's conceivable energy futures becomes clearer.

The figures presented here are results of the supply analyses detailed in this chapter. They are summarized here for introductory purposes, before a full description of the underlying assumptions is given.

Looking back over the previous twenty-five years with such an analysis (Figure 17-1), it is easy to see the shift throughout the world to oil and gas and the decreasing reliance on coal. (Chapter 8, on market penetration, offers further illumination on the historical trends.)

The High and the Low scenario projections for the next fifty years are recorded in Figure 17-2, leading to a few observations:

- The oil and gas era is not over. While the share of total primary energy demand met by both of these fuels would decline, they would still provide large amounts of energy—two and a half times their 1975 levels in the High scenario by 2030. (A large fraction of this oil is unconventional, as shall be reported later.)
- Nuclear energy would fill a rapidly expanding wedge. This source of electricity would meet effectively all new off-peak load electricity demand in the developed regions, in the scenarios.
- Coal production, after growing slowly to the end of this century, must

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[a] The wealth of data being what it is for analyses of this kind, we present here the important highlights of the supply scenario results. All global results presented here are the aggregate of the seven world regions.

Figure 17-1. Global primary energy supply for the period 1950-1975 (excluding noncommercial sources).

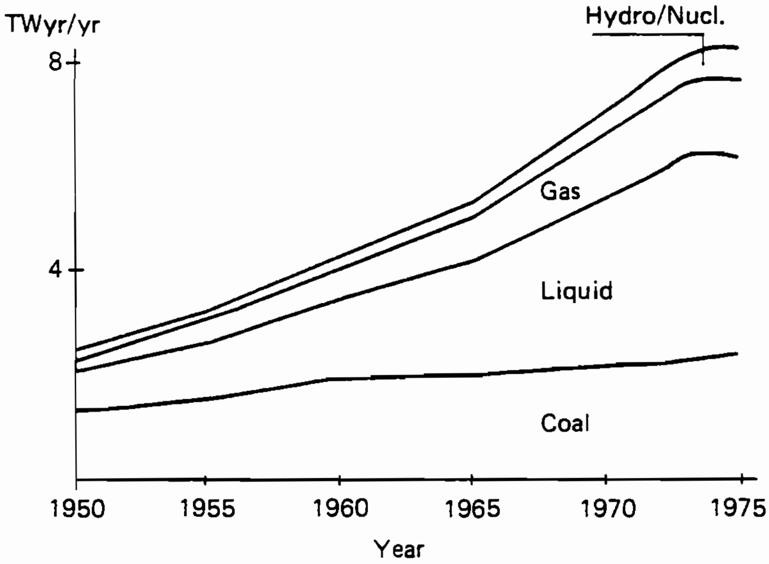


Table 17-2. Two supply scenarios, global primary energy by source, 1975–2030 (TWyr/yr).

Primary Source[a]	*Base Year 1975*	*High Scenario 2000*	*High Scenario 2030*	*Low Scenario 2000*	*Low Scenario 2030*
Oil	3.83	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar[b]	0	0.10	0.49	0.09	0.30
Other[c]	0	0.22	0.81	0.17	0.52
Total[d]	8.21	16.84	35.65	13.59	22.39

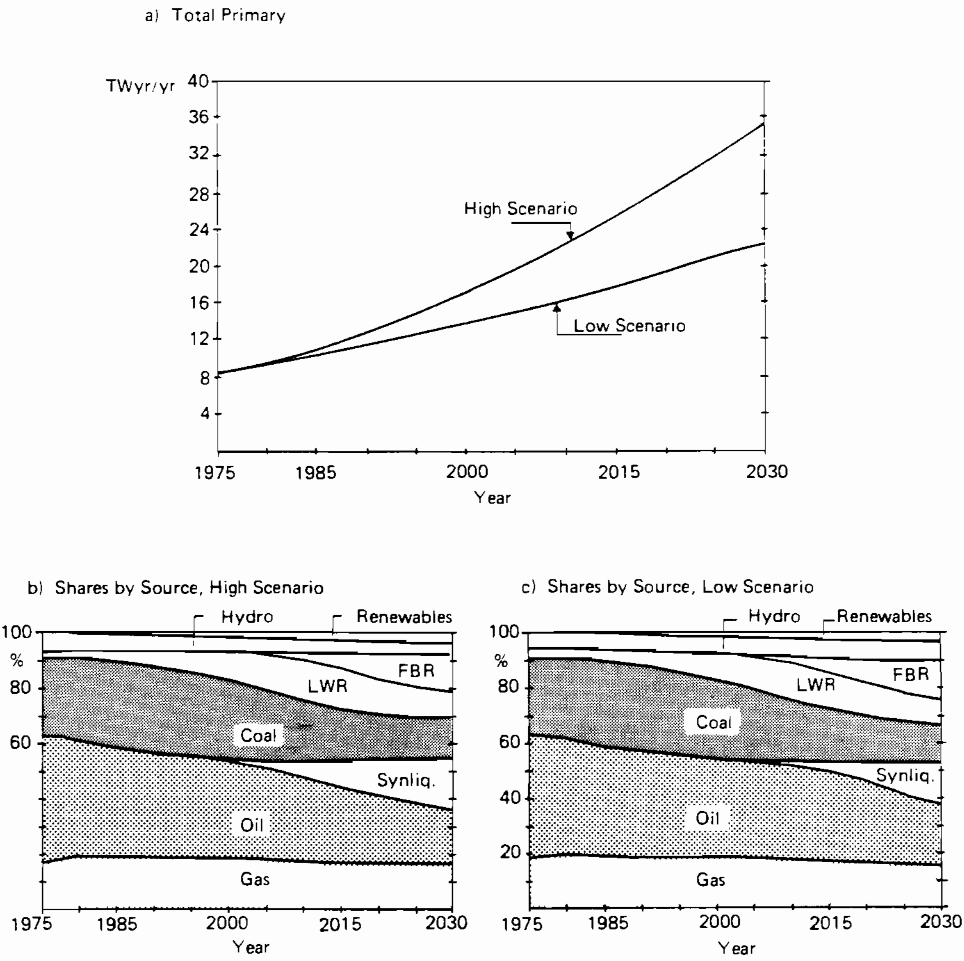
[a] Primary fuels production or primary fuels as inputs to conversion or refining processes—for example, coal used to make synthetic liquid fuel is counted in coal figures. (For definition of energy types, see Figure 1-1.)

[b] Includes mostly "soft" solar—individual rooftop collectors—also small amounts of centralized solar electricity.

[c] "Other" includes biogas, geothermal, commercial wood use.

[d] Columns may not sum to totals because of rounding.

Figure 17-2. Global primary energy: two supply scenarios, 1975-2030.



expand rapidly thereafter; this is the result of the demand for synthetic fuels.

- Solar and other renewable energy sources contribute a noticeable, but hardly dominating, share to primary energy by the year 2030. (The bases for their contributions are reported in Chapter 16 and also briefly in a later section of this chapter.)

In Table 17-2, the primary energy totals are given by source for the High and Low scenarios for 2000 and 2030. In Table 17-3, the same totals are given by region. These results are aggregate world totals. They mask important regional details and major changes in the forms and uses of energy that are considered in these analyses. They also mask the role of new technolo-

Table 17-3. Two supply scenarios, primary energy by region, 1975-2030 (TWyr/yr).

		High Scenario		*Low Scenario*	
Region	*1975*	*2000*	*2030*	*2000*	*2030*
I (NA)	2.65	3.89	6.02	3.31	4.37
II (SU/EE)	1.84	3.69	7.33	3.31	5.00
III (WE/JANZ)	2.26	4.29	7.14	3.39	4.54
IV (LA)	0.34	1.34	3.68	0.97	2.31
V (Af/SEA)	0.33	1.43	4.65	1.07	2.66
VI (ME/NAf)	0.13	0.77	2.38	0.56	1.23
VII (C/CPA)	0.46	1.44	4.45	0.98	2.29
Total[b]	8.21[a]	16.84	35.65	13.59	22.39

[a] Includes 0.21 TWyr/yr of bunkers—fuel used in international shipments of fuel.

[b] Columns may not sum to totals because of rounding.

gies and of constraints on the uses of energy resources. Yet they do reveal a theme that will be repeatedly sounded throughout this chapter: in spite of considerable shifting of liquid fuels away from nonessential uses and increased efficiency of their use, oil supply will remain the crucial problem in the coming decades. A very large unconventional crude oil industry and a large coal synthetics business could well be in the offing.

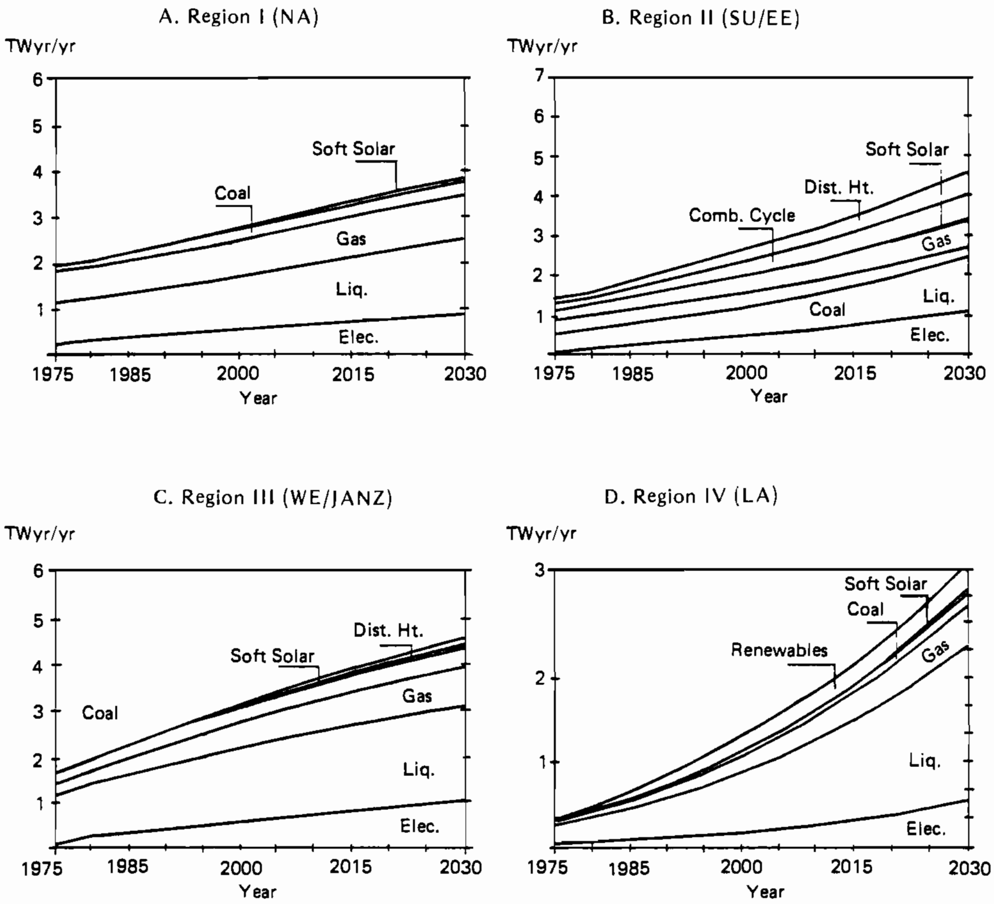
SECONDARY ENERGY DEMANDS

The supply system analyses of this chapter indicate the consequences of meeting the secondary energy demands of Chapter 16. These consequences—relative price dynamics, constraints on fuels supplies, constraints on the buildup of new facilities—induce judgmental feedback alterations of the original demand estimates or of the fuel mix assumptions. The resulting new set of energy demand estimates enters the supply analyses (as inputs or assumptions), and the iteration goes on until a reasonably consistent scenario is obtained.

Secondary energy demands come from the final energy demand estimates of Chapter 16 by adding average transmission and distribution losses (see Figure 16-2). This calculation is done for each fuel and varies somewhat from region to region. But approximate figures used for these losses, as a percent of total secondary energy by each type, are oil 0 percent (all losses counted in MESSAGE runs); gas 7 to 10 percent (local pipeline losses); coal 2.5 percent (mostly coal blown off trains); electricity 12 to 18 percent (counted from power plant busbar to final consumer); soft solar 0 percent (a convention adopted here).

Figure 17-3 contains seven plots showing secondary energy demands for the High scenario region by region. The Low scenario is in many respects quite similar, yet has somewhat higher oil fractions than in the High sce-

Figure 17-3. Secondary energy demand, High scenario, 1975-2030.



A. Region I (NA)

B. Region II (SU/EE)

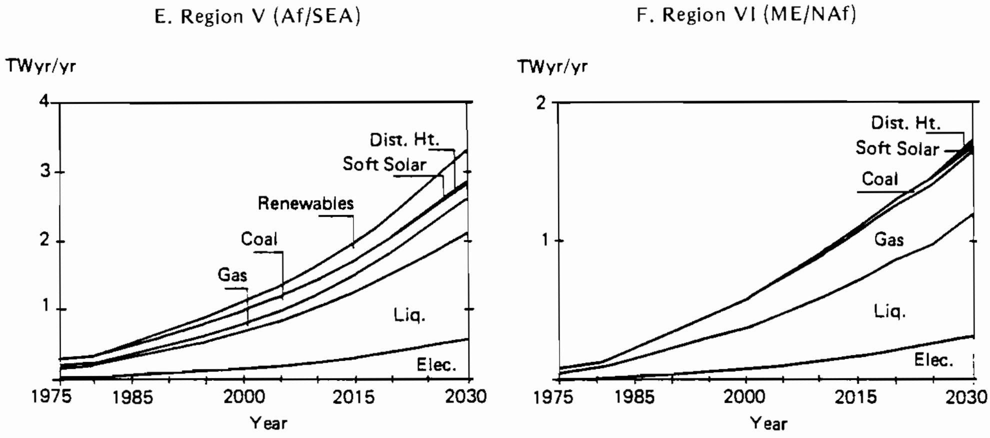
C. Region III (WE/JANZ)

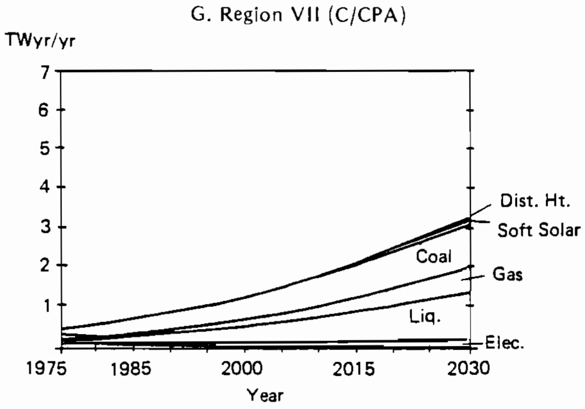
D. Region IV (LA)

nario, since oil prices do rise more steeply in the High scenario than in the Low scenario. The higher energy consumption levels of the High scenario force oil supply to increasingly expensive sources. (The derivation of the oil price dynamics appears later, in the section on interregional oil balancing.)

In these scenarios, liquid fuel consumption continues to be large, while liquids demand, as a fraction of total secondary energy use, drops (from 60 percent in 1975 to 45 percent in 2030 in region III [WE/JANZ] in the High scenario, for example). Liquid fuel is a premium one, highly preferred for many uses and virtually irreplaceable for some. Nonetheless, the increasing relative prices for liquids in these scenarios—stemming from the constraints on resource and production—dampen the use of liquid fuels in many instances where they are not essential. The potential for further reduction in the consumption of liquid fuels rests largely on the possibility of substitute fuels for use in transportation and in petrochemicals production.

Figure 17-3 continued.





The share of secondary energy from gaseous fuels increases in some regions in these scenarios; coal increases in all regions. The extent of this substitution is somewhat problematic; a host of local factors makes individual regional situations importantly different. By 2010 or 2020, gas and coal compete for the heating market with solar and, to a limited extent, electricity at the same time that efficiency improvements are shrinking the size of this market. This limits the potential gas share. This is indeed a significant observation. In spite of vigorous efforts to substitute gas for oil and generally to expand gas use wherever possible, gas demands increase only modestly in these scenarios. Gas is market limited.

These secondary energy demands, then, are inputs to the supply analyses; the supply and conversion system sees them as assumptions. They are the results of the assumptions and calculations of Chapter 16.

CONSTRAINTS ON SUPPLY: COST AND BUILDUP RATE ASSUMPTIONS

A variety of energy supply and conversion technologies can compete to meet demands. Here, it is assumed that technologies compete primarily on a cost basis, with the cheapest technology available being used first. But there are constraints on the rates at which new resources can be exploited or new facilities built and on the total amount of any single activity (such as coal mining) that a society will tolerate. And deliberate planning to maintain flexibility—for example, to provide diversity of supply in order to cope better with unexpected changes in energy supply systems—can affect decisions that would otherwise be dominated by cost considerations alone. In a sense, all of these constraints, taken together, are the singular characteristic of the scenarios—the aspect of their analysis that sets them apart from considerations elsewhere in this book.

Table 17-4 lists competing technologies for fuels and electricity supply and assumptions used here for their capital and operating costs. These data, while arrived at by averaging many sources, are still highly judgmental. And while they will surely change over time, perhaps dramatically, just one cost estimate for each technology is used here for the entire planning horizon. Sensitivity analyses can test alternative cost estimates. Yet the possibility that the cost figures used here might be greatly understated should not be overlooked. It can be observed that the real costs of complex energy supply systems today invariably exceed expectations, and this may not change in the future. (The 1970 to 1977 costs of power plants in the United States, for example, rose much faster than the domestic consumer price index.) This possibility could well heighten interest in the potential economic attrac-

Table 17-4. Cost assumptions for major competing energy supply and conversion technologies.

	Capital Cost (1975\$/kW)	*Variable Cost (1975\$/kWyr)*	*Final Product Cost (1975\$/kWyr)*
Electricity Generation			
Coal with scrubber	550	23	154
Conventional nuclear reactor (e.g., LWR)	700	50	136
Advanced reactor (e.g., FBR)	920	50	143
Coal, fluidized bed	480	36	152
Hydroelectric	620	8.5	85
Oil fired	350	19	256
Gas fired	325	16	216
Gas turbine	170	17	241
Solar central station	1900	28-60	297
Synthetic Fuels			
Crude oil refinery	50	3.7	75
Coal gasification ("high Btu")	480	40	125
Coal liquefaction	480	40	125

Table 17-4 continued.

District Heat Technologies					
Type	*Electric-Heat Ratio*	*Capital Cost (1975\$/kW$_{SE}$[a])*	*Variable Cost (1975\$/kWyr$_{SE}$[a])*	*Final Product Cost (1975\$/kWyr$_{SE}$[a])*	*LF*[b]
Combined Heat and Power (Region II [SU/EE])					
LWR	38/62	320	25	65	0.7
Coal	23/77	220	18	79	0.75
Liquids	23/77	180	15	137	0.75
Gas	23/77	180	15	74	0.75
Heat Production (Region II [SU/EE])					
LWR	0/1	160	13	35	0.7
Coal	0/1	90	9	52	0.85
Liquids	0/1	60	5	100	0.85
Gas	0/1	60	5	46	0.85

[a] SE ≡ secondary energy.
[b] LF ≡ load factor.

Notes: The figures for electricity generation and synthetic fuels are assumed to apply, mostly, to both developed and developing regions; differences are noted in the text. The costs are assumed to apply, as averages, over the fifty-year planning horizon.

Capital cost: Capital costs per kW of capacity. Assumed to represent average capital costs (paid at once) for standard facilities of thirty-year lifetime; intended to include owner's costs (interest during construction, land lease, etc.). Escalation is not included. Extraordinary other costs (litigation, unspecified social costs) are not included.

Variable costs: Operating and maintenance plus fuel cycle costs (not including fuel costs) per kWyr of product (electricity or synthetic fuel).

Final product cost: Static cost per kWyr of secondary energy (electricity or synthetic fuels) including fuel costs. Fuel costs are taken to be the cheapest category of the corresponding fuel. The cost figures in this column are not the dynamic figures in MESSAGE; here they serve only the purpose of quick comparison. The data on plant life (thirty years; hydro fifty years) and on the load factor (70 percent hydro and 57 percent solar) enter the calculations, as does the discount rate (6 percent). For a time interval of five years and a plant life of thirty years, the formula for the annualized capital cost is

$$cap \cdot \frac{\beta^{5} - 1}{(\beta^{30} - 1)\beta^{2.5} 5} \tag{1}$$

where β is the one-year discount factor (1/1.06 here) and *cap* is the total capital cost. In order to get the levelized capital costs per kWyr of output, equation (1) must be divided by the load factor. For example, a LF of 0.7 yields a levelizing factor of 0.101.

Hydroelectric: The high, but so far unexploited, potential of hydroelectric in regions IV and V led to a specification of two capital cost categories for hydro in each of these regions; the second category, including additional costs, reflects transmission from remote sites.

Solar central station: Including storage costs allowing an annual average load factor of 57 percent. Variable costs include an estimate for long distance transmission costs and are lower in high insolation developing regions.

Sources: The following sources (often contradictory and/or incomplete) were aggregated to generate rough average (sometimes consensus) estimates: report of the Modeling Resources Group of the Synthesis Panel of CONAES; inputs to PILOT model (G. Dantzig, Stanford University, California); Brookhaven National Laboratory, Upton, New York; American Gas Association, Arlington, Virginia; Pacific Gas and Electric Co., San Francisco, California; Bechtel Corporation, San Francisco, California.

tiveness of energy efficiency improvements (or energy productivity increases) as an alternative "supply" source. The cost estimates used here are, for better or for worse, no more than a composite of the presently best recognized estimates.

The technologies of Table 17-4 are not the only ones that would contribute to the future supply mix. For example, combined cycle facilities—such as gas turbine combined cycle plants with on site, "low Btu" coal gasifiers—might well contribute importantly. While these omissions may not be optimal, the analysis is simplified by having few instead of many technologies; the results would not change markedly with the introduction of further technologies.

As pointed out in Chapter 8 on market penetration, there are limitations on the maximum rate at which a new energy supply source or a new energy technology can be brought on stream. This fact is reflected here by a constraint on annual buildup rates. This constraint is defined in relative terms, so that an annual buildup rate in one five-year period cannot exceed that of the previous period by more than a specified percent. In addition, one parameter is provided that allows for an initial startup. Together these buildup rates and startup parameters define asymptotically the exponential growth, with higher growth rates at the beginning. Table 17-5 summarizes these assumptions. As a general feature, these constraints are more stringent in developing regions, reflecting typically lower productivity, lack of complete supporting infrastructure, smaller markets, and (frequently) dependence on imports of technology.

The constraints are not only those of technology. For example, in spite of enormous coal resources, coal production in the United States may be limited by environmental, social, and transportation considerations and by lack of water. Developing countries and regions with large resources may decide to impose production (or export) ceilings to stretch out the lifetime of their wealth, allowing development to keep pace only with their need for income. In other words, political and institutional issues may alter strategies that seem "economically" compelling. Assumptions that reflect these constraints were incorporated in the analyses presented below.

ENERGY RESOURCES: INPUTS TO THE SUPPLY ANALYSES[b]

It has been the hope of resource economists, energy planners, and/or modelers to generate reliable resources versus cost curves or tables. This, of course, is the very spirit of the McKelvey classification (see Figure 1-8). Unfortunately, the reality is far from the ideal situation.

Nonetheless, modelers must use such curves or tables of available resources as a function of costs and/or prices. Thus, an endeavor has been made to distribute the various fossil reserve and resource estimates—dis-

[b] This section (not including the boxed material) is contributed by M. Grenon, leader of the Resources Assessment Group at IIASA.

Table 17-5. Startup and buildup constraint assumptions for new energy technologies.

	Increment, as Percent of Previous Period's Expansion	*Startup Capacity (GW/yr)*	*Commercially Available After*
For Developed Regions[a]			
Conventional nuclear reactor (e.g., LWR)[b]	150	2	today
Fast breeder reactor[b]	200	2	1995[c]
Coal, fluidized bed	200	2	1990
Coal liquefaction	200	6	1990
Coal gasification	200	6	1990
For Developing Regions[d]			
Conventional nuclear reactor (e.g., LWR)[b]	120	0.4	today
Fast breeder reactor[b]	120	0.4	2000
Coal, fluidized bed	140	0.4	1995
Coal liquefaction	140	2.0	2000
Coal gasification	140	2.0	1995
Solar electric	140	0.5	2005

[a] Regions I (NA), II (SU/EE), and III (WE/JANZ).

[b] For nuclear technologies, a total (LWR plus FBR) buildup constraint is also imposed; see text for more details.

[c] The year 2000 for region I; 1995 for regions II and III.

[d] Regions IV (LA), V (Af/SEA), VI (ME/NAf) and VII (C/CPA).

Note: The numbers in Table 17-5 are transformed into constraints for the MESSAGE model as follows: The asymptotic increment and startup parameters refer to γ and g, respectively, in

$$y^t \leqslant \gamma y^{t-1} + g \tag{1}$$

where y^t is the annual addition to the capacity of the respective technology in time period t (y^0 being a boundary condition). Thus, the maximum capacity in the first period in which, say, FBRs in developed regions are allowed is 5 [yrs] X 2[GW/yr] = 10 GW of installed capacity. This occurs in the period labeled 2000—i.e., FBRs are "commercially available after" 1995 by the third column in the table. The maximal increase in the period "2005", according to formula (1) is 30 GW/yr yielding a maximum total of 40 GW/yr for that period. In addition to these buildup constraints, there is a constraint on the buildup of total nuclear capacity. This constraint is based on the following assumptions:

- An asymptotic value of 30 TW(e) of installed nuclear capacity (reached only well after the year 2030) is shared among the regions according to their share of global population in 2030.
- The values of the first three periods are estimated for each region on the basis of present knowledge of plans, commitments, and so forth, making up the start of an S-shaped curve toward the asymptotic value above.

cussed more fully in Chapter 2—among different cost categories. This has been made with the single purpose of providing a working tool, and it can be considered at best a zero order approximation. However, the approach is tempting, and efforts to improve the first preliminary results are continuing.

In order to achieve this objective, broad use has been made, first, of the important comments accompanying the studies by the World Energy Conference (1978a, 1978b, 1978c), which provide basic data. Second, many discussions were held with numerous experts, especially during the second IIASA Conference on the Future Supply of Oil and Gas (Meyer 1977). Finally, one is obliged, although reluctantly, to rely on "guesstimates."

The results are summarized in Tables 17-6 and 17-7. A further examination of energy resources is reported in the chapters of Part II of this book. There, the intent was to stretch to the boundaries of the possible, to identify and analyze the real potentials of various energy sources. Here, in the scenario analysis, the aim is different. A balancing of various alternatives is sought, within an array of real world constraints. These constraints, as will be shown, are the real determinants of the scenario results.

Table 17-6. Summary of estimates of ultimately recoverable resources by cost category.

Resource[a]	*Coal*[b] *(TWyr)*		*Oil* *(TWyr)*			*Natural Gas* *(TWyr)*			*Uranium* *(TWyr)*	
Cost Category[c]	*1*	*2*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*
Region										
I (NA)	174	232	23	26	125	34	40	29	35	27
II (SU/EE)	136	448	37	45	69	66	51	31	ne	75
III (WE/JANZ)	93	151	17	3	21	19	5	14	14	38
IV (LA)	10	11	19	81	110	17	12	14	1	64
V (Af/SEA)	55	52	25	5	33	16	10	14	6	95
VI (ME/NAf)	< 1	< 1	132	27	ne	108	10	14	1	27
VII(C/CPA)	92	124	11	13	15	7	13	14	ne	36
World	560	1019	264	200	373	267	141	130	57	362

[a] For oil, gas, and coal, see estimates given in the text (translated here into units of TWyr); for uranium, see estimates given in Chapter 4.

[b] For coal, only a part of the ultimate resource (~15 percent) has been included because the figures are already very large for the time horizon of 2030 and because of the many uncertainties about very long-term coal resources and production technologies.

[c] Cost categories represent estimates of costs either at or below the stated volume of recoverable resources (in constant 1975$).

For oil and natural gas:	Cat. 1:	12$/boe
	Cat. 2:	12-20$/boe
	Cat. 3:	20-25$/boe
For coal:	Cat. 1:	25$/tce
	Cat. 2:	25-50$/tce
For uranium:	Cat. 1:	80$/kgU
	Cat. 2:	80-130$/kgU

A subcategory of oil, 1A, exists only for regions I (NA) and IV (LA) and includes oil available at production costs of $12 to $16/boe. Also, a subcategory of gas, O, exists only for region VI (ME/NAf), with gas available at $2/boe.

ne—no estimate.

Note: For conversion to other units see Appendix B to Chapter 1.

Sources: Ashley, Rudman, and Whipple (1976); Eckstein (1978); Grenon (1977); Grossling (1976); Institute of Geological Sciences (1978); Lambertini (1976); Meyer (1977); *Oil and Gas Journal* (1978); O'Shaughnessy (1976); Penner and Icerman (1975); Perrine (1978); Uhl (1977).

Table 17-7. Summary of estimates of ultimately recoverable fossil resources by cost category (physical units).

Resource[a]	*Coal*[c] *$(10^9$ tce$)$*		*Oil* *$(10^9$ toe$)$*			*Natural Gas* *$(10^9 m^3)$*[c]		
Cost Category[b]	*1*	*2*	*1*	*2*	*3*	*1*	*2*	*3*
Region								
I (NA)	188	250	16.2	18.3	88.2	28,900	34,000	24,650
II (SU/EE)	149	489	26.8	31.8	49.4	52,700	40,800	24,650
III (WE/JANZ)	100	163	12.0	2.1	14.8	16,150	4250	11,900
IV (LA)	11	12	13.4	57.1	77.6	14,450	10,200	11,900
V (Af/SEA)	59	56	17.6	3.5	23.3	13,600	8500	11,900
VI (ME/NAf)	0	1	93.1	19.0	d	91,800	8500	11,900
VII (C/CPA)	99	134	7.8	9.9	10.6	5950	10,200	11,900
World	606	1105	187.0	141.7	263.9	223,550	116,450	108,800

[a] See Table 17-6.

[b] See Table 17-6.

[c] See Table 17-6.

[d] See Table 17-6.

Note: The natural gas resources of region II (SU/EE) are worthy of special note here. Estimates for the Soviet Union alone (M. Styrikovich, personal communication, 1979) put natural gas resources of categories 1, 2, and 3 at $90{,}000 \times 10^9 m^3$; $43{,}000 \times 10^9 m^3$; and $17{,}000 \times 10^9 m^3$, respectively. Such resources would allow a greater use of gas and probably less of coal than has been projected here.

Sources: See Table 17-6.

Coal Reserves and Resources

Two cost categories are proposed for coal—less than $25/tce (category 1) and between $25 and $50/tce (category 2). It seems that in many regions, large amounts of coal can be produced at these costs. This includes region III (WE/JANZ); it is known that some production costs in Europe are already higher than the upper limit of $50/tce (e.g., in France and the FRG the minimum cost is $75/tce, and in Belgium it is $100/tce), but this region includes also South Africa, Australia, and the United Kingdom, with reasonable to very low production costs.

Generally, the "economically recoverable" coal reserves in each region are in the first category (except for region III, because of the above comment), and part of the resources remaining to be identified are in the second category. In the case of the USSR, the United States, and China, only 10 percent of the total resources are considered. However, the figures are already sufficiently high so that including more would not change very much, at least with our time horizon of 2030. Moreover, for these countries, and probably also for others, the possibility that some of the reserves may finally appear in the higher cost category is not excluded, but some of the resources remaining to be identified can replace them in the lowest category.

To put these figures in perspective, for the United States, for instance, it is perhaps worth mentioning that EPRI (1977) has independently calculated the cumulative coal production required to reach $25/ton from July 1, 1975 (with a starting cost of less than $10/ton), which amounted to 850 billion tons (50 billion tons for the Appalachian region, 110 billion tons for the Rocky Mountains, 240 billion tons for the interior plains, and 450 billion tons for the Great Plains). The figures in Tables 17-6 and 17-7 for region I (NA), at least, may thus appear conservative in light of some current analyses.

Oil Reserves and Resources

Three categories of oil resources are used (all costs in 1975 dollars). Category 1 is oil available at production costs of $12 per barrel of crude oil. It includes the known reserves plus a fraction of the resources remaining to be discovered. This fraction varies with the regions and is a matter of judgment, taking into account past history and geological and geographical factors. (It was the general opinion of the Delphi experts [Desprairies 1977] that most of the conventional oil remaining to be produced could be produced at $12 or less per barrel of crude oil.) A subcategory, 1A, exists only for regions I and IV; it includes oil available at production costs of $12 to $16 per barrel of crude oil. Only some oil shales, tar sands, and heavy crude oils are in this group.

Category 2 has production costs of $12 to $20 per barrel of crude oil and includes the second part of the resources remaining to be discovered, plus a small amount of possibly recoverable heavy crude oils, tar sands, or oil shales.

Category 3 has production costs of $20 to $25 per barrel of crude oil and includes supplementary heavy crude oils, tar sands, and oil shales plus "unconventional" oil according to the WEC (1978b) definition (deep offshore and polar areas). The total amount of heavy crude oils, tar sands, and oil shales considered is about 300 billion tons (at less than $25 per barrel of oil equivalent production cost). This has to be compared with the 300 (plus) billion tons of heavy crude oil in place in Venezuela alone, 150 billion tons of tar sands for Canada, and 420 billion tons of oil shales estimated by Donnell (1977)—totaling more than 800 billion tons.

In the WEC study (1978b), the range for deep offshore and polar area oil varies from zero to 230 billion tons of oil, with an average value of about 40 billion tons. Based on discussions with many experts, and taking into account the longer time horizon of the IIASA study (2030 instead of 2000) and the higher price range ($20 to $25 per barrel instead of less than $20 per barrel), a value of 60 billion tons has been selected.[c] These 60 billion tons were distributed tentatively among the seven IIASA regions according to a reasoning close to prospective areas as defined by Grossling (1976).

[c] Once more, it must be stressed that this was done for the modeling exercise reported in this chapter. Values chosen result in a kind of "sub-Delphi" set of discussions with various experts.

Note that most of the crude oil produced today in the world still has production costs of less than $2 per barrel.

Gas Reserves and Resources

The same kind of reasoning was used in estimating gas reserves and resources. (The experts of the WEC gas study [1978b] thought that probably 75 percent of gas resources remaining to be discovered could be produced at less than $14/boe [1974 dollars] in the year 2000 and that the total could be produced at less than $20/boe.)

For unconventional gas resources, information is very poor outside the United States. Moreover, because of the importance of conventional gas reserves and resources and the less developed utilization of these resources compared to oil, conventional gas resources will probably not be used to any large extent before 2020-2030, with the possible exception of region I. There is nevertheless no geological reason that this region should be the only one to own such varied resources as methane in coal fields, gas in tight formations or in Devonian shales, or geopressured gas. Most of these unconventional gases were included in the highest cost category ($20 to $25/boe). Some experts argue that this is highly speculative; others say that it is probably conservative.

At the end of this chapter, the total fossil resources consumed in the High and the Low scenarios are compared with these estimates of resource availabilities. (The accompanying boxed material compares the fossil fuel resource estimates used here with those of other recognized energy studies.) Still, in the scenarios throughout this chapter, other constraints are in many cases binding, while resources remain available, albeit at higher costs. One of these other constraints—maximum annual production rates for oil—is considered next.

OIL: FROM RESOURCES TO PRODUCTION

Given the estimates of total energy resource availability, maximum potential outputs from each source can be estimated. This demands consideration of the geological potential, the economic trade-offs, and the infrastructure requirements for the energy supply system. One example of this analysis is presented here—an example that must represent the lion's share of primary energy for any scenario of the future. This is oil.

Table 17-8 translates the oil resource estimates of Tables 17-6 and 17-7 into conventional and unconventional resources[d] (other than shale), into enhanced recovery, oil shale, tar sands, and heavy crude oil resources. Assumptions and definitions are given as notes to Table 17-8. The cost categories

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[d] The terms "conventional" and "unconventional" when applied to oil resources have different meanings to different users. Throughout this chapter, these terms will take on the definitions in the notes to Table 17-8.

COMPARATIVE WORLD RESOURCE ESTIMATES

The estimation of world fossil fuel resources used in the supply scenarios of this report do not deviate markedly from the recent estimates of several recognized groups. This general consistency is no accident. The estimates used here result from (among other things) careful study of the experts' views, published and unpublished. Indeed, with only very minor modifications the estimates of the World Energy Conference (1978c) were used directly. The figures below summarize the estimates used here and those of three well-known sources.

Variable (and/or vague) definitions in different studies preclude precision in these comparisons. Yet the general consensus is clear. One also can observe some measure of agreement in regional and national estimates, although differences do appear. For example, this study sees some 40 billion barrels more oil in Latin America (region IV) than the Moody and Geyger assessment, and somewhat less coal in North America than does WAES. However, in most regions where comparisons can be made the convergence is remarkably close.

World Recoverable Resources (rounded figures)

	Moody & Geyger	*WAES*	*WEC*	*IIASA*
Oil[a]				
Conventional 10^9 bbl(10^9 toe)	2000(274)	2000(274)	2200(302)	2100(288)
Unconventional 10^9 bbl(10^9 toe)				397 (54)
Gas[a]				
Conventional 10^{12} m^3 (10^9 toe)	233(186)	210(175)	285(237)	291(242)
Unconventional 10^{12} m^3 (10^9 toe)				42 (35)
Coal[b]				
Category 1 10^9 tce		598	640	605
Category 1+2 10^9 tce		2506		1707

[a] "Conventional" resource estimates include enhanced recovery and offshore to less than 200 m and some heavy crude oil, all at less than $20/boe; "unconventional" oil resource estimate of IIASA includes deep offshore, polar areas, and tar sands. Oil shales not included here.

[b] Category 1: $25/ton extraction cost; category 2: $25-$50/ton extraction cost. (Varying fractions of total resource base are assumed to be recoverable in different studies.)

Sources: Moody and Geyger (1975); WEC (1978c); Desprairies (1977).

of Tables 17-6 and 17-7 and the physical resource categories here overlap. The two types of categories are defined for different purposes, and in any case, there is no reason why the total amount of any physical type (conventional, unconventional) should be expected to have just a single production cost.

Table 17-8. Ultimately recoverable oil resources (TWyr).

		Unconventional			
Region	*Conventional*	*Deep offshore and polar areas*	*Enhanced recovery*	*Oil shale and tar sands*	*Total*
I (NA)	26	12	10	126	174
II (SU/EE)	43	12	20	76	151
III (WE/JANZ)	15	7	6	13	41
IV (LA)	23	–	8	178[a]	210
V (Af/SEA)	23	13	7	20	63
VI (ME/NAf)	139	–	–[b]	20[c]	159
VII (C/CPA)	12	8	5	14	39
Total[d]	281	52	56	447	837

[a] Includes 170 TWyr of heavy crude oil.

[b] Region VI is not expected, within the next fifty years, to make extensive use of tertiary recovery techniques.

[c] Includes heavy crude oil and some possibly deep offshore oil.

[d] The analysis of region VII is necessarily rough, as few published data are available.

Notes: Conventional resources, all (usually) of category 1 and some of category 2, include known reserves and some remaining to be discovered resources; onshore and offshore resources at depths of less than 200 m; not including enhanced recovery. Deep offshore and polar areas resources, a subset of categories 2 and 3 of Tables 17-6 and 17-7, include deep offshore resources (depths greater than 200 m) and polar areas oil. Enhanced recovery, in category 2 and 3 of Tables 17-6 and 17-7, includes oil available only with tertiary techniques. Oil shale and tar sands, in category 2 and (usually) category 3 of Tables 17-6 and 17-7, includes oil shales and tar sands as well as heavy crude oil estimates.

Sources: See Table 17-6.

These are oil resources: but resources must be discovered (added to reserves) and produced. Demands are met only from discovered, produced, and delivered products. There is a large and significant (if apparently imponderable) difference between resources and supplies.

Additions to Reserves

It is from future additions to oil reserves that oil production will come. Additions to oil reserves come from extensions to existing fields; exploration for and discovery of further conventional oil fields; enhanced recovery from operating fields; and exploration for, discovery of, and improvements in recovery techniques for unconventional oils such as in deep offshore and polar areas.

Future additions to reserves of conventional oil depend largely on the success of oil exploration ventures and the intensiveness of exploratory drilling. Discoveries of large—giant or supergiant—fields of conventional oil are not anticipated. Thus, additions to reserves would largely come from discoveries of new small to medium fields, as well as from extensions to old fields (see Nehring 1978). In general, a correlation exists between oil-finding rates, new exploratory drilling footage, and cumulative discoveries (as a share of ultimately recoverable resources). Qualitative analysis of such correlations for different regions has served as a basis for extrapolation of the past behavior of additions to reserves of conventional oil for the next five decades.

Little is known about the future of additions to reserves of unconventional oil around the world. With no better approach available, it is assumed that the correlation between finding rates, intensiveness of exploratory drilling, and cumulative discoveries is the same for unconventional as for conventional oil. While it may be that high investment costs will inhibit rapid development of individual unconventional oil fields, it is assumed here that, in aggregate, the potential unconventional oil resources could be discovered in the future more quickly than conventional oil resources have been in the past—because of improved exploratory methods and expected price incentives.

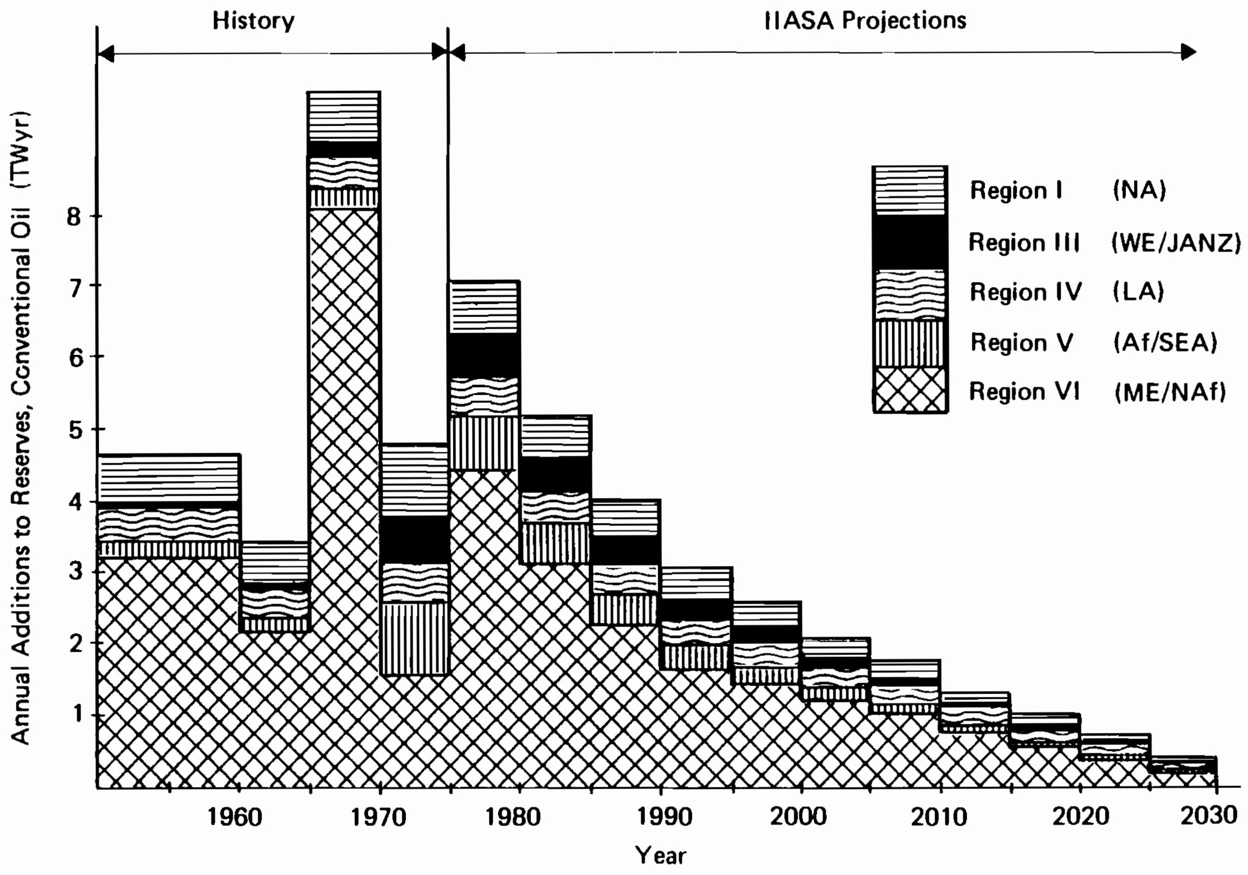
Figure 17-4 summarizes the results of these and other considerations for regions I (NA), III (WE/JANZ), IV (LA), V (Af/SEA), and VI (ME/NAf) (for conventional oil only). Notice that the assumptions give large additions to conventional oil reserves in the next few years, with additions dropping off toward 2030 as the ultimately recoverable resource total is neared.

Enhanced Recovery and Oil Shales

Enhanced recovery of oil can substantially increase maximum production possibilities. New techniques improved the average rate of recovery of oil in the United States from 25 to 32 percent between 1950 and 1975. But several cautions should be observed. First, many improved (secondary and tertiary) recovery techniques have not yet been mastered on a large scale. Progress on the carbon dioxide projects in the United States, for example, has been slow. Second, a multitude of factors, including viscosity of the oil, porosity of the rock, and structure of the oil layers, can dramatically influence the chances for success. Also, tertiary recovery (which we call here enhanced recovery) from a field occurs only after primary and secondary techniques have been applied; the timing of enhanced recovery in a given oil field depends on the rate of development of the reserves of that field.

Enhanced recovery data exist in significant quantities only for oil fields in the United States. (Recent estimates [Perrine 1978] put the potential from tertiary recovery in the United States by 1990 at up to 200 GWyr/yr [2.8 mbd].) U.S. data are therefore used as a means of establishing estimates for enhanced recovery in all regions. It is assumed here that enhanced recovery applies only to conventional oil fields in the next fifty years and that such technologies are available today in the developed regions and only after 2000 in the developing regions. Enhanced recovery in the High and the Low scenarios increases total cumulative recovery from conventional oil in place to 2030 by a factor of 1.25.

Figure 17-4. Annual gross additions to reserves of conventional oil, world (except centrally planned economies), 1975-2030.



Total resources of oil shales, tar sands, and heavy crude oils are by most estimates enormous. Growth rates of known reserves are not expected to constrain future production rates, but buildup rates of this new industry and environmental constraints may. As a result, these sources of oil can be thought of as alternatives to coal liquefaction; the assumption here puts the maximum buildup rates for oil production from these sources and coal liquefaction at the same value. The final choice between the two must be a matter of national priorities, resource availabilities, environmental considerations, and economic trade-offs.

The total additions to reserves resulting from all of these considerations of conventional and unconventional oil and enhanced recovery are discussed in the accompanying boxed materials. There also, these figures are compared with the WAES assumptions—a comparison meant to indicate the extensive use in this study of and (with some modified judgments and new information) reliance on the WAES analyses and findings.

Maximum Potential Production

A region's oil production is the aggregate of the production of many fields—large ones and small ones, fully developed ones, and ones just starting to develop. Each field—even each elementary unit or sector of each field—has its own dynamics of the buildup to (and maintenance of) peak production capacity, followed by the gradual decline of production. Small- to medium-sized new fields require three to five years to reach peak capacity (it was two to four years from the start of production for many sectors of the North Sea, for example, and about ten years from first discovery), and many produce at peak rates for only five to ten years (or less, as is certainly the case for many North Sea fields) before production rate limits (reserve-to-production ratio constraints) force a gradual decline of output.

With these considerations in mind, maximum potential oil production rates over the next fifty years have been calculated for several regions. Maximum potential oil production rates are those that could be reached potentially under assumed economic, technical, and environmental constraints. These include constraints on additions to reserves (as described above); buildup rate constraints (especially for enhanced recovery, oil shales, tar sands, and heavy crude oils); production ceilings of oil from shales (representing environmental constraints); and reserves-to-production ratio constraints.

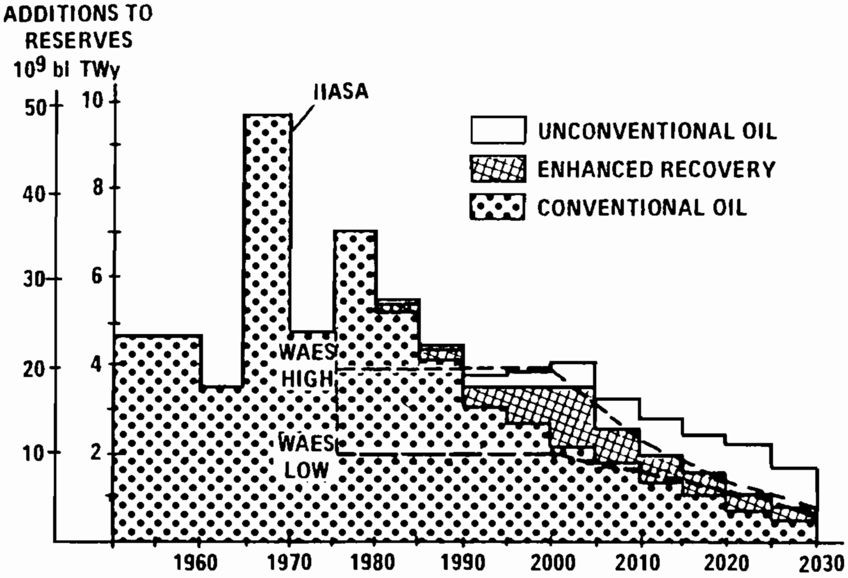
With these constraints, the following assumptions are used to calculate the oil production rates:

- The limiting ratio of reserves to production is taken at a worldwide average of 15 to 1 for conventional oil and for deep offshore and polar area oil; 7.5 to 1 for enhanced recovery methods; and 25 to 1 for the portion of heavy crude oil resources that can be recovered by conventional methods.

GROSS ADDITIONS TO RESERVES, OIL OF ALL TYPES, AND COMPARISON WITH WAES

While the amount of ultimately recoverable oil (Table 17.8) is surely of major importance, it is, in the end, annual oil production that meets liquid fuel requirements. As WAES observes, "Oil can be produced only from fields that have been discovered and for which production facilities have been installed. Oil production is based on proven reserves, the rate at which they are added to and on the rate at which production facilities are developed. The importance of ultimately recoverable reserves is that they determine how long a rate of additions to reserves can be maintained." Here, it is flatly assumed that all the ultimately recoverable resources of Table 17.8 (except shale oil and tar sands) are discovered and added to reserves by the year 2030.

Assumptions of gross additions to oil reserves from conventional and unconventional oils and enchanced recovery for regions I (NA), III (WE/JANZ), IV (LA), V (Af/SEA), and VI (ME/NAf) (that is, the world outside regions II, SU/EE and VII, C/CPA) are shown below, together with the WAES estimates for the additions to *conventional* oils in, basically, these same regions. Assumed are somewhat greater additions in the near term than WAES assumed (recent evidence from Mexico, for example, tends to confirm this), with additions dropping off faster later. The slack could then be taken up by unconventional oil additions, enhanced recovery and ultimately (and possibly) shale oils and/or tar sands.



Global annual additions of reserves of oil. Oil trading regions only.

- After having reached peak production levels, production rates decline exponentially.
- Reaching peak production rates for enhanced recovery methods takes five years (because of the injection stage).
- Oil production plants for tar sands, shales, and heavy crude oils (treated by advanced methods) keep constant production levels over their thirty-year lifetimes.

The buildup of a shale or tar sands facility requires five years and, like coal liquefaction, once a rate of 6 GWyr/yr is reached (for the developed regions), the previous period's capacity may be doubled each five-year period.

These several assumptions about buildup and decline rates, aggregated, allow estimation of the maximum potential oil production profiles shown in Figure 17-5. These profiles differ from the global oil production profile of Chapter 2. This is because, as noted before, the two exercises are performed for different purposes. The chapters of Part II of this book seek to explore global potentials; here, regional real world possibilities are sought. The profiles of Figure 17-5 are a first step in the latter process, which ends with oil production rates lower than those of Figure 17-5.

Potential Oil Supplies by Region

In region I (NA), production from known oil reserves would continue its already begun precipitous decline. Presently known reserves would be virtually exhausted by the end of the century. Increasing total production (or even holding it constant) requires the finding and developing of new conventional reserves. High, but gradually declining, additions to reserves could add some 430 GWyr/yr (2.4 billion barrels per year) annually to North American oil production by the year 2000. Beyond that date, the assumed limiting reserve-to-production ratio[e] forces production of conventional oil downward, to just 120 GWyr/yr (0.6 billion barrels per year) by 2030 (Figure 17-5A). Enhanced recovery can stall the decline somewhat, but its considerable potential is limited in varying degrees by technological development, commercial risk, and water and carbon availability. The maximum contribution from enhanced recovery could be about 730 GWyr/yr (3.8 billion barrels per year) in 2005; the potential is likely to decline after that, as presently known oil reserves (which have the greatest enhanced recovery potential) become depleted. Deep offshore and polar area oil might add a certain fraction to maximum production. But the major resources potentially available to halt the region I production rate decline are shale oils and tar sands. For the Canadian tar sands, a wide application of conventional (strip mining) and in situ methods could allow production of up to 1 TWyr/yr (5.2 billion barrels per year) by the year 2030. The difficulties of handling

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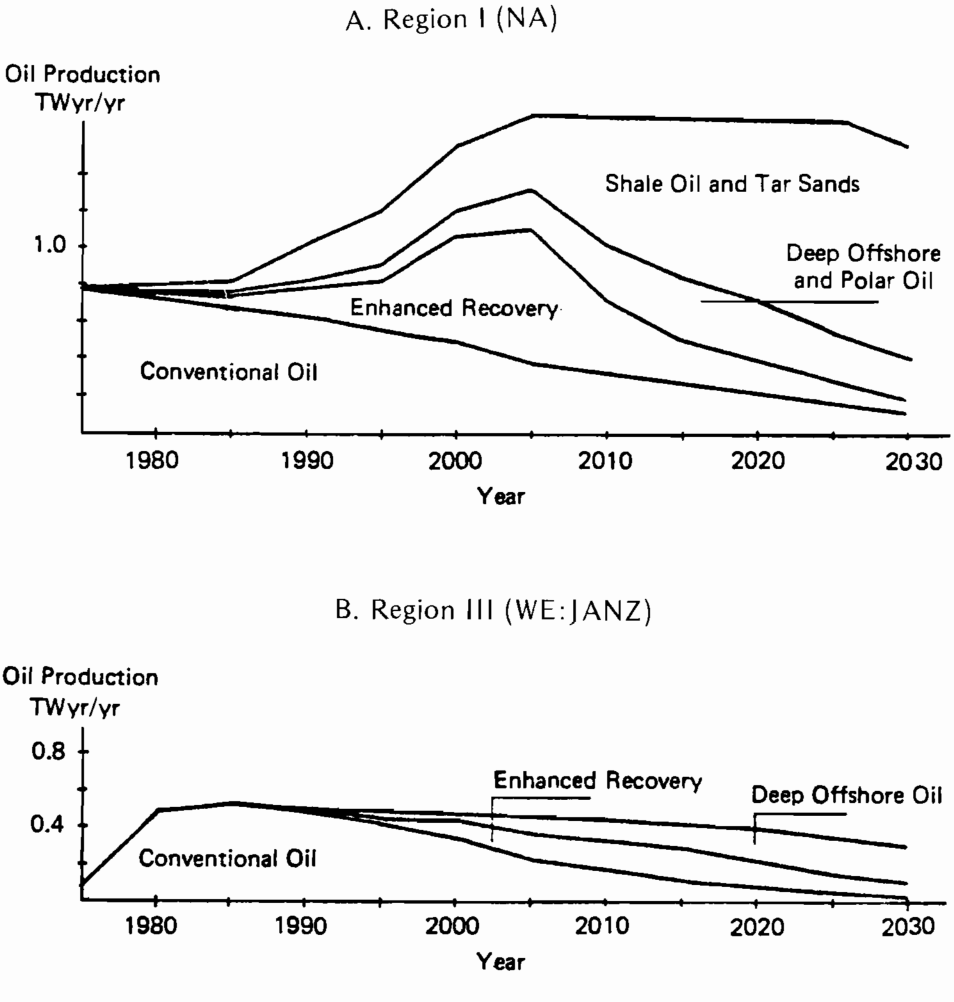
[e] It is assumed that the current U.S. reserve-to-production ratio of about ten to one could not be economically maintained over the long term.

Figure 17-5. Maximum potential production profiles by type of oil, regions I, III, IV, and V.

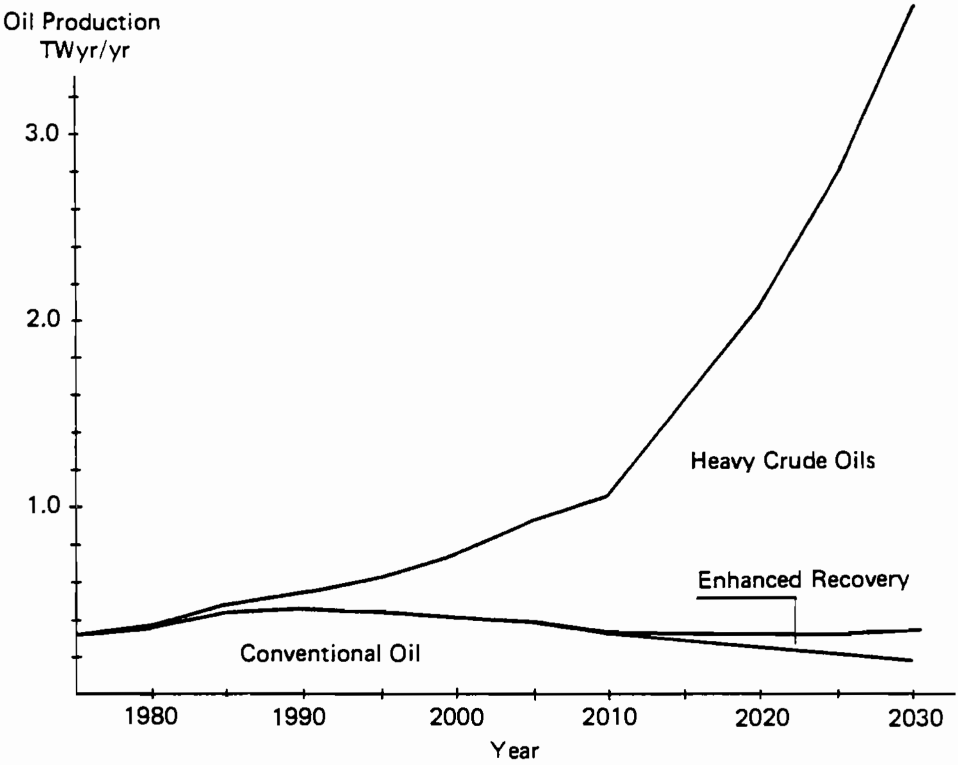


the waste from oil shale production and the lack of sufficient water supplies strongly restrict their development. Therefore, rather minor contributions of shales are assumed in the oil supply in North America.

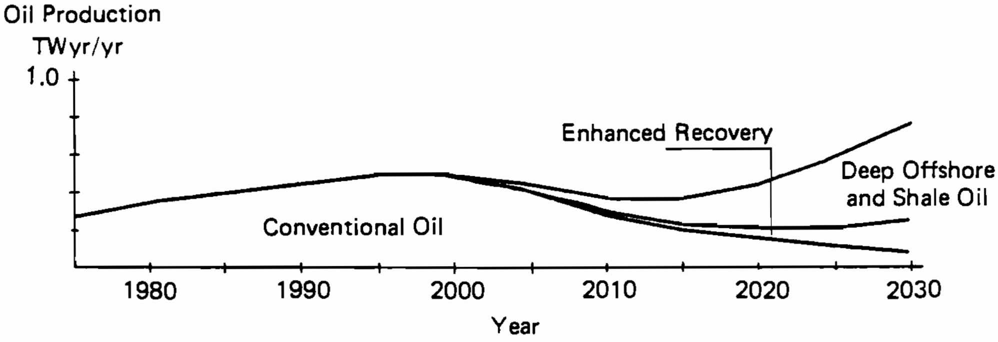
In region III (WE/JANZ), the North Sea oil deposits will be the greatest contribution to potential domestic oil production. They could add some 350 GWyr/yr to annual production by 1985-1990. (This, again, is potential. A more realizable figure is likely to be on the order of 3 mbd [200 GWyr/yr] from the North Sea.) The drop in production of conventional oil might be delayed by new discoveries in Turkey, Australia, and New Zealand, but the impact is not expected to be large. Total conventional oil production would

Figure 17-5 continued.

C. Region IV (LA)



D. Region V (Af/SEA)



not exceed 340 GWyr/yr (1.8 billion barrels per year) in 2000 and would fall to just 30 to 50 GWyr/yr (0.15 to 0.25 billion barrels per year) by the year 2030. The peak contribution of enhanced recovery (160 to 170 GWyr/yr) is expected to be in 2010-2015. Another 180 to 200 GWyr/yr in 2030 could come from deep offshore areas. Production of oil from shales in region III (some resources of which are available in the United Kingdom, the FRG, and Italy and are of economic size) would apparently depend on commercial availability of in situ methods and water supplies and is not, in any case, expected to occur on a significant scale.

A major portion of the potential conventional oil resources of region IV (LA) is found in offshore Mexico. This, and the rather large conventional resources elsewhere in region IV, could allow some 430 to 450 GWyr/yr of oil production by 1990-1995 and about 160 GWyr/yr by 2030. Increasing the total production after the year 2000 requires the development of the deposits of heavy crude oils, which would be affected by buildup constraints on drilling equipment, steam generation, and upgrading capacity. Heavy crude oil production could be enormous, depending on the extent of technological assistance by highly developed countries. It seems likely that much smaller rates of production will actually occur. Here, a moderate development of heavy crude oil resources is assumed—one that would nevertheless provide a substantial contribution to the potential oil production after the year 2000 (i.e., more than 3 TWyr/yr or 15.5 billion barrels per year by 2030).

Oil production in region V (Af/SEA) has had a short history; most countries in the region started their oil production in the 1950s and 1960s. Development in the previous five years, especially, has been rapid. Rather high additions to the existing reserves up to the end of the century are assumed, with a decline thereafter. The peak potential conventional oil production of 480 to 500 GWyr/yr may come around 1995-2000. By 2030, production could reach some 750 GWyr/yr, taking account of enhanced recovery and other unconventional resources.

The total production in region VI (ME/NAf) is discussed in the next section.

Summarizing, the gross maximum potential oil output for regions I, III, IV, and V is assessed to be 2.2 TWyr/yr (about 11 billion barrels per year) in 1985, 3.2 to 3.3 TWyr/yr (16.5 to 17 billion barrels per year) in 2000, 3.8 to 4.0 TWyr/yr (20 to 21 billion barrels per year) in 2015, and as much as 6.3 to 6.5 TWyr/yr (32.5 to 33.5 billion barrels per year) by 2030. When compared with demands for liquid fuels, these numbers seem to be too high. For example, under assumptions of the Low scenario, the oil-importing regions appear (in aggregate) to be self-sufficient as early as 2020.

However, one should not forget that the maximum potential oil production rates reported here represent those that could not be higher and that are supported by all potential sources of oil no matter how much they cost. In fact, production rates would certainly be much lower than these maximum assumptions. The oil production rates actually used in the High and the Low scenarios are significantly lower, as will be shown in the section on oil demand and supply, following a discussion of the oil production and export prospects from region VI (ME/NAf).

The Special Case of Region VI

There are two overly broad categories of members of the Organization of Petroleum Exporting Countries (OPEC)—the "swing producers" or "low absorbers" (of oil revenues) as they are sometimes called and the "competitors" or "high absorbers". The swing producers can relatively easily expand or restrict oil output; they are not critically dependent on large oil revenues. The "competitors," on the other hand, need all the oil revenues they can get and must therefore maintain production at highest possible levels. Most of this latter group have large (and growing) populations, substantial development needs, and limited oil reserves. Most of the former group have somewhat smaller populations, (therefore) limited development needs, and tremendous oil reserves. It is not an equitable world.

The world region labeled here region VI (ME/NAf) includes, intentionally, the large, swing producers of OPEC—in particular Saudi Arabia, Kuwait, and the United Arab Emirates. These countries dominate the aggregated region VI. The swing producers of OPEC hold about one-third of the world's oil reserves, and they could (theoretically) expand their annual production by several times. Within this "core of balancers," Saudi Arabia has been thought to hold the ability to be quite literally the residual supplier for the world, varying its production up or down to meet the fluctuations in demand and supply of the rest of the globe.

With very large oil reserves and with little or no other resources, it is in region VI's self-interest to stretch out the lifetime of its reserves—to avoid an early, high peak of production followed by rapid decline. Oil revenues, optimally, should keep pace with (but need not exceed) development needs and should continue as long as possible—that is, until alternative sources of income (new industries, business, etc.) can be created.

In 1975, Saudi Arabia received an estimated \$23 billion in oil revenues: an estimated \$6 billion was spent in Saudi Arabia or for imports, and an estimated \$3 billion was invested in other Arab or developing nations. Most of the rest of the surplus was put into Saudi Arabian official reserves—making these national reserves third largest in the world, smaller only than those of the United States and the FRG. Today Saudi Arabia has about the same per capita income and total imports as Sweden. Saudi Arabia, and some of the other Arabian Peninsula countries, are expanding their economies at rates not thought possible even two or three years ago. While their "low absorbers" label may therefore be in some doubt, it remains true that there are reasons why the region may well restrain its oil production and exports.

Too rapid development can create economic and social instability—rampant inflation and quick riches to the elite. This, of course, is one partial explanation of the political upheaval in Iran in 1978. Peninsula nations are recognizing the wisdom of moderate production and export levels, of stretching out the lifetime of their oil wealth, and of attempting to distribute the benefits carefully and equitably. And so they announce their intent to stabilize production.

At the same time, there is reason to doubt the ability of these countries to literally be swing producers on a large scale. Recent estimates of present productive capacity put region VI at just over 30 mbd, while present actual production is about 27 mbd. One must ask where—in which country—an increase in capacity beyond the estimate in this study (33.6 mbd, as noted below) could occur. And one must not ignore political instabilities in the region when estimating future production potentials.

Because of these considerations, it is assumed that total production in region VI will rise (in the near term) to meet demand until a level no more than 50 percent higher than the region's 1975 production is reached (see Table 17-9). This ceiling of 33.6 mbd, or 12.2 billion barrels per year (2380 GWyr/yr), is highly arbitrary. Variations up or down can have rather large implications for the timing of and needs for new energy technologies. This should be borne in mind as the results of the global supply scenarios appear in the following pages. But ultimately, even region VI will be forced by limited resources to lower production rates, thus pushing the world sooner or later toward alternative energy sources. By 2030, region VI would in fact be forced toward lower outputs by reserve-to-production ratio constraints if a production level of 33.6 mbd were maintained up to that time.

A FRAME OF REFERENCE

Before presenting the results of the global and regional supply analyses, a frame of reference for interregional energy trade is offered—a set of assumptions about the potential evolution of world energy markets, particularly oil.

The oil market will remain a global one because oil is virtually irreplaceable for some essential purposes such as transportation and (to a certain extent) petrochemical feedstocks; oil resources of industrialized countries are rapidly being exhausted; and oil is easily transportable.

The use of coal could increase markedly if oil (and gas) reserves prove insufficient to meet industrial heat needs; if natural gas and oil cease to be used as primary fuels in central conversion processes; and/or if coal liquefaction technologies prove to be relatively inexpensive. These represent major uncertainties that cloud any projection of the role of coal as a substitute fuel for oil in industry and central conversion processes. The fact that coal is more difficult to transport than oil is only partly mitigated by the fact that coal deposits lie largely within the same countries where demand will be large. Unlike oil trade, the coal trade is not likely to be dominated by a few exporters forming a cartel.

Like coal, natural gas has so far been a major energy source generally only within the countries or regions in which it is found (the notable exception being Japan with its sizable gas imports): the question is, Will this continue to be the case? Gas is an important fuel in industry; it can increasingly be

Table 17-9. Region VI oil production rates and capacity and assumed production ceiling (million barrels of oil per day).

Production Rates

	1975	*1977*
OPEC member countries	27.19	31.53
non-region VI OPEC[a] member countries	- 5.82	- 6.52
OPEC and region VI[b] countries	21.37	25.01
non-OPEC region VI[c] countries	+ 1.05	+ 0.99
Region VI	22.42	26.00
of which exported	21.23	24.64

Production Capacities

	1975 DOE Estimate[d]	*1977 PIW Estimate*[e]
Saudi Arabia	10.7	10.8
Iran	6.5	6.8
Iraq	3.0	2.6
Kuwait	2.9	3.0
Libya	2.3	2.5
UAE	2.3	2.3
Algeria	1.3	1.0
Qatar	0.6	0.7
Estimate of other region VI[f] countries	1.4	1.4
Region VI	31.0	31.8

Estimated long-term region VI "ceiling": 33.6

[a] Non-region VI OPEC countries are Venezuela, Ecuador, Nigeria, Gabon, and Indonesia.

[b] Eight OPEC member countries are in region VI—six in the Middle East (Saudi Arabia, Kuwait, UAE, Iran, Iraq, Qatar) and two in Northern Africa (Algeria and Libya).

[c] Seven countries in the Middle East—Bahrain, Jordan, Lebanon, Oman, Syria, Yemen and Yemen (Democratic)—and one in Northern Africa (Egypt).

[d] U.S. Department of Energy estimate, International Energy Indicators, April 1979.

[e] *Petroleum Intelligence Weekly* (1979).

[f] IIASA estimate.

used in buildings. But very difficult and costly long-distance transportation problems—the alternatives are undersea pipelines or cryogenic tankers—may restrict gas to local or regional markets in the future. The potentials are great (as explored briefly in Chapter 18), but so are the obstacles.

The cost of long-distance transmission of electricity is also high, and in general this will continue to limit the market for electricity. But electricity may turn out to be less expensive than moving coal over long distances, particularly if major improvements in superconducting cables can be realized or if long-distance DC transmission proves conclusively to be economic.

Energy markets interact, to the extent that one fuel whose price is lowered may substitute for another whose price increases. For example, if crude oil becomes relatively scarce and expensive, synthetic oil from coal liquefaction would be stimulated. Large-scale development of liquefaction plants would in this way dampen growth in oil prices, while at the same time stimulating the demand and price for coal. Also, successful development of in situ coal gasification schemes, with combined cycle gas turbine plants, enhances the potentials of coal supplies and gas markets.

INTERREGIONAL OIL BALANCING

As already observed, oil dominates international energy markets today, and this dominance will not decline quickly. The procedure followed in this study for interregional oil balancing recognizes this and is designed to produce acceptable balances only after several iterations. Also, it should be noted that it is primarily the long term that is of interest here; these procedures are not precise ones for the short to medium term.

A Procedure for Interregional Oil Balancing

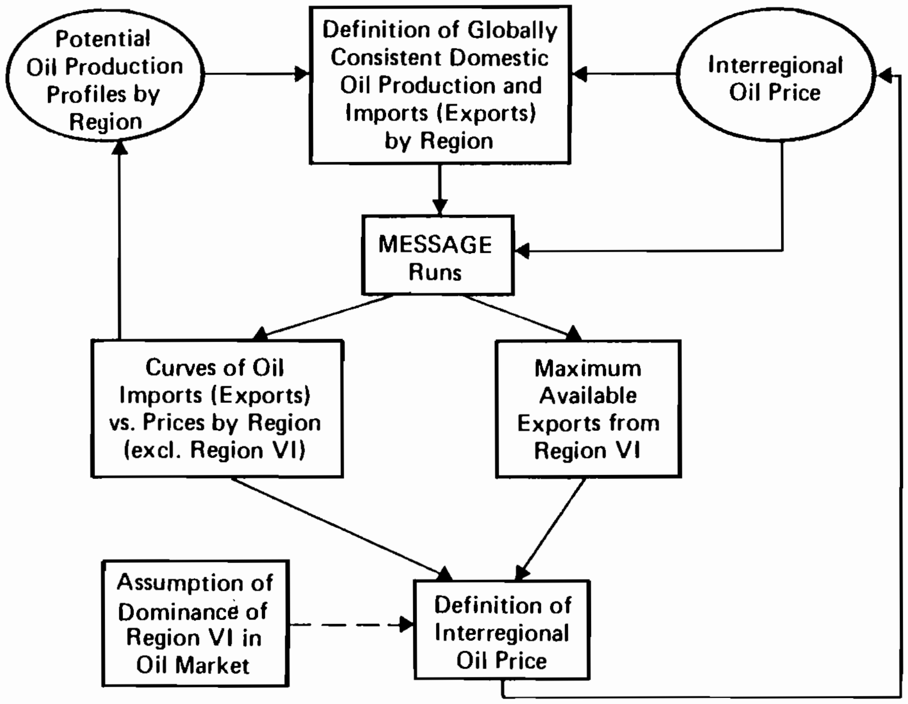
Three dynamic elements of the world oil market must be reflected in any study of global, long-term energy supply systems—regional domestic oil production, interregional oil trade, and oil prices. The procedure of Figure 17-6 describes their assessment as performed in this study.

Dealt with first is the problem of integrating the demand for imported oil of the potentially importing regions (regions I, III, IV, and V) and available oil exports from region VI. It is assumed that regions II and VII are neither oil exporters nor oil importers. Second, region VI is believed to dominate the world oil market through cartel-like behavior. The maximization of revenues over the planning period is assumed to be a driving force for region VI in choosing oil production (and, thereby, export) figures. Third, oil-exporting countries outside region VI are taken as price-takers; their trade with importing countries is assumed to take place under perfect market conditions.

The response of importing regions to changing oil prices must result from their domestic oil supply elasticities. Such elasticities have been generated by considering the potential oil production profiles of Figure 17-5, as well as estimates of various types of oil resources available at different prices (Tables 17-6 and 17-7), and taking account of other published studies of national and international energy research teams such as the World Energy Conference, EPRI, and the U.S. Office of Technology Assessment. The resulting regional potential oil production profiles as a function of prices represent the first major input to interregional oil-balancing calculations. Two more inputs to the process are demands for liquid fuels over time and judgments about the dynamics and costs of synthetic liquid fuel production from coal.

Comparing the domestic oil supplies available at varying prices with liquid fuel demands region by region (and taking account of production of synthetic liquid fuels from coal), regional curves of economic oil imports versus prices, period by period, can be produced, followed by generalized curves

Figure 17-6. Interregional oil balancing methodology.

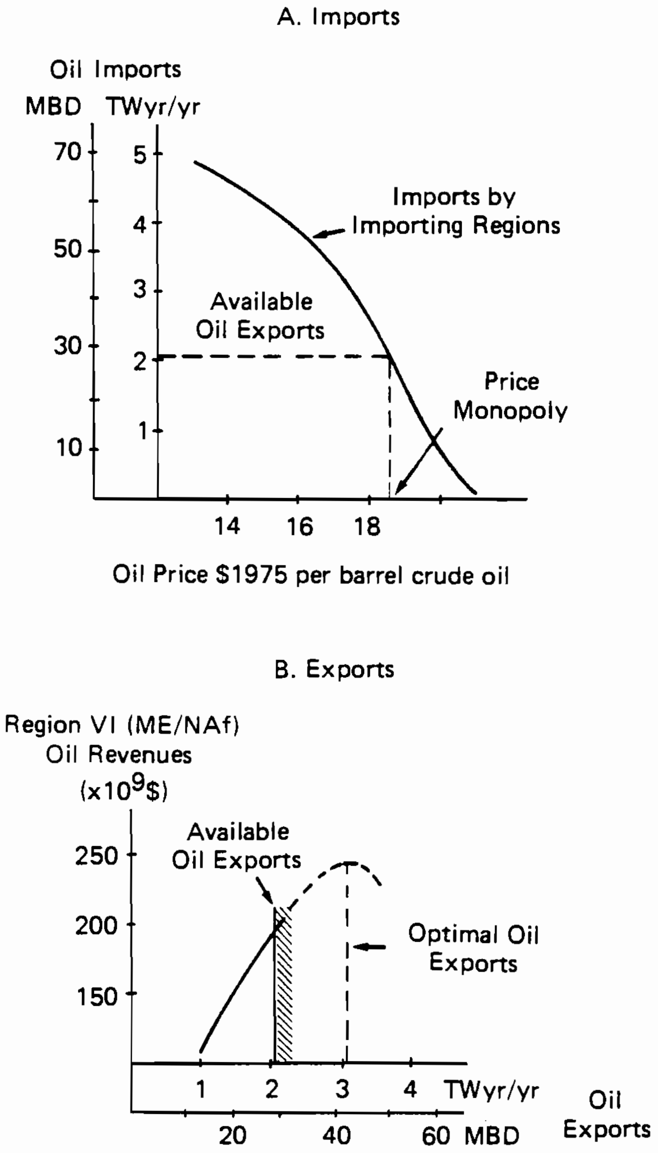


for the whole group of importing regions. The top graph in Figure 17-7 shows a sample of such a generalized curve, for the year 2015, in the Low scenario.

Looking at these curves from the perspective of region VI, values of imports and prices that give maximum revenues to the exporter over time are selected, while not exceeding values of admissible exports (see the lower graph in Figure 17-7). The prices chosen represent world oil market prices.

Unfortunately, one iteration of the balancing procedure is insufficient to achieve acceptable results, because of feedbacks of prices to the amount of synthetic liquid fuels that could be economically produced from coal—and thereby to the amount of coal available to compete with nuclear energy in the production of electricity and heat. To take this into account, the IIASA energy supply model (MESSAGE) is involved in the procedure. At the initial iteration of interregional oil balancing (assuming some dynamics of oil prices), the first order values of the price-consistent portion of domestic oil production and values of imports region by region over time are selected. These values are input into the MESSAGE model, which gives the regional dynamics of production of liquid fuels from coal, consistent with assumptions concerning oil prices, production, and imports and the development of other sectors of the energy supply systems. This is then used in the

Figure 17-7. Oil imports and exports versus price, Low scenario, 2015.



balancing calculations. Having more reasonable estimates of oil prices and interregional oil trade by the end of each iteration, the inputs to MESSAGE are corrected and the runs repeated until acceptable results are reached.

Several iterations of this procedure are required for acceptable results—to remove inconsistencies among oil demand, production, and import/export. Also, note that this procedure is designed for long-term analyses. That is, it lacks the degree of disaggregation and careful consideration of national politics that would be essential to a study of the near-term prospects of the world oil market. This is not, of course, to say that the next few years of development of the oil market are unimportant; surely the opposite is true. Still, the long-term perspective offered here may not be valueless, in spite of certain short-term dynamics that have not been treated here.

Prices and Oil Trade

The prices of globally traded liquid fuels over the next fifty years can be estimated from the methodology just described. Of course, there are great uncertainties in such exercises, not least among them the potential impacts of noneconomic, nontechnical forces. Nonetheless, these procedures allow one to postulate consistent price dynamics for the High and Low scenarios, to evaluate the consequences, and to draw inferences about the range of real possibilities. The major arguments in the logic of these analyses for generating international oil prices in the long term are as follows:

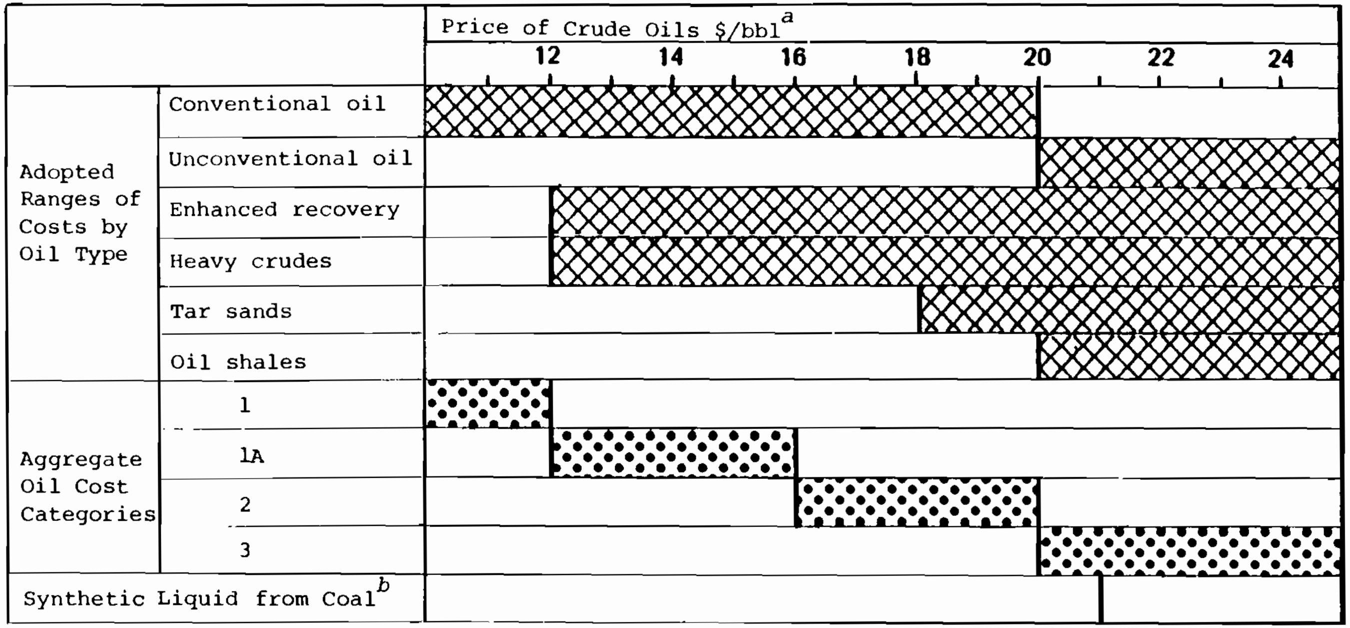
Prices of oil from region VI are highly flexible because of low production costs; they are calculated in these scenarios, as described, to maximize revenues within a stated production ceiling. In order to compete, region VI must maintain its oil price just below the price of that source (the "backstop" source) that could displace its oil exports in each case. As a response to the price policies of region VI, importing regions could vary their domestic oil production within the entire range from zero (in theory) to the "maximum potential" ceiling already described. The flexibility of such a response is described, of course, by the price elasticities of potential oil supplies.

The cost categories used in these analyses for domestically available liquid fuels are summarized in Figure 17-8. The cost figures are necessarily aggregate, reflecting substantial uncertainties. Note that only one estimate is used as the cost assumption for synthetic liquid fuels from coal (at about $21.50 per barrel) and that this is somewhat less than the cost of most of the very large category 3 oil resources (oil shales, tar sands, heavy oils).

These considerations result in estimates of prices for internationally traded crude oil. In the Low scenario, prices would increase in real terms (from about $13.40 per barrel in 1975) at about 4 percent per year (in current dollars) until reaching $19 per barrel (1975$) in 1990, and then remain constant to 2030. In the High scenario, prices would rise in real terms at about 5.5 percent per year (in current dollars) until reaching $21 per barrel (1975$) in 1990, and then remain constant to 2030.[f] The current (late 1979) OPEC price of approximately $20 (1979$) would be just $15 in 1975 dollars; the two scenario prices in 1979 dollars would be about $25 and $28 per barrel, respectively.

[f] For flights of fancy, consider these scenario price projections in current dollars: assume a 7 percent average annual inflation rate from 1975 to 1990 and a 5 percent average annual rate from 1990 to 2030 and get some $100 per barrel in the year 2000 (in year 2000$) and some $800 per barrel in the year 2030 (in year 2030$).

Figure 17-8. Costs of oil sources, High and Low scenarios.



[a] Constant (1975) U.S.$.

[b] Refined product.

NOTES: Shaded areas represent range of cost estimates. Oil types are defined in Table 17.8; oil price categories are defined in Table 17.6.

The Low scenario analysis leads to prices of internationally traded liquid fuels that reach levels just under the prices assumed for coal liquefaction. The assumed liquid fuel demand, supply, and constraints in the Low scenario indicate that at international oil prices greater than that of synthetic liquid fuels, these synthetic fuels (being cheaper) would replace imports in certain regions to the extent that region VI would sell less oil and (even at somewhat higher prices) would therefore earn lower total revenues.

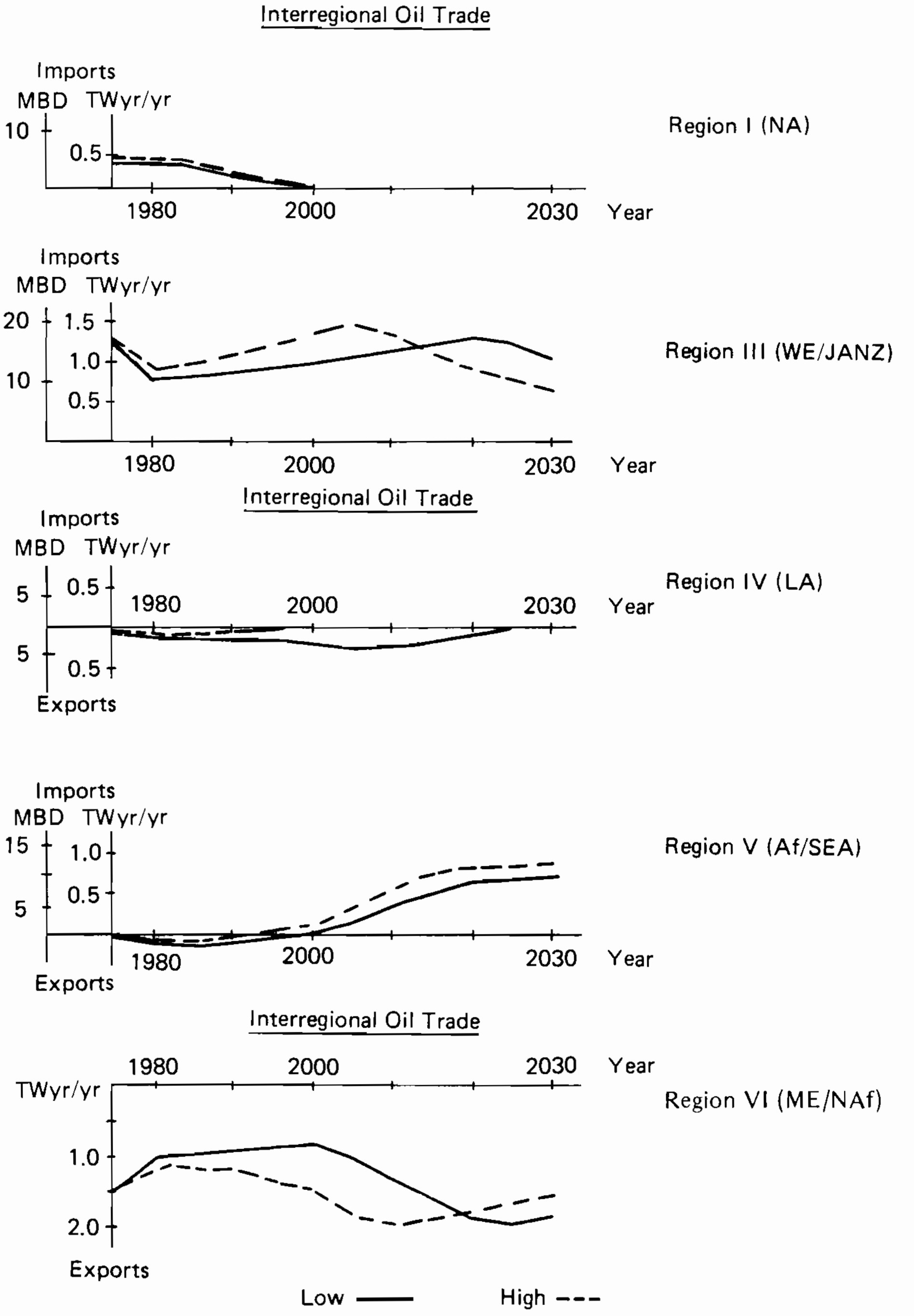
Conversely, the replacement (or "backstop") source in the High scenario is largely unconventional oil—oil shales, tar sands, heavy crude oils, polar area oil deposits, and so forth—not because the synthetic liquid fuel resource has been exhausted, but because imposed coal production constraints and the constraints of the synthetic liquid fuel industry buildup rate limit the coal available for synthetic liquid fuels production.

Clearly—as has been suggested recently by many—it could turn out that tar sands and oil shales (for example) will be available in large quantities at costs less than those of coal liquefaction. If this were the case, then these sources would replace synthetic liquid fuels in these scenarios, and international prices would be set just below shale prices (say). This implies large exports of these fuels from North America (if they are to be a true global "backstop") and would result in increased availability of coal for power production. Yet much of the rest of these analyses remains insensitive to whether synthetic liquid fuels or shales or tar sands or heavy crude oils are the backstop liquid source. Another very possible source, not considered carefully here, is liquid fuels produced from natural gas. With relatively large and inflexible liquid fuel demands and economic gas sources (and available liquified natural gas technology), this may ultimately prove to be a very important and practical source.

These international oil prices are the same for all world regions—in spite of very different capabilities in different regions to respond to price changes imposed by the exporters. The only available alternative to this simplifying assumption, it would seem, would be multitiered price structures, with highest prices being paid by the regions (as it turns out, the less developed countries) without cheap alternatives, and lowest prices being paid by regions (the developed ones) with relatively cheap alternatives. This would not appear to be a likely outcome. It is not the purpose of this study to postulate bidding contests with differential prices stemming from relative political muscle or abilities to pay. So, the single global price calculation was done as described, recognizing the desires to restrain total production in region VI and to keep oil prices roughly comparable among regions.

Data for internationally traded oil, following these price considerations, are given in Figure 17-9 (for both the High and the Low scenarios). Figure 17-9 graphically illustrates the changing nature of global oil trade in the scenarios. With the projected price dynamics, demand for oil exports from region VI is believed to decline in both scenarios within the next 10 to 15 years. This is a measure of the response of importing regions to the oil price escalations of the 1970s (in part, more non-region VI domestic oil potential becomes economic in these regions). After 2000, as the domestic resources

Figure 17-9. Interregional oil trade, 1975-2030, High and Low scenarios, primary equivalent.



of importing regions become increasingly expensive, the attractiveness of exports would again grow.

In the High scenario, global demand for oil exports is expected to decrease to around 1.3 TWyr/yr (6.7 billion barrels per year) by 1990 (compared to nearly 8.5 billion barrels per year in 1975), and would grow afterward, reaching a ceiling of around 1.9 TWyr/yr (9.8 billion barrels per year) by 2010. In the Low scenario, the demand for exports would decrease to 0.8 TWyr/yr (4.1 billion barrels per year) by 2000, and increase thereafter until reaching about 1.9 TWyr/yr by 2025.

Region I (NA) with relatively substantial resources of relatively cheap oil, and with enormous resources of cheap coal, is believed to be capable of becoming self-sufficient by the end of the century or soon thereafter, under the assumptions of both scenarios. For region III (WE/JANZ), results show high import dependence through 2030, by which time region III would need as much as 7.5 billion barrels of imported oil per year (in the High scenario) or 6.2 billion barrels per year (in the Low scenario).

According to assumptions here concerning maximum rates and costs of heavy crude oil development in region IV (LA), this region is expected to be neither a net importer nor a net exporter in the long term in the High scenario. In the Low scenario, region IV could even be an exporter of oil. Its oil exports in that case are projected to grow to 1.2 to 1.5 billion barrels annually 2005–2010, but to decline thereafter to zero by 2025.

Region V (Af/SEA) is believed to stay a net exporter of oil until 1990, but to turn then into a rather major oil importer. It would have to import annually from 3.6 billion barrels (Low scenario) to 4.1 billion barrels (High scenario), in order to meet its 2030 demand for liquid fuels.

The oil trade figures described here provide—after having achieved consistency through numerous iterations—inputs to the supply scenario results which follow.

OIL SUPPLY AND DEMAND

Under the assumptions of the High and Low scenarios, the oil era would not be over by 2030. The world would be moving from the petroleum era to the unconventional fossil era. In the High scenario, the share of conventional oil in the total liquid fuels supplies of the globe would be declining from today's nearly 100 percent to 80 percent by the year 2000, to 56 percent by 2015, and to as little as 30 percent by 2030. In the Low scenario, this share would equal 80 percent in 2000, 66 percent in 2015, and 47 percent in 2030.

In order to meet 70 percent of the High scenario's or 53 percent of the Low scenario's primary demands for liquid fuels by 2030, world unconventional oil production would have to reach as much as 7.8 TWyr/yr (40.2 billion barrels per year) in the High scenario and about half as much in the Low scenario. No single source of liquid fuels could support this level of demand.

However, these analyses show that economic production from natural sources of unconventional oil would not exceed 3.5 TWyr/yr (18 billion barrels per year) in the High scenario and 1.6 TWyr/yr (8.2 billion barrels per year) in the Low scenario by the year 2030. Another 2.2 to 4.4 TWyr/yr could come from coal liquefaction. Synthetic oil in 2030 in the High scenario at 4.4 TWyr/yr exceeds present total global oil production by 16 percent; it provides almost 40 percent of total demands for liquid fuels in 2030.

What does this mean? Will the coal-rich countries mine their vast resources at rates sufficient to quench the world's thirst for liquid fuels? The analyses here point to few other solutions, if liquid fuels continue to be required on a large scale, even if for only premium uses.

By 2030, world crude oil production would have peaked and begun a slow decline under the conditions of the scenarios, as Figure 17-10 indicates. At the global oil production peak (around 2020 in the High scenario, 2015 in the Low scenario), the annual rate would be nearly 6.9 TWyr/yr in the High scenario and 5.6 TWyr/yr in the Low scenario compared to 3.6 TWyr/yr today.

The regional oil supply and liquid fuel demand results of the two scenarios are presented in Figure 17-11, in order to underscore the long-term liquid fuel supply dilemma and to illustrate the different characteristics among different regions. This figure shows the High and the Low scenarios for all seven world regions.

As noted, region I (NA) is projected to be capable of becoming self-sufficient by the year 2000 or soon thereafter at both (high and low) growth rate assumptions on demand for liquids. In the High scenario (Figure 17-11B), domestic oil production could increase gradually to a peak of 1.2 TWyr/yr (6.2 billion barrels per year) in 2000, but the rate could not be sustained. In the Low scenario (Figure 17-11A), a peak of domestic oil production of 1.1 TWyr/yr (5.7 billion barrels per year) could occur by 2010, with a decline to 0.5 TWyr/yr (2.6 billion barrels per year) by 2030.

Development of coal liquefaction technologies in region I is expected to start in 1995 in the High scenario and in 2000 in the Low scenario. Coal liquefaction could contribute some 1 TWyr/yr (5.2 billion barrels per year) of liquid fuels by 2030 in the High scenario (0.75 TWyr/yr in the Low scenario) or about 50 to 55 percent of all liquid fuel supplies in region I.

Region II (SU/EE), Figures 17-11C and 17-11D, with substantial resources of oil and with large resources of cheap coal, is believed to be self-sufficient through the next fifty years—that is, neither a net importer nor exporter. Its domestic oil production could reach a peak of 0.8 to 0.85 TWyr/yr in the High scenario and 0.75 to 0.8 TWyr/yr in the Low scenario by 2005-2010, matching demands for liquid fuels. Thereafter, a growing gap between total liquid fuel demand and conventional oil supplies could be expected—a gap that could reach some 0.4 to 0.9 TWyr/yr by 2030. To meet this need, liquid fuels from coal and oil shales could be produced starting from about 2010-2015. Coal liquefaction, especially, is expected to contribute 0.7 TWyr/yr of liquid fuels in the High scenario or 0.3 to 0.4 TWyr/yr in the Low scenario by 2030.

Figure 17-10. Global oil supply and demand, 1975-2030, High and Low scenarios, crude oil equivalent. (See Table 17-6 for definitions of categories.)

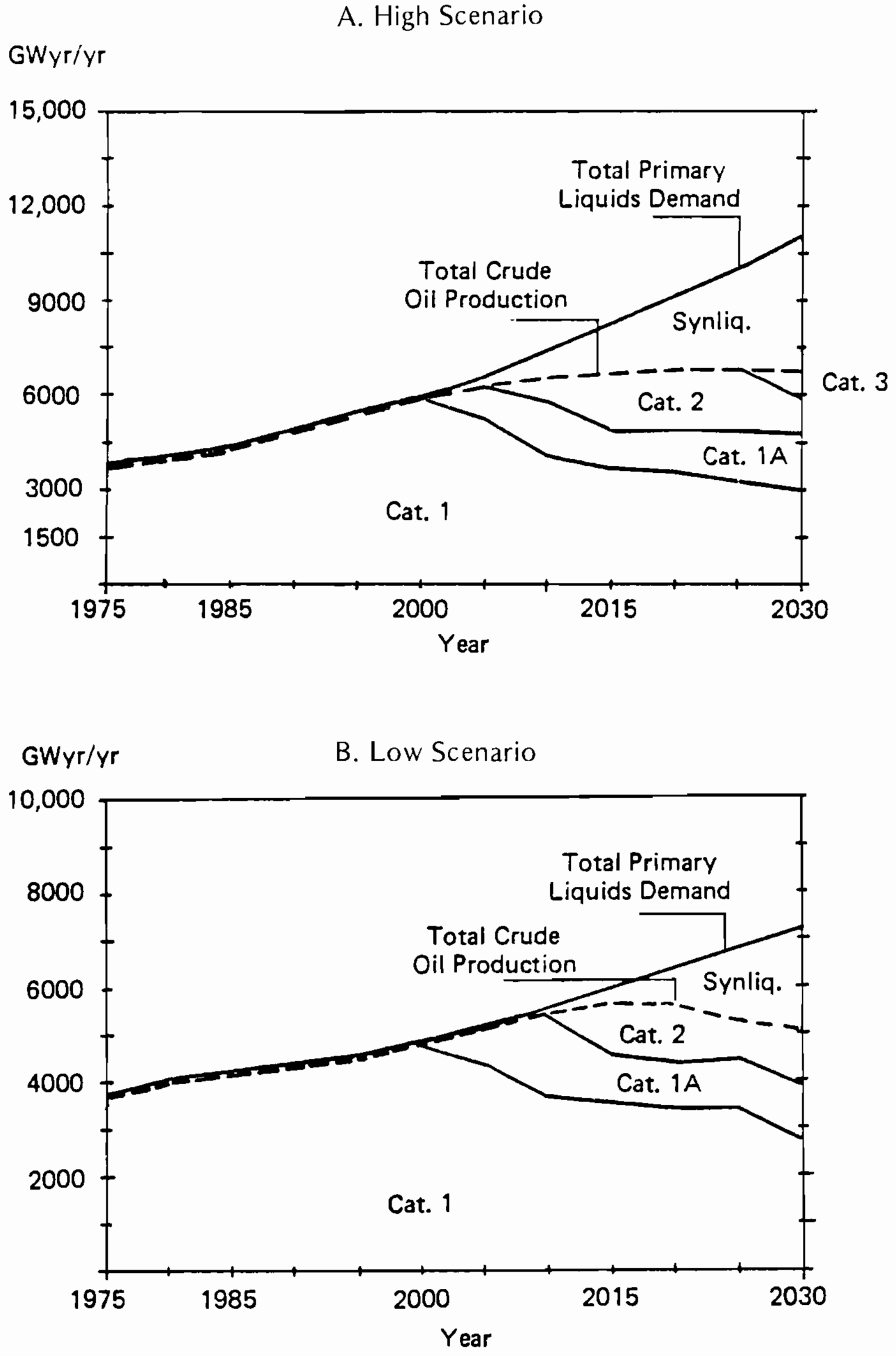
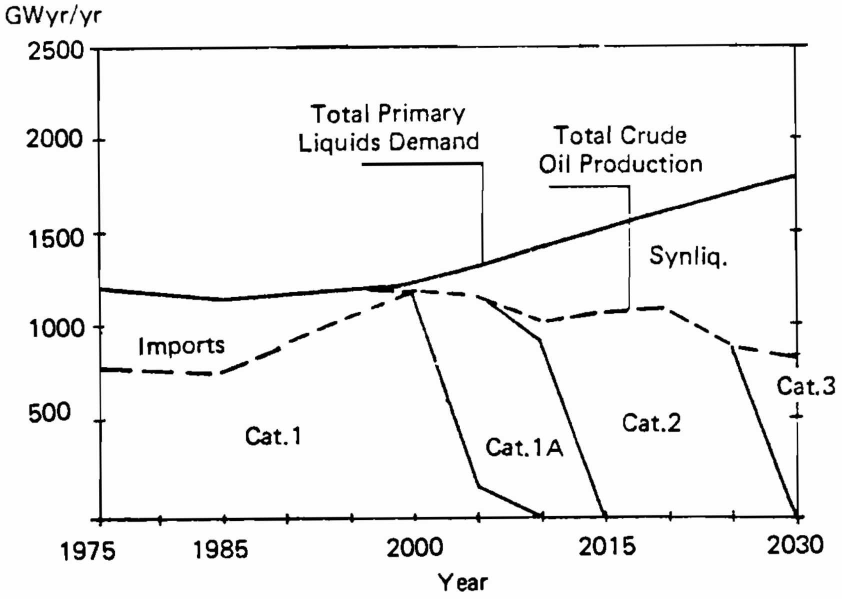


Figure 17-11. Oil supply and demand, regions I through VII, 1975-2030, High and Low scenarios, crude oil equivalent. (See Table 17-6 for definitions of categories.) All plots of Figure 17-11 result directly from the linear programming MESSAGE model runs and do not include constraints for the gradual buildup and depletion of separate oil categories. (There are constraints on total oil production, of course.) Therefore, the dynamics of the exploitation of different oil categories should not be taken literally. Also note: Only the five year period around 1975 (see pages 412 to 414) is the basis for the scenario calculations.

A. Region I (NA), High Scenario



B. Region I (NA), Low Scenario

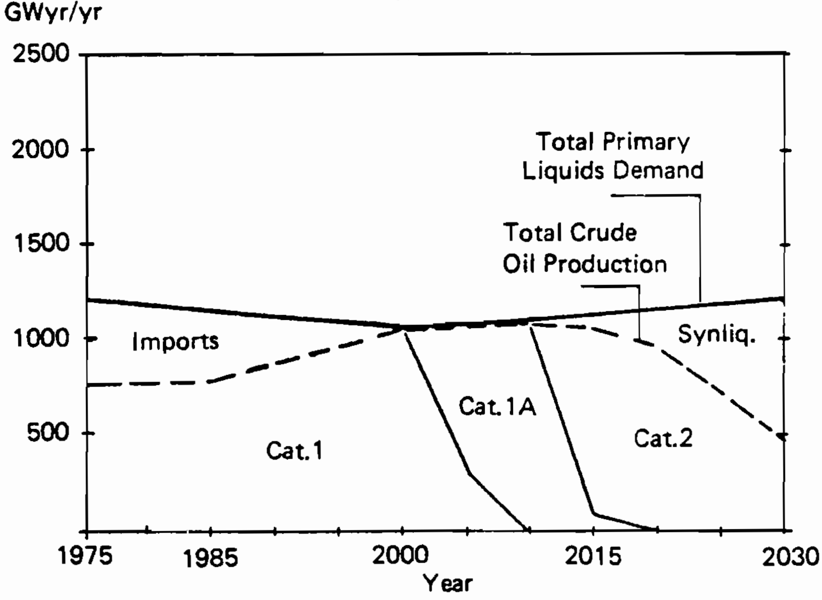
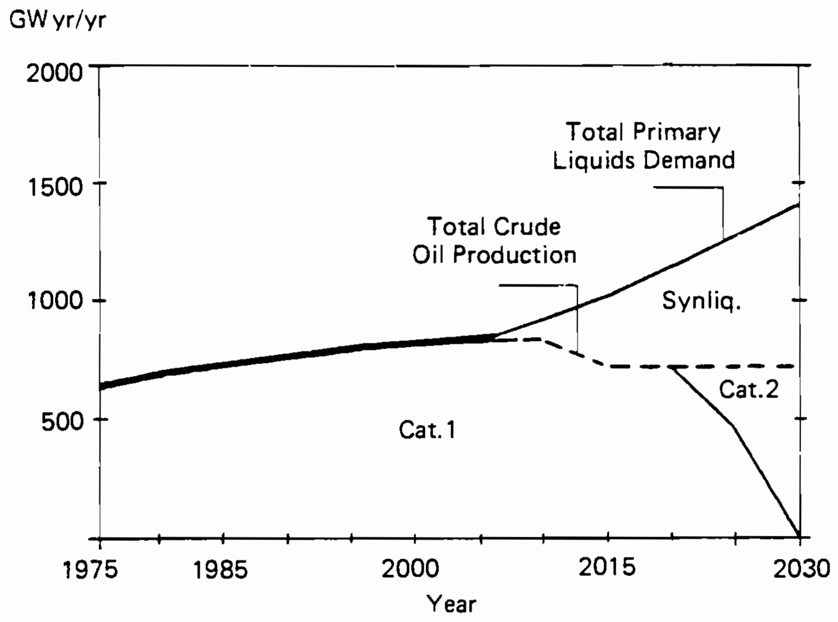


Figure 17-11 continued.

C. Region II (SU/EE), High Scenario



D. Region II (SU/EE), Low Scenario

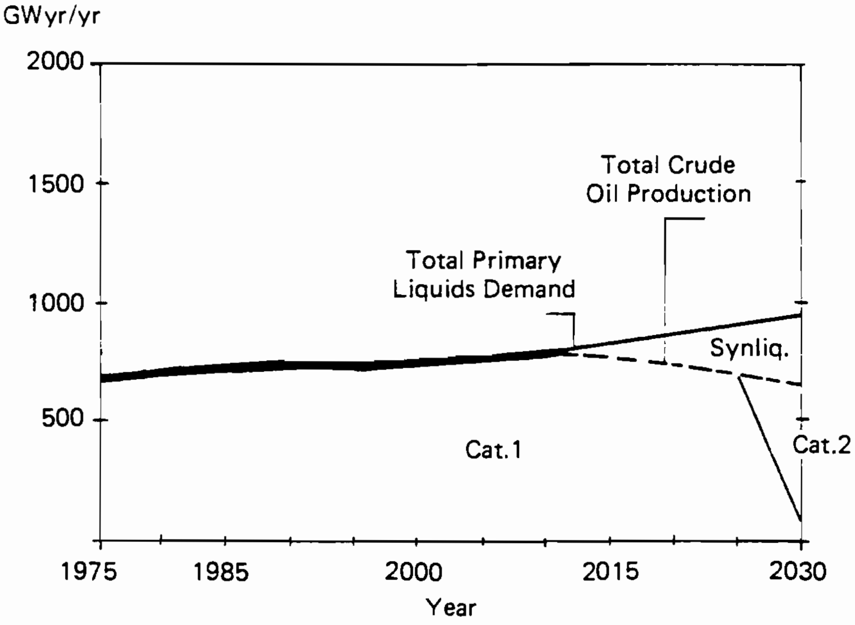
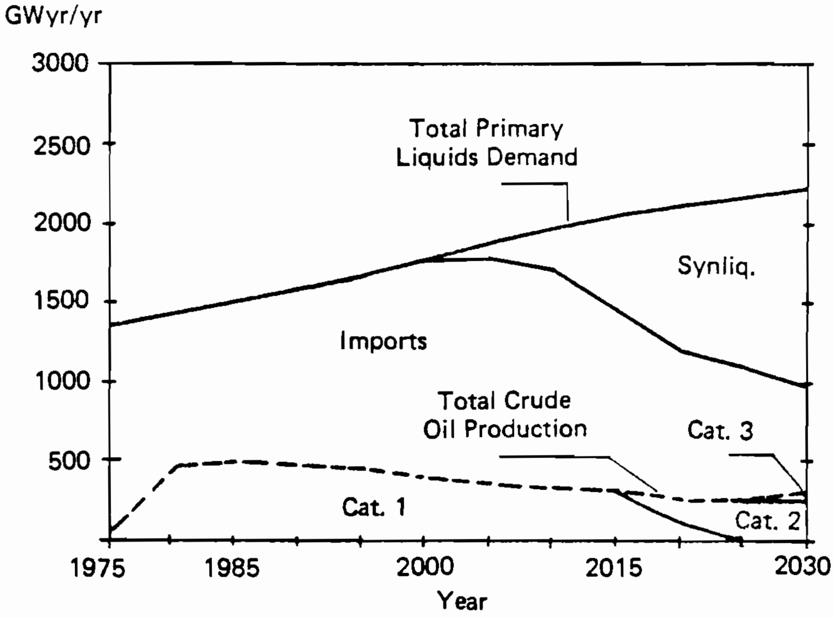


Figure 17-11 continued.

E. Region III (WE/JANZ), High Scenario



F. Region III (WE/JANZ), Low Scenario

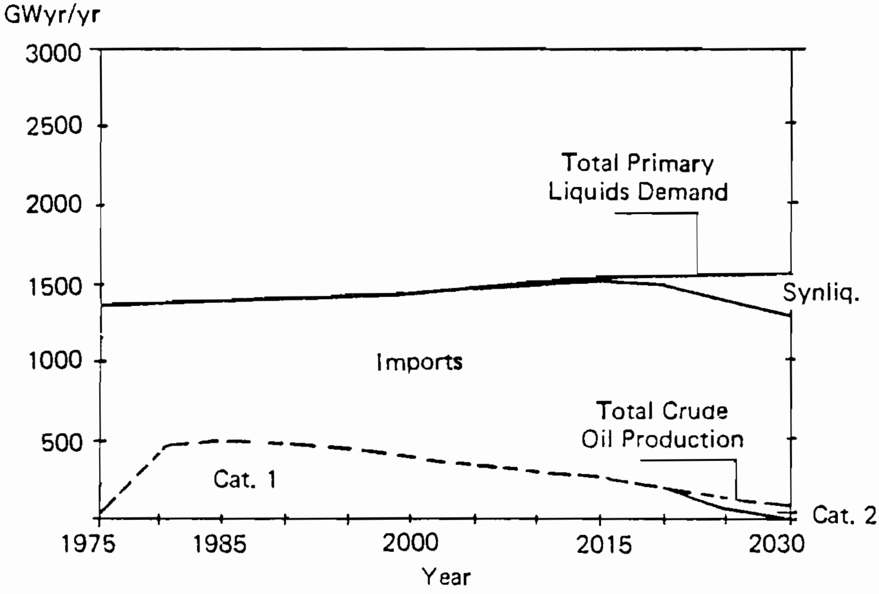
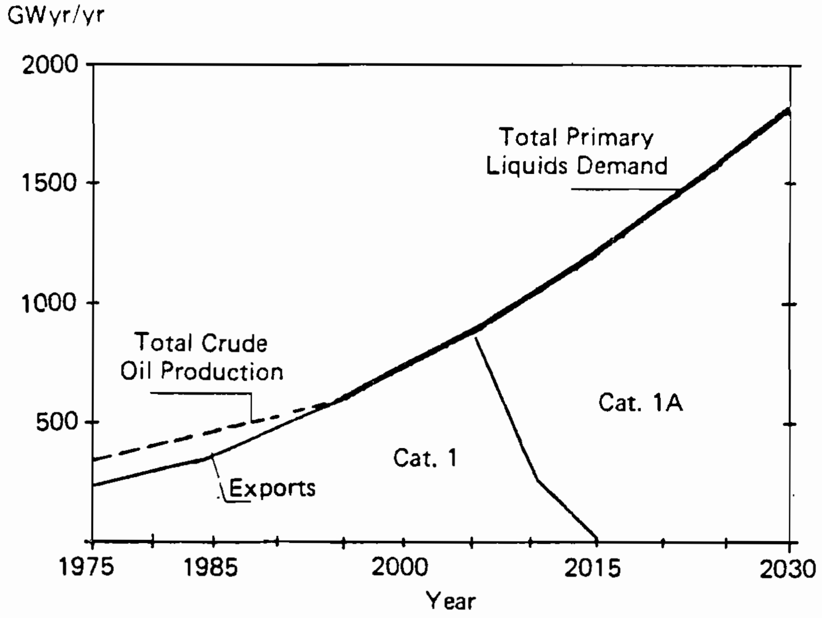


Figure 17-11 continued.

G. Region IV (LA), High Scenario



H. Region IV (LA), Low Scenario

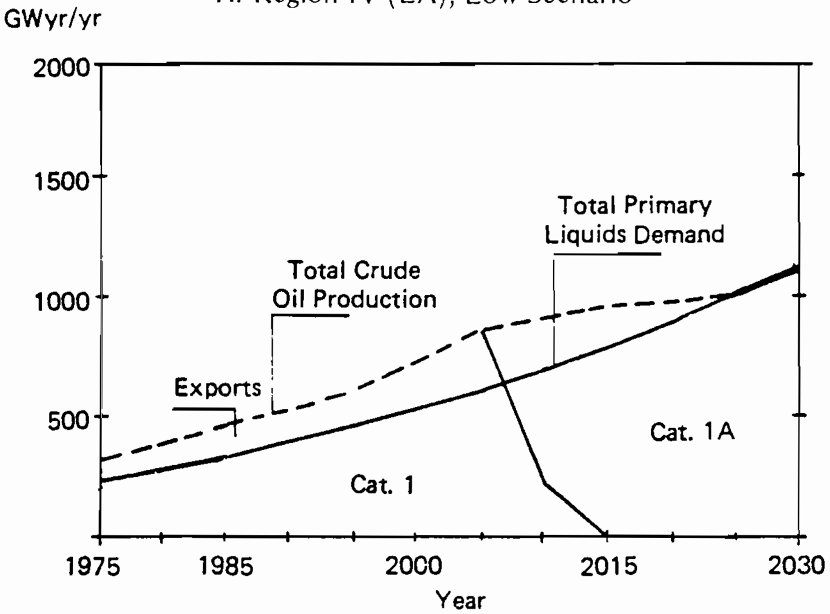
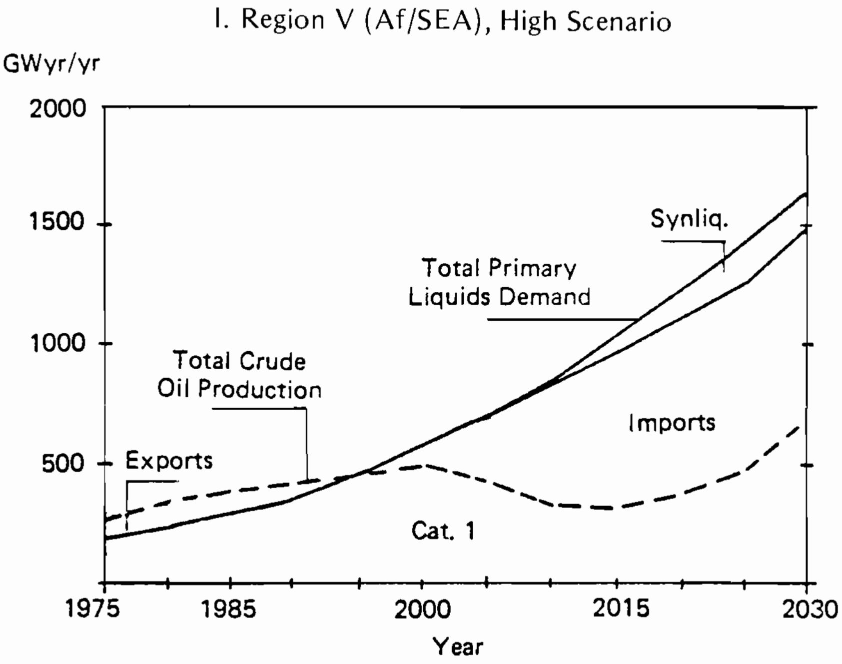


Figure 17-11 continued.



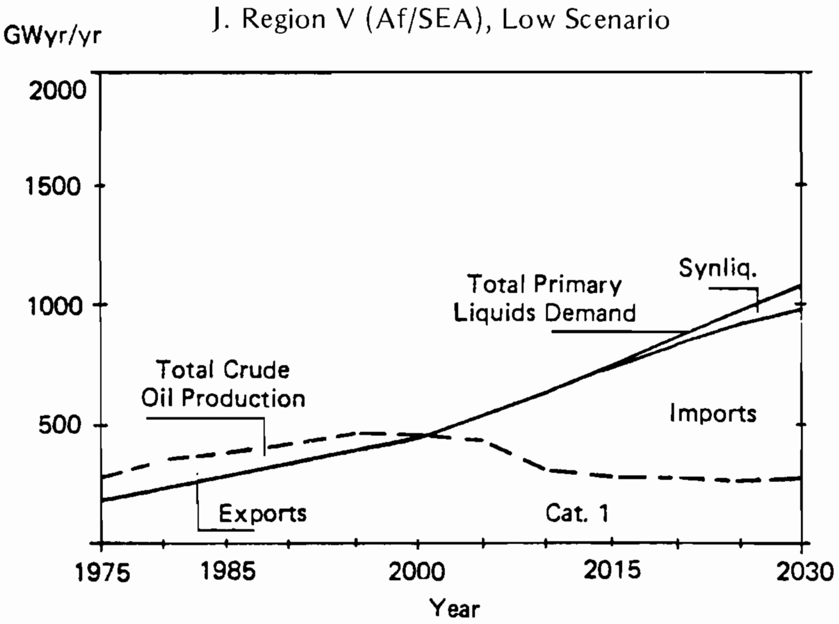
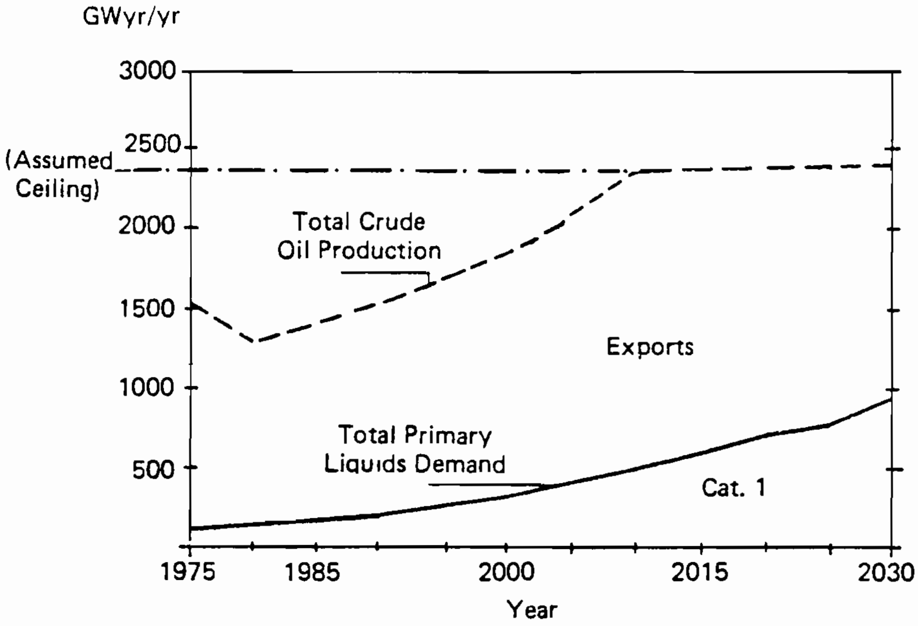


Figure 17-11 continued.

K. Region VI (ME/NAf), High Scenario



L. Region VI (ME/NAf), Low Scenario

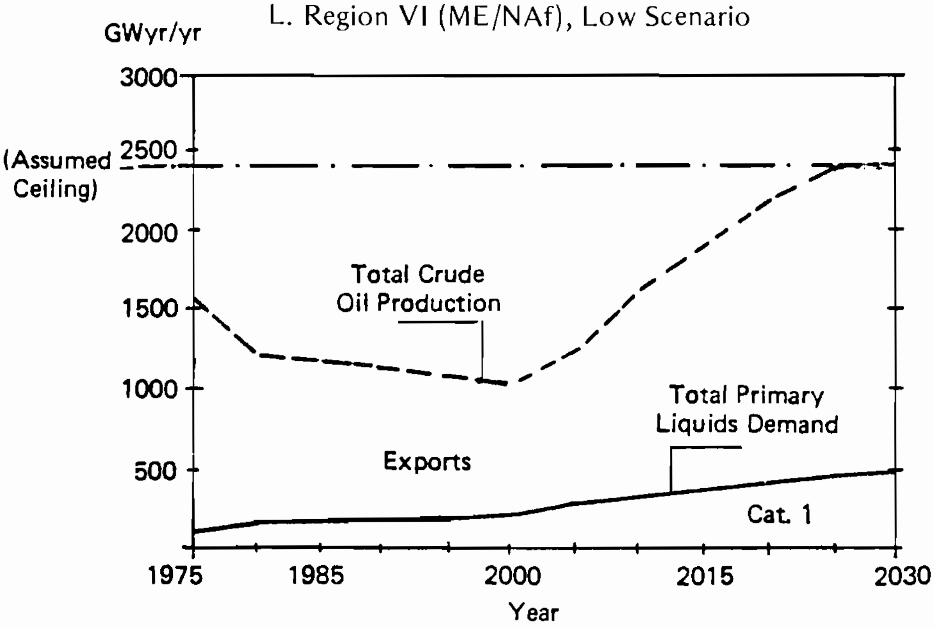
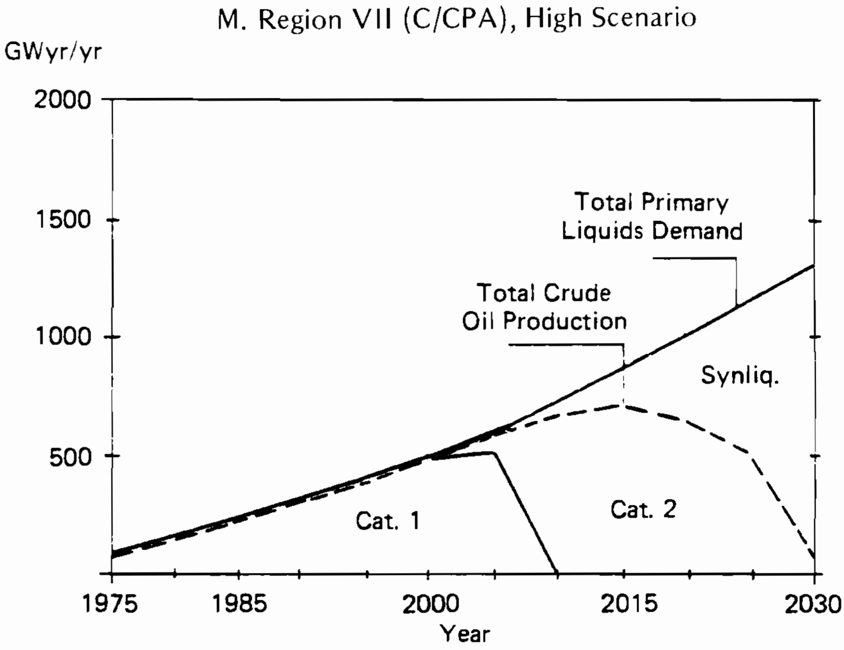
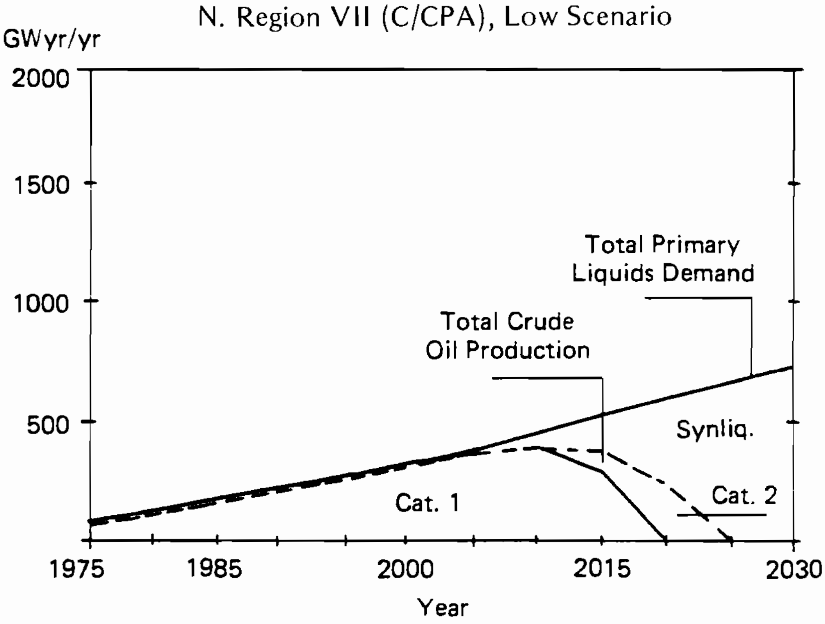


Figure 17-11 continued.





Region III (WE/JANZ), Figures 17-11E and 17-11F, would continue its high import dependence through 2030 under the conditions of the scenarios. Its domestic oil production could reach a peak of some 0.5 TWyr/yr (2.6 billion barrels per year) by 1985-1990 in both scenarios (because of expansive development of North Sea oil deposits, but would tail off afterwards. By 2030, the gap between primary demand for liquid fuels and domestic oil supplies would be as large as 1.9 TWyr/yr in the High scenario and 1.5 TWyr/yr in the Low scenario. In the High scenario, because of a tighter interregional oil export-import balance, region III would have to produce a rather large amount of synthetic liquid fuels from coal, starting in the year 2000. To provide the required synthetic liquid fuel production of some 1.2 to 1.3 TWyr/yr, coal imports (a total of nearly 1.7 billion tons per year by 2030) would be necessary either as coal for domestic liquefaction or as synthetic liquids produced in the exporting region. In the Low scenario, the import dependence is nearly total, since imports of oil are cheaper than liquefaction.

In region IV (LA), Figures 17-11G and 17-11H, conventional oil that could be produced economically at projected interregional oil prices could meet only short-term demands for liquids. In the long term, liquid fuel demands will exceed production of conventional oil by around 0.3 TWyr/yr by the year 2000 and by as much as 1 to 1.6 TWyr/yr by 2030, depending on the scenario considered. To meet these needs, however, enormous heavy crude oil resources are available. Given the judgments of this study concerning maximum rates of development and costs, the High scenario production of heavy oils would make region IV neither a net importer nor a net exporter in the long term. Its oil exports in the Low scenario could, however, grow to 0.2 to 0.5 TWyr/yr by 2005-2010, but decline thereafter to zero by 2025.

The major feature of the region V (Af/SEA), Figures 17-11I and 17-11J, long-term liquid fuel demand-supply integration, is that under the conditions of the scenarios, it would stay as a net exporter of oil until 1990 (High scenario) or until 2000 (Low scenario), but then become a rather substantial oil importer.[g] Domestic production of conventional oil could support a peak of nearly 0.5 TWyr/yr (2.6 billion barrels per year) by 2000 in both scenarios. Further decreases of conventional oil production could economically be replaced, partially, by developing a coal liquefaction capability. These could supply a total of 0.7 TWyr/yr, produced domestically, in the High scenario by the year 2030 and about half that amount in the Low scenario. Another 0.7 to 0.8 TWyr/yr, necessary to meet 2030 demand, would have to be imported.

Region VI (ME/NAf) would continue to be the main supplier of oil to other regions. Although this region would produce, cumulatively, some 105 TWyr (541 billion barrels) of oil by 2030 in the High scenario, this is entirely conventional oil and represents about 80 percent of total category 1 oil availability. (For the Low scenario, cumulative production to 2030 would be 82 TWyr—427 billion barrels—or about 63 percent of total category 1.)

[g] Region V is an exporter at present because of the few exporting countries—Indonesia, Nigeria, Gabon—within the region. The scenarios here show aggregate domestic liquid fuel demand surpassing the ability to export; hence the region would become a net importer.

Nearly all of the oil produced is exported, although as Figures 17-11K and 17-11L indicate, domestic uses grow steadily and are hardly negligible (20 to 40 percent of total production by 2030). Demands for imports from other regions imply that the assumed region VI production ceiling of 2.38 TWyr/yr (33.6 mbd) would be constraining by 2010 in the High scenario and by about 2030 in the Low scenario.

Region VII (C/CPA), Figures 17-11M and 17-11N, would experience rapid growth of both liquid fuel demand and crude oil production under the conditions of the scenarios. While this analysis does not claim any special insights into region VII, it does seem that domestic oil and coal resources may be adequate to make the region neither a net importer nor an exporter of oil over the next several decades. If this is the case, then—as in some other regions—a large coal liquefaction industry would be called for sometime after the turn of the century.

Of course, such regional considerations are necessarily aggregate and thus mask the special characteristics of the many different countries comprising each region. The regional results should be seen in this light.

GAS SUPPLY AND DEMAND

Natural gas, as is well known, is a clean and convenient fuel. It is also well known that natural gas is difficult to transport over long distances; its major markets to date have been within national or regional boundaries. The High and Low scenarios project a range of increasing gas uses, in relative terms at least, in the developed regions, where significant amounts of gas resources are believed to be located. Gas use in region VI would probably increase dramatically; resources there are almost certainly enormous.[h] In regions IV and V gas use may be relatively moderate.

Although, here, major international gas trade has not been studied with care, one should not exclude the possibilities of undersea pipelines or cryogenic tankers, in spite of complexities and potential dangers. And projects such as the pipeline under the Mediterranean are already in progress. Whether such schemes prove to have large-scale significance remains to be seen.

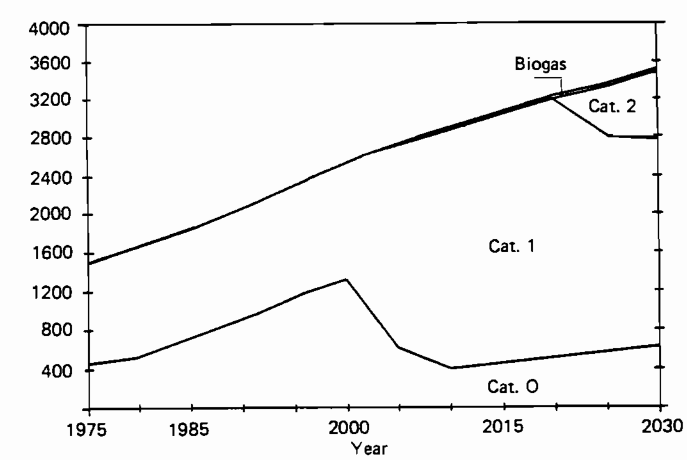
Gas markets compete with oil, electricity, and to a certain extent, coal—and they will most likely come to compete with solar devices. Iteratively, demands for different fuels were modified in these analyses in order to arrive at reasonably consistent prices among fuels—given assumptions about market constraints and the built-in price differentials that naturally accompany local conditions, regional singularities, and national policies. (These preferential value considerations are described in Chapter 16.)

Figures 17-12A and 17-12B show global supplies of gas for the High and the Low scenarios. In the High scenario, gas demands exhaust (regionally)

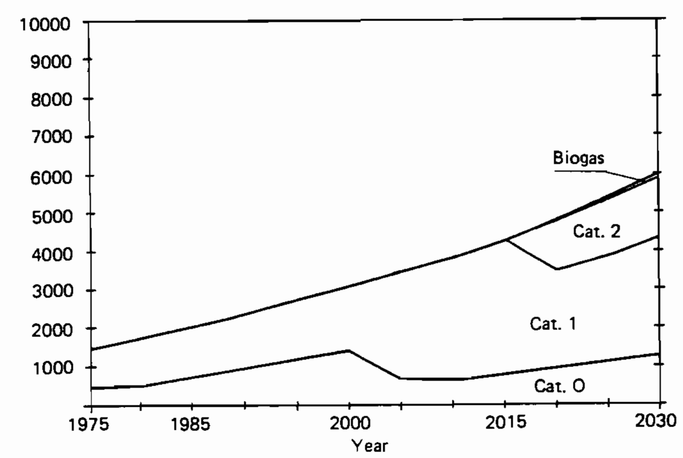
[h] This increased gas use may well be at the expense of local oil use. That is, oil may be more and more reserved for the valuable export market, while otherwise flarable gas would be used for domestic consumption.

Figure 17-12. Gas supply and demand, 1975-2030, globally and by region. (See Table 17-6 for definitions of categories.)

A. World, Low Scenario



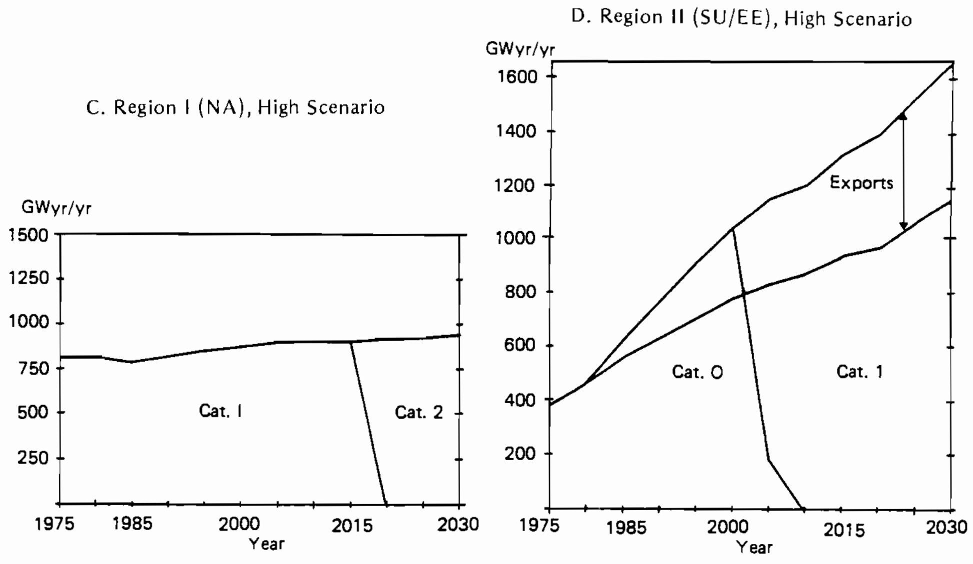
B. World, High Scenario



category 1 gas (conventional gas resources at costs of \$12/boe or less) and use (regionally) 35 percent of category 2 gas (conventional gas but from enhanced recovery and offshore areas, for example, at costs from \$12 to \$20/boe). In the Low scenario, all of category 1 gas is used (regionally), as well as 15 percent of category 2 (regionally). (For region VI only, there is also a category 0, with natural gas available at \$2/boe.)

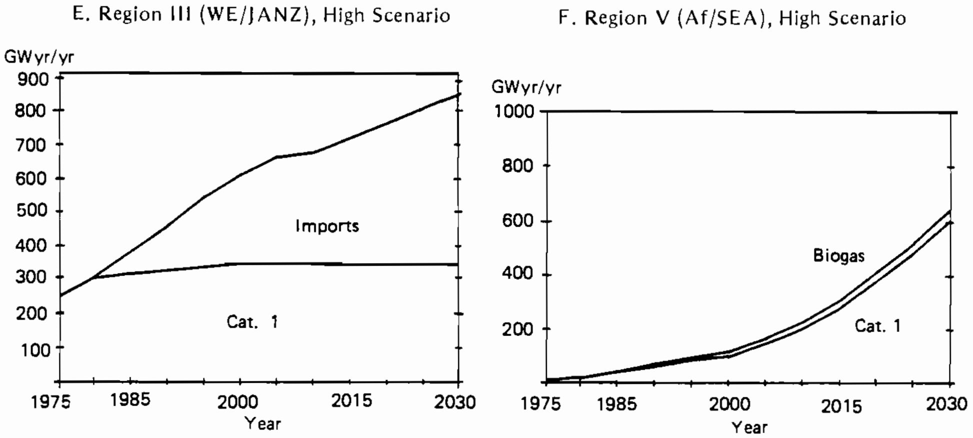
Two regions, compared in Figures 17-12C and 17-12D illustrate some of the local diversities in gas supplies. Region I relies on domestic production

Figure 17-12 continued.



C. Region I (NA), High Scenario

D. Region II (SU/EE), High Scenario



E. Region III (WE/JANZ), High Scenario

F. Region V (Af/SEA), High Scenario

of gas to meet all projected gas needs. Region II is able in these scenarios to export rather substantial amounts of gas, in spite of increasing its own demands for gas quite markedly. (Gas production and demand in region II should begin to level off by 2020 or so.) Region III (Figure 17-12E) would import substantial amounts of gas from region II to meet its needs. Region V (Figure 17-12F) produces small quantities of its relatively limited conventional natural gas resources and relies to some extent (13 to 17 percent of gas demands) on biogas.

Region VI (not shown in Figure 17-12), with prodigious resources of easily and cheaply accessible gas (most of it still flared away as a nuisance to oil production), is projected to increase its uses of natural gas—for industry, for buildings, and for electricity generation. Gas in this region seems to be a perfect match of an abundant source and local (if relatively small) market.

COAL SUPPLY AND DEMAND

Much has been said already of the vast potentials and real limitations on future large-scale production and use of coal. Here, the coal possibilities are placed within the overall supply-demand frame of the High and Low scenarios.

Again, it should be pointed out that the scenario considerations are not meant to repeat or conflict with the considerations of Chapter 3. There, the global coal potential was assessed; here, the global and regional coal needs, in relation to other energy sources, are assessed.

A Large Resource

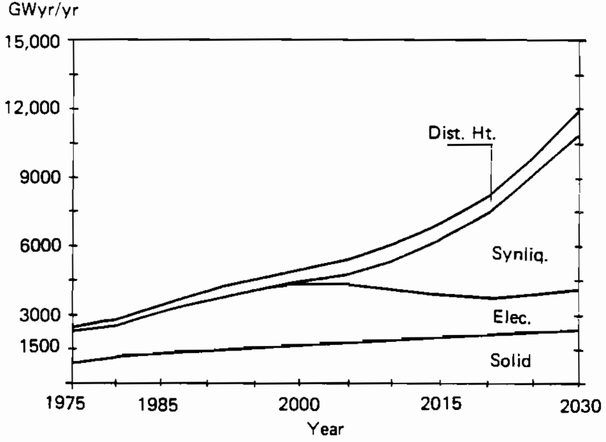
In both the High and Low scenarios, virtually only category 1 coal is required; the regions that use coal are those (by assumption, mostly) that have large coal resources. And the resource base of coal category 1 is (as already noted) by almost any measure enormous. For region I, category 1 coal is nearly as large as the oil resources of the Middle East. Globally, of the total resource base of 561 TWyr in category 1, only 341 TWyr, or 61 percent of the total, are used by 2030 in the High scenario (224 TWyr, 40 percent in the Low scenario). In region I, 46 percent in the High scenario (24 percent in the Low scenario) of the category 1 is consumed by 2030. Region III uses nearly 50 percent of its category 1 resource: If this region were to not import coal, use of domestic resources could reach 83 percent. The coal resource amount in regions II and V are also sufficient to easily avoid depletion, even in the High scenario, by 2030. Region VII, assumed to not enter the import market for energy in the next fifty year, faces the prospect in the scenarios of using much of its vast coal resource for domestic growth. In the High scenario, nearly all of its category 1 coal is exhausted, yet all of its higher cost (up to $50/ton) category 2 coal remains available after 2030. The region VII options, other than imports, seem few in our rather data-scarce and aggregate analysis of that region.

Coal Liquefaction

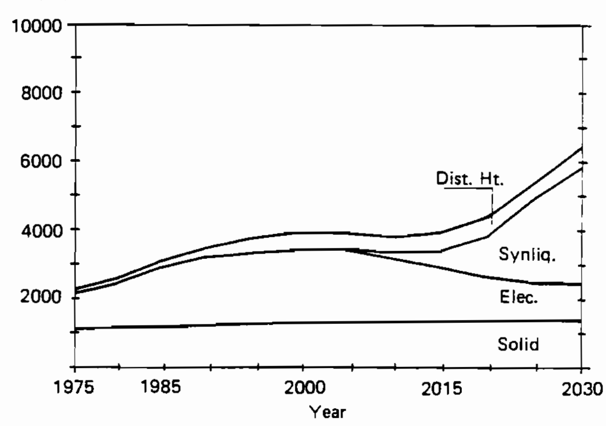
The uses of coal over time for the world are illustrated in Figure 17-13 for the High and Low scenarios. The "solid" uses of coal were outlined in Chapter 16: coal use in production of synthetic fuels is driven by demands for gaseous and/or liquid fuels and the availability of other sources.

Figure 17-13. Global coal supply and demand, 1975-2030.

A. High Scenario



B. Low Scenario



It is clear from Figure 17-13 that the assumptions behind the High and Low scenarios lead to very large future coal liquefaction industries. Indeed, the lowest assessment of demands for liquid fuels, coupled with optimistically high oil availabilities in various regions, coupled with favorably low cost estimates for synthetic liquids production, produce great needs for liquids produced from coal.

This is a major observation. Coal will be needed in very great amount for the production of liquid fuels. Unless the scenario estimates of demands for liquid fuels (see Chapter 16) are greatly in error, there seems little margin for other than synthetic liquid fuel production to meet the needs. The magnitude of the result warrants some careful regional looks.

The United States has fantastic coal resources. So does the USSR. The open question in both cases is the rate of extraction. And the range of answers can make great differences in the long-term energy picture in region I, region II, and the world. For region I, a ceiling of nearly 2.9 billion tons per year (2700 GWyr/yr) of coal production has been assumed—based on limitations of rail transport, water availability for Western U.S. surface mining, limited coal uses (as coal) within the United States and Canada, few deep water port facilities, and air quality and other environmental considerations. This ceiling, and the constraints assumed for region II and other regions, are summarized in Table 17-10. Three billion tons of coal per year in the United States is an enormous mining activity: it is nearly five times the 1978 U.S. production rate. (For comparison, in the High scenario, the North America gross domestic product grows by 3.75.) It is nearly twice the present coal mining of the whole world. It means great capital investments, large land uses, substantial numbers of new miners. Presumably, it could be done; the assumptions of these scenarios imply that it must.

The rapid rise in coal output (including coal for export) in North America from 2015 to 2030 (Figures 17-14A and 17-14B) in these scenarios is at an annual rate of about 3.5 percent per year. This vigorous but not implausible effort at coal expansion during the peak of the "transition period" signals again the great need for—and the restricted availability of—liquid fuel during that time.

The coal supply and demand in the High and Low scenarios in region II does not differ greatly from that in region I, as Figures 17-14C and 17-14D illustrate. Coal is used for solid fuel demands and for liquefaction, with electricity-generated uses declining near the end of the period in the High scenario as coal production limits (3500 GWyr/yr, including coal produced for export either as coal or as synthetic liquids) are reached. Some 1060 GWyr/yr of coal are input to coal liquefaction by 2030 in the High scenario (480 GWyr/yr in the Low scenario) or nearly 40 percent of all coal produced for domestic use.

Table 17-10. Coal maximum production assumptions, High and Low scenarios (maximum annual domestic production constraint [GWyr/yr[a]]).

Region	*Base Year 1975*	*Year*			
		1985	*2000*	*2015*	*2030*
I[b] (NA)	559	900	1500	2000	2700
II[c] (SU/EE)	807	1300	2400	3000	3500
III (WE/JANZ)	466	600	800	1000	1000
V (Af/SEA)	116	225	450	825	1315
VII (C/CPA)	325	800	1500	2000	3500

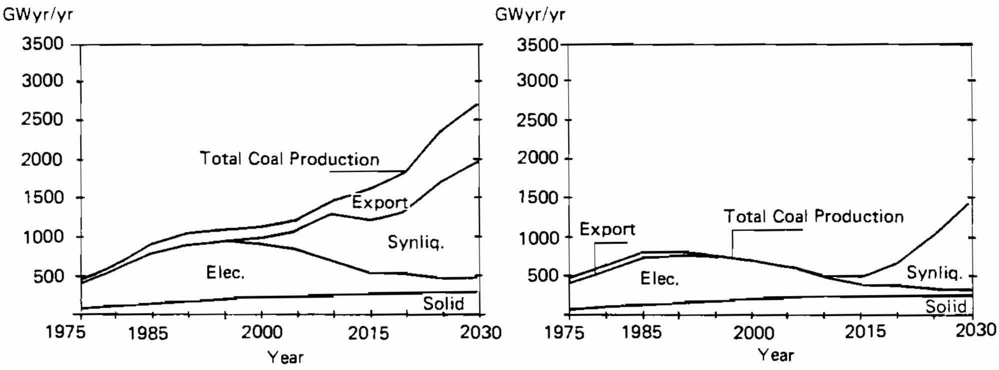
[a] 1 GWyr/yr = 1.08 × 10^6 tce per year.

[b] To reach 2700 GW by 2020.

[c] Figures given are for High scenario; Low scenario limits, from 1985 to 2030, are 1600, 2600, 2900, 3000.

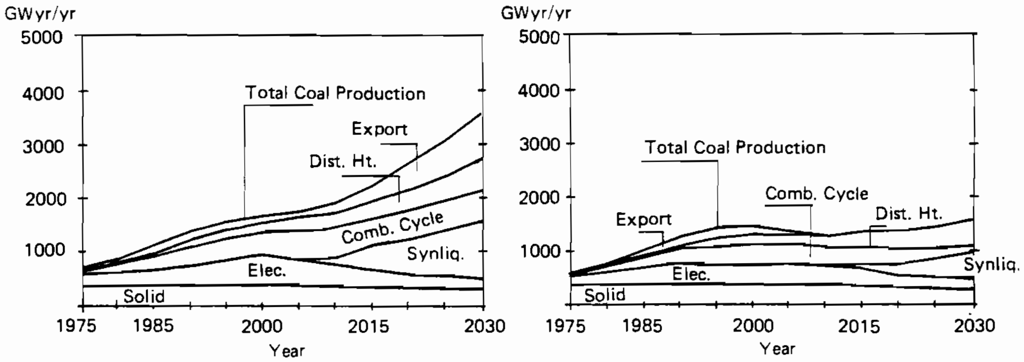
Note: These constraints represent the roughly assessed composite and aggregate limitations of water, manpower, transport, environmental safeguarding, and so forth in each region.

Figure 17-14. Coal supply and demand for regions I, II, III, and V, 1975-2030.



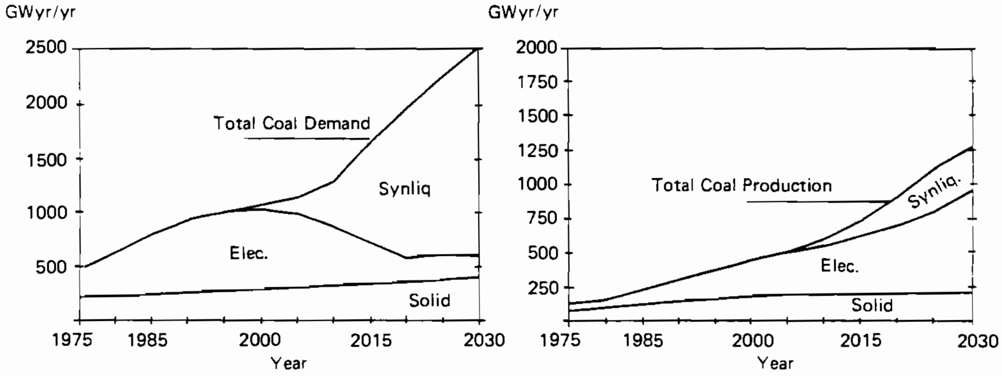
A. Region I (NA), High Scenario

B. Region I (NA), Low Scenario



C. Region II (SU/EE), High Scenario

D. Region II (SU/EE), Low Scenario



E. Region III (WE/JANZ), High Scenario

F. Region V (Af/SEA), High Scenario

At the same time, coal is in increasing demand as a source of district heat and heat from combined heat and power plants. This use of coal reflects a definite intent in the Soviet Union and several East European countries to make use of available primary resources (coal as well as nuclear and natural gas) in this way (see the section below on centralized heat supply).

Part of the coal outputs from regions I and II is exported to region III in the scenarios. Figure 17-14E shows the reason why. With restricted oil exports from region VI in about the period 2005-2020 and with limited domestic oil production possibilities, region III is forced to import coal from coal-rich regions I and II for rising liquid fuel needs. Region III options in these scenarios are quite limited. Domestic oil production is small; coal production is large—even at 1076 million tons per year it is two and a half times today's level—but it is not sufficient for the requisite scale of synthetic liquid fuel production within the region. The greatest expansion in coal production is assumed to occur in Australia—with completely internal (to region III) movement of coal assumed. Still, the truly binding constraint for region III is the supply of liquid fuels. By 2030 in the High scenario, regions I and II could be liquifying an aggregate total of over 2.5 TWyr/yr of coal (1.6 TWyr/yr in the Low scenario). Total coal imports to region III in 2030 are more than 1.5 TWyr/yr.

Although coal trade is treated here, the traded quantity could as well (perhaps better) be synthetic liquid fuels produced from coal. Whether regions I and II would choose to produce coal and export it or to produce coal, convert it, and export the synthetic oil is not crucial to these analyses. What is vital is the need for liquid fuels in region III and the availabilities of coal as the ultimate source of these liquids on a truly global scale.

The vast exploitation on a global scale is mirrored also in a relative way in region V (see Figure 17-14F). There, domestic coal production would expand more than elevenfold in fifty years in the High scenario (GDP would grow tenfold in the same period, High scenario). However, in this region coal is used directly as a solid fuel to a large extent in these scenarios, but with a significant portion generating electricity as well, while a relatively modest fraction goes into a synthetic fuels industry.

In region VII (not shown) the same general trend of coal results appears. The coal resource base is large, but so is demand growth. By 2030, 72 percent of all primary energy uses would be met by coal. This coal would be used in fairly large proportions both as a solid fuel and to produce synthetic liquid fuels. Economic growth and development in region VII is likely to be constrained, as in other regions, by limited resources: more growth than postulated here would mean more coal, already produced at 3.2 TWyr/yr (nearly 3.5 billion tons per year) by 2030 under the conditions of the High scenario. This is some 19 percent higher than region I coal output in the High scenario in that year. Nearly 60 percent of total coal output is required to produce liquid fuels.

Worldwide in 2030, about 6.7 TWyr/yr—56 percent of all coal production—would go to the production of synthetic liquid fuels under the assumptions of the High scenario. This 6.7 TWyr/yr is over 80 percent of the total energy use in the world today. Some 38 percent of all the liquid fuels consumed in 2030 in the High scenario originates with coal. And 80 to 90 percent of this liquid fuel consumption total, as explained in Chapter 16, is for difficult to substitute transportation and feedstock uses.

All of this leads to the central observation that liquid fuel supply is the critical problem in the long-term—that meeting essential needs for liquid fuels poses the greatest challenge to future energy supply systems. And in particular, it leads to the observation that the world's oil resources are inadequate for the job unless shale oils, tar sands, or heavy oils are developed on a truly global, terawatt scale without the supplement of synthetic liquid fuels from coal. Even then, coal is pressed to (and maybe beyond) its feasible limits of supply. New technologies that stretch out the lifetime of coal resources by greater efficiencies—coupled with large heat sources such as the breeder reactor or the sun— have been mentioned in Chapters 4 and 5, respectively; in Chapter 18 they will be placed generally in an overall supply context. Also in Chapter 18, the possibility of exploiting the world's natural gas resources as a means of producing liquid fuels will be taken up. The analyses here seem to point to the need to explore alternatives of these kinds.

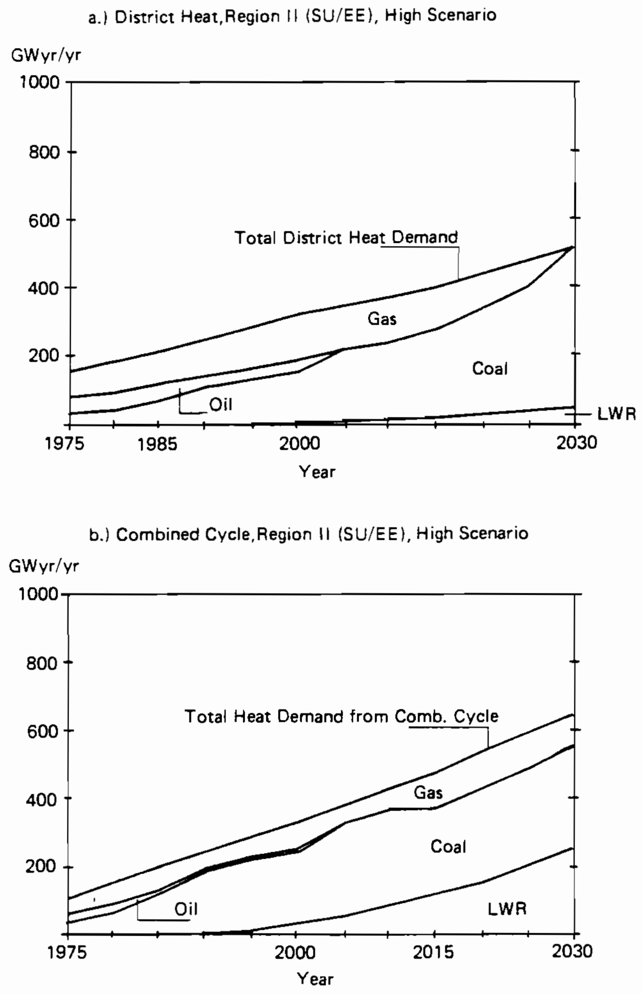
CENTRALIZED HEAT SUPPLY

In several world regions steps are being taken (and have been taken) to use indigenous primary energy sources for the centralized production and distribution of heat. These schemes include district heat plants and facilities for the combined generation of heat and power (commonly called cogeneration).

In the Soviet Union, and in a number of Eastern European countries, district heat and cogeneration plants already supply a substantial fraction of heating requirements—70 percent of total low and medium temperature heat needs in the Soviet Union, for example. Also, some 30 percent of heating needs of buildings in urban areas come from cogeneration plants; this share is thought to rise to perhaps 50 percent by the year 2000 and to 70 percent by 2030. Soviet national planning and siting of industrial and housing construction is being designed to facilitate the expansion of high capacity cogeneration plants. This continuing move toward centralization, it is argued, will improve urban air quality and allow for a broader use of a variety of fuels (including indigenous low grade coal, for example—an extremely important consideration in much of Eastern Europe).

In cities in the Soviet Union, centralized heat sources (both district heat plants—large boilers—and combined heat and power plants) now account for some 45 percent of all heat consumption. Plans to expand these facilities are vigorous and include the use of many primary sources, including nuclear energy, solely for heat supply. As Figure 17-15A shows, coal is likely to be the largest source of total district heat in region II, with abun-

Figure 17-15. Centralized heat supply in region II (SU/EE), High scenario, 1975-2030.



dant gas also being used extensively, particularly in the near to medium term.

Figure 17-15B shows the projected sources of heat for combined cycle plants in region II, High scenario. Coal is seen as the largest source of the future, with conventional nuclear reactors contributing a growing share, particularly after the turn of the century, when coal comes more and more to be required for synthetic liquid fuel production.

Oil will not be used as a major source for centralized heat supply. Indeed, in region II at least (and to lesser degrees in other regions), it is precisely the desire to minimize liquid fuel consumption that leads to the centralized heat supply exploitation. The planned concentration of residential areas and industrial complexes not only facilitates centralized heat supply, it also mitigates the need for long-distance daily travel—and hence dampens the growth in liquid fuel demand.

Other regions are projected in these scenarios to have growing centralized heat supplies, but none approaching the scale of that in region II. In region III, several Western European countries (most notably Sweden) already make use of district heat schemes. While in the region as a whole the number is still quite small, the scenario assumptions lead to as much as 138 GWyr/yr of district heat demand by 2030—or about 3 percent of total secondary energy needs.

Widespread global adoption of centralized heat schemes is uncertain. As buildings become better insulated, heat demands become less intense, and the economics of district heat become less clear. Cogeneration, however, should be an attractive option wherever industries can be suitably concentrated. In general, most regions are projected to continue the present pattern—decentralized heat supply and centralized electricity generation.

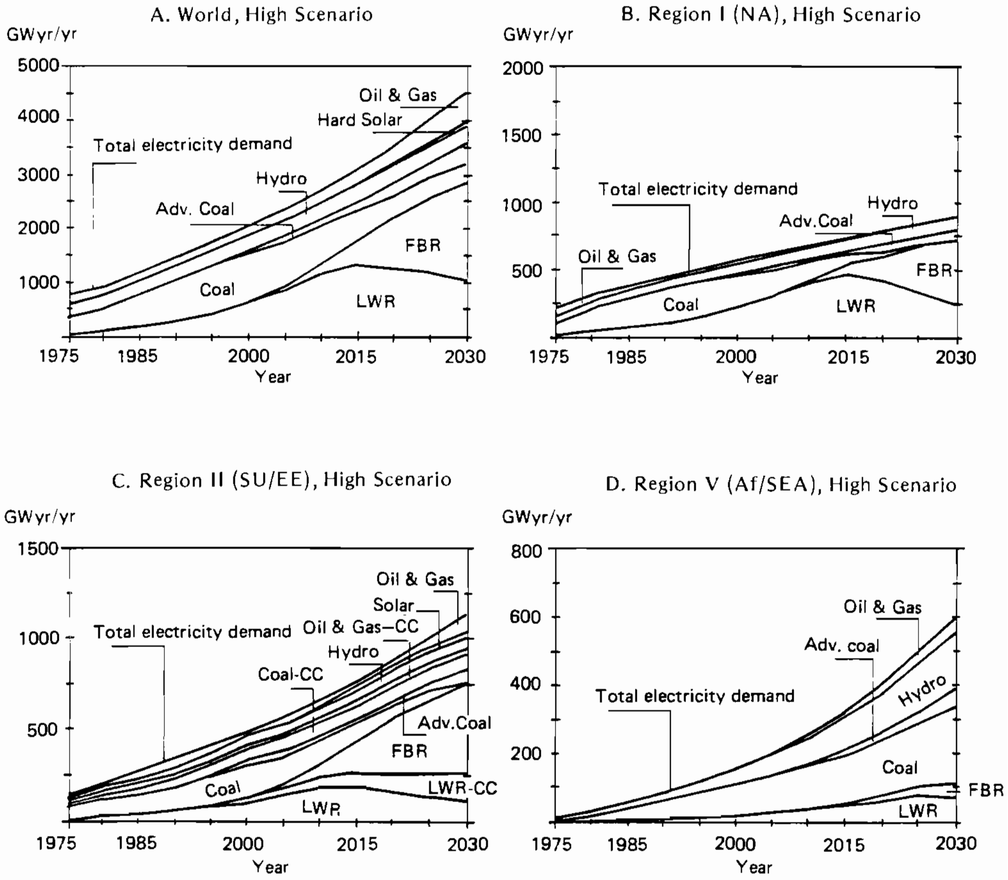
ELECTRICITY GENERATION

The sources of electricity today vary considerably from region to region. In North America (region I) in 1975, 43 percent of electric power was generated with coal, 27 percent with oil and gas, 21 percent with hydroelectric power, and 8 percent with nuclear reactors. (The nuclear share was nearly 15 percent by 1979.) In Western Europe and Japan, the role of fossil fuels was somewhat lower and that of hydroelectric power higher. In the developing regions, however, hydroelectric power provided in 1975 as much as 40 percent of the electricity generated, with coal providing 30 percent, and oil and gas together about 30 percent.

In contrast, by 2030 the picture may change markedly. Figure 17-16 shows electricity generation globally and for three sample regions for the High scenario to 2030, as they result from the assumptions already stated and the calculations in the MESSAGE model. Hydroelectric resources, for example, contribute in significantly different ways in different regions, as Figure 17-17 illustrates.

Total secondary electricity demand for the world grows at an average 2.4 to 3.3 percent per year in the two scenarios to 2030—reaching 3000 to 4700 GW(e) of capacity. This electricity, as was described in Chapter 16, is used primarily for those purposes for which electricity is specially suited. Thus, the electrical capacity estimate here is less than the 10 TW(e) of installed nuclear capacity considered in Chapter 4, whereas in other chapters of Part II, the maximum potential of a particular supply source is evaluated. When real world constraints are introduced region by region, as in these scenarios, revised estimates inevitably result.

Figure 17-16. Electricity generation, 1975-2030, High scenario, globally and by regions I, II, and V.

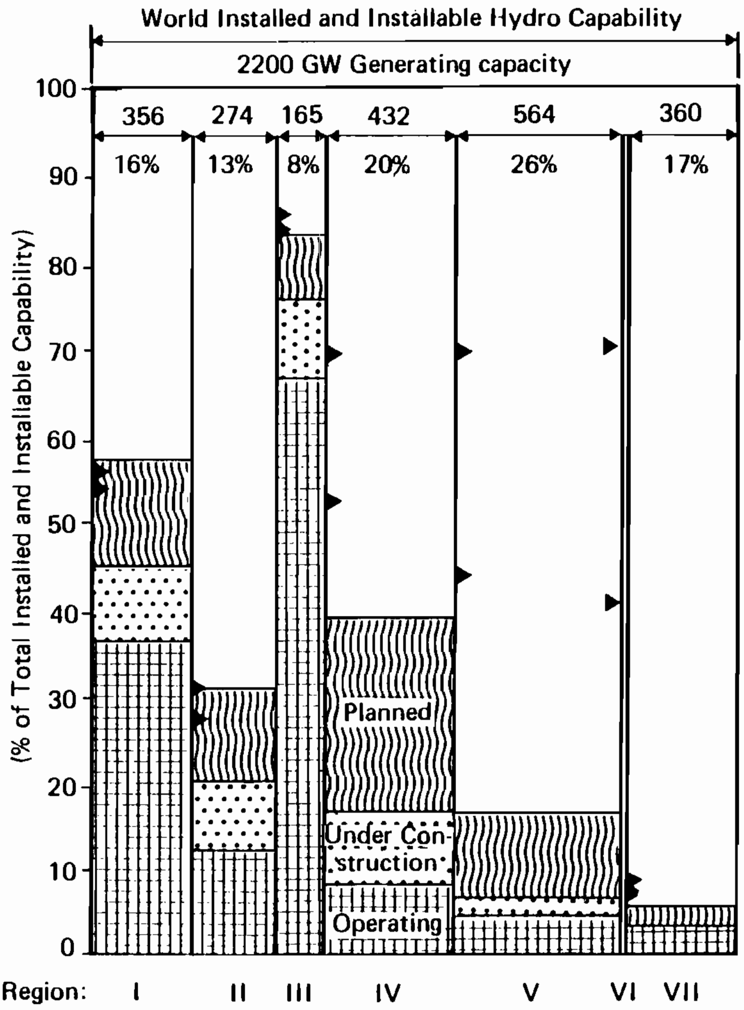


Some Regional Characteristics

In regions I and III, electricity demand and generation grew at rates of 5 to 7 percent per year during the 1960s and early 1970s. But the 1973-1974 global recession, coupled with rapidly rising oil prices and heightened attention to holding down energy use, reduced electricity growth in the late 1970s. In both the High and Low scenario projections, electricity is reserved more and more for its special purposes—for example, lighting and home appliances (see Chapter 16). Because of this, secondary electricity demand in region I would grow by just 1.4 to 2 percent per year, to 640 to 880 GW(e) of capacity in 2030 in the scenarios.

As Figure 17-16B illustrates, nuclear power would be a dominant source of electricity in region I in these scenarios by 2030. Nuclear power would

Figure 17-17. Global hydroelectric resources, total installed and installable capability, world regions. Top arrow in each regional column is the assumed maximum realizable by MESSAGE. Bottom arrow is the actual realized by MESSAGE in 2030, both High and Low scenarios; area of column proportional to total potential installable capacity.



provide 39 to 43 percent of electricity production in the year 2000 (from 15 percent today) and nearly 81 percent by 2030 in region I. The situation is very similar in region III: 85 percent of all electricity would be from nuclear power in 2030 in the High scenario (76 percent in the Low scenario). Such large shares mean that virtually all baseload power generation would be from nuclear power, as well as some intermediate load: however, the projections represent growth rates that are only a fraction of the maximum rates considered in Chapter 4. Because natural uranium supplies are limited, fuel for conventional reactors would be very costly after 2000. The breeder reactor would become economically competitive under these scenario assumptions from 2010 to 2030, and the installed capacity of breeders would grow at a rate of some 15 percent per year in region I in the High scenario. Other potential sources of electric power—oil, gas, and coal—would be required to meet other fuels demands, with only nuclear and to a certain extent hydroelectric power remaining to supply electricity needs.

In region II, the same general trends as in region I can be observed. Nuclear sources would provide as much as 66 percent of all electricity generated in 2030. Coal declines as an electricity source in the High scenario as it becomes increasingly needed for synthetic fuels production; it meets 6 percent of electricity needs in the High scenario and 17 percent in the Low scenario. Hydroelectric power supplies a relatively constant 3 to 4 percent of electricity needs (see Figure 17-16C).

As the plot for region V in Figure 17-16D indicates, the situation for the developing regions differs substantially from that of the developed regions. Nuclear power would provide a noticeable but relatively modest share of electricity needs by 2030 in both of the scenarios. Hydroelectricity would meet a substantial and growing share of demand; a large potential for hydropower development remains in many countries of Africa and Asia. (Of course, the resource is not inexpensive, as shown in Table 17-4, and the infrastructure needs for development are not small. But the potential is large.) Where hydroelectric power is not available, coal could be a major source of electricity, and oil and gas would provide substantial fractions.

By 2030 in region V, the mix of electricity generation is very roughly one-third coal, one-third nuclear, and one-third hydroelectric power—but coal seems to be declining (relatively) while hydroelectric and particularly nuclear power grow. The result is qualitatively the same in the High and the Low scenarios. In region IV, where coal is not plentiful, hydroelectric plants would provide nearly 30 percent of electricity generated by 2030. Region VI would rely heavily on cheap, locally available natural gas—coupled with modest amounts of nuclear energy—for electricity production. The massive coal deposits in region VII would provide for up to 34 percent of electricity output; nuclear and hydroelectric power generate most of the remaining electric demand.

The large emphasis on nuclear power in these scenarios warrants closer examination. What will be the character and timing of worldwide nuclear power development during the coming five decades?

Electricity Sources: The Choices

Many constraints to worldwide nuclear power development are obvious—the time and cost and both design and construction, especially of breeders or advanced converter reactors; the uncertain availability of natural uranium and plutonium; and the social constraints resulting from the popular distrust of nuclear power because of perceived environmental, safety, or military risks. The attempt here is to embrace (in a highly aggregate fashion) all these issues in the MESSAGE model, where the calculations for the development of nuclear power for the two scenarios are performed. One observation from these calculations is that, whether breeder reactors or an intermediate population of advanced converters are visualized, the availability of uranium is a serious constraint. The amount of "cheap" ($80/kg U) uranium is fully used everywhere, and in the High scenario in the developed regions I, II, and III the total available amount of even high cost ($80 to $130/kg U) uranium is consumed. Indeed, in the High scenario virtually all of category 1 and more than 15 percent of category 2 uranium throughout the world would be consumed by 2030. In the Low scenario, nearly all of category 1 and some of category 2 uranium would be consumed. The total potential uranium resources assumed here was some 24.5 million tons worldwide (see Chapter 4).

By 2030, the total global installed capacity of conventional and advanced reactors would reach 2600 to 4400 GW(e) in the scenarios from 72 GW(e) by 1975. Table 17-11 shows that this is some 40 percent of all installed electrical capacity by 2030 or about 60 percent of total electricity generated (from 5 percent today). By the year 2000, the nuclear capacity would be 630 to 870 GW(e). Since present worldwide plans and commitments for nuclear power stations (which take ten years or so to bring on stream) are well known, we know that the global 1990 nuclear installed capacity can be

Table 17-11. Global electricity generation in two supply scenarios to 2030: highlighting nuclear shares.

	Base Year	*High Scenario*		*Low Scenario*	
Secondary Electricity	*1975*	*2000*	*2030*	*2000*	*2030*
Generated					
Electricity, secondary (TWyr/yr)	0.75	2.1	4.7	1.7	3.0
Electricity as share of total secondary (%)	(12)	(16.4)	(19.3)	(16.4)	(19.1)
LWR (TWyr/yr)	0.04	0.61	1.06	0.45	0.57
LWR[a] as share of total electricity (%)	(2)	(29.4)	(22.9)	(27.1)	(19.2)
FBR (TWyr/yr)	0	0.01	1.81	0.01	1.21
FBR[b] as share of total electricity (%)	(0)	(0.67)	(38.2)	(0.44)	(40.6)
Rest (TWyr/yr)	0.67	1.46	1.87	1.21	1.21
Rest[c] as share of total electricity (%)	(95)	(59.9)	(39.4)	(72.5)	(40.3)
Installed Capacity[d]					
LWR (TW)	0.08	0.85	1.8	0.62	0.91
LWR as share of total capacity (%)	(5)	(19)	(18)	(17)	(14)
FBR (TW)	0	0.02	2.6	0.01	1.7
FBR as share of total capacity (%)	(0)	(0.5)	(26)	(0.3)	(27)
Rest (TW)	1.49	3.5	5.5	2.9	3.7
Rest as share of total capacity (%)	(95)	(80)	(56)	(82)	(58)

[a] LWR includes conventional burner reactors (e.g., light water reactors and CANDU reactors).

[b] FBR includes breeder reactors and advanced converter reactors.

[c] "Rest" are all nonnuclear electricity generating sources—coal, advanced coal, oil and gas, hydro, hard solar.

[d] Assuming a load factor of 70 percent.

no more than 390 GW(e). It could easily be less. Thus, the estimates of the year 2000 nuclear installed capacity in the High and Low scenarios here reflect a renewed commitment, over the next few years, to nuclear power buildup in many regions of the world. And, the year 2030 estimate reflects a continued nuclear buildup, constrained only by the buildup rate limits of Table 17-5, the availability of uranium, and certain restrictions on the extent to which nuclear can produce nonbaseload power.

Obviously, the renewed and vigorous buildup of nuclear electric capacity over the next few years is in some doubt. At this writing, the 1979 incident at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania, has caused U.S. utilities, government regulators, and the public to pause—indefinitely, perhaps—and to rethink the swirl of issues surrounding alternative sources of electricity. It is not the intent here to say whether this is right or wrong. Rather, the point is to produce estimates, for scenarios, that speculate on the possible. To constrain nuclear more than has been done for these scenarios would, in our judgment, be to unduly react to very complex current modes and tendencies. There is no telling, for example, to what extent coal-fired power plants may face similar or even more serious obstacles than nuclear. The constraints on all energy sources in these scenarios are intended to represent best available assessments of what is possible in each case, given economic, physical, and (only generally) environmental and institutional realities.

Still, one observes that the energy supply-demand-balancing analyses produce large nuclear shares and much smaller shares of other sources of electricity. There are two main reasons for this. First, cost. Table 17-4 reported the assumptions that show the cost advantage that nuclear may hold over certain alternative sources of electricity (solar, in particular). Solar, in addition, would be constrained by maximum buildup rate limits.

Second, the viable large-scale nonnuclear sources of electricity are supply constrained in these cases. Coal, a potential major contributor to power production, is constrained by the assumptions of Table 17-10 and is needed in large measure for synthetic liquid fuel production. Oil is clearly supply limited; gas turns out to be a very expensive electricity source. Hydropower is exploited, as already noted, to perhaps its feasible limits. On a large scale, only nuclear is left.

Clearly, the collective assumptions here point to the global need for nuclear electricity in the medium and long term. And there is much in the scenarios presented here, it would seem, to substantiate that view. But in this instance, as in others, there are choices—choices that have costs. Nuclear electric shares could be much lower if electricity demands were lower (see discussion in Chapter 16), or if the coal constraints were much higher, or if solar technologies become viable much sooner than anticipated. Prudent planning would, in our judgment, argue against any of these choices. If the world is to have low nuclear shares, then some of the consequent hard choices must be made.

Recognizing the potentiality of this, in Chapter 18 a "no nuclear" case is explored. The choice for little or no nuclear can be made, as will be demonstrated for the Low scenario. In the final analyses, it may simply be a question of relative priorities and values. Different regions of the world are likely to take very different paths to the future.

RENEWABLE ENERGY SOURCES[i]

Nuclear energy is not the only new source on the horizon. Over the next fifty years, one would expect substantial energy contributions to come from renewable energy sources—for example, "soft" solar systems, biogas, wood, wind. This, to a degree, will be the case. Yet one should carefully examine the technical and practical production potentials of these sources, and this has been done (see Chapters 5 and 6).

Here, only commercial supplies of renewables are discussed—energy sources bought and sold. Noncommercial sources are discussed briefly in Chapter 16, as are the potentials for soft solar. In this section, the potentials for certain other renewable and local energy sources in developing regions are assessed.

Although these sources are in principle eternally available, their use to date has been limited by generally unfavorable economics. This may change, as costs of traditional energy supplies rise. Also, the difficulties of exploiting, harvesting, transporting, distributing, and using renewable energy sources are today generally greater than for fossil fuels. Nonetheless, some renewable sources are in rather wide use already—notably hydroelectric power in both the developed and the developing regions and biomass as a noncommercial source in some developing regions.

Large-scale, centralized hydroelectric capacity plays an important role in the scenario projections reported here (see Figure 17-17). In addition, small-scale hydroelectric power facilities and wind converters may have useful applications in certain favorable locations. (Romania, for example, plans the construction of a series of 50 MW(e) hydroelectric stations along the Danube.) In spite of typically high per unit generation costs, transmission costs for small-scale facilities sited close to villages and small towns near rivers or high wind coastal areas may be lower than costs for electricity transmitted to these places from distant central grids. While the reliability of such sources might be a question, this should pose no serious problem for rural and agricultural requirements. By assuming that about half of the villages and small towns in the developing regions are sufficiently favorably located, one can roughly estimate the possible supply from small-scale hydroelectric and wind sources—up to 80 percent of electric power needed for agriculture and as much as 60 percent of the electricity needs of villages (and 30 percent of that of small towns). These assumptions lead to small-scale hydroelectric and wind power supplying 6 to 8 percent of all electricity demand in 2030 in regions IV, V, and VI. However, there are many uncertainties underlying these estimates—the geographical distribution of populated areas,

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[i] This section reports on the work of A.M. Khan. For further analysis, see Khan (1980).

the financing and management of large numbers of decentralized facilities, cost economics, and so forth. Accordingly, these potentials are not incorporated explicitly in the supply schemes of the High and Low scenarios already described, but are assumed to be implicitly covered in the shares of hydroelectric power projected for the developing regions.

The possible share of biomass (wood from forests and plantations, agricultural and animal wastes) in meeting the substitutable fossil fuel demands in regions IV and V was considered in Chapter 16. It was estimated that if an aggressive policy is pursued in regions IV and V to make use of charcoal, wood, and biogas, by 2030 about 166 to 247 GWyr/yr of substitutable fossil fuel in region IV and 273 to 424 GWyr/yr in region V could be replaced by charcoal/wood or biogas—if a sufficient supply of these could be organized on a commercial basis. In addition to these it should also be possible to use charcoal in place of coke in steel making. Assuming that up to 60 percent of coke requirements of steel industries in regions IV and V in 2030 would also be met by charcoal, the total quantity of fossil fuel to be replaced by wood/charcoal would, by 2030, amount to 196 to 301 GWyr/yr of final energy in region IV and 259 to 433 GWyr/yr in region V. An additional 35 to 40 GWyr/yr of fossil fuel equivalent in region V could be met by biogas generation by 2030. These demand estimates have been incorporated in the supply scenarios as part of "renewables" supply (see Figures 17-2 and 17-3).

The estimated fuel production costs from organized harvesting of the natural forests, from plantations based on fast-growing trees, and from biogas plants are already quite competitive with the prices of some fossil fuels. Their costs may even gain an edge as fossil fuels become more scarce and their prices increase. However, the question is whether available resources of biomass could meet the above estimates of demand on a sustainable basis. The present land utilization patterns of different world regions are shown in Table 17-12. Developing regions IV and V both have relatively large resources of forests—extending over areas of the order of one billion hectares—while region VI has a meager 28 million hectare area covered under forests and woodland. The potential regenerative capacity of forests in these re-

Table 17-12. Distribution of population and land in 1975, by region.

Region	Population (10^6)	Arable Land[a] (10^6 ha)	Permanent Pastures (10^6 ha)	Forests and Wood Land (10^6 ha)	Other Land (10^6 ha)	Total Land (10^6 ha)
I (NA)	237	253	240	627	715	1835
II (SU/EE)	363	278	387	949	712	2327
III (WE/JANZ)	560	192	651	318	239	1400
IV (LA)	319	142	527	1071	374	2115
V (Af/SEA)	1422	456	710	963	1074	3203
VI (ME/NAf)	133	44	172	28	802	1045
VII (C/CPA)	912	141	359	201	450	1150

[a] Including area under permanent crops.
Source: FAO (1977).

gions, expressed in terms of average annual increment of dry wood above ground, is estimated at about 3.5 tons per hectare (Earl 1975). This gives a total annual regeneration of about 3.5 billion tons of dry wood with an energy content of about 2 TWyr in each of the two regions. Much higher yields of wood—6 to 30 tons per hectare and even higher (e.g., Earl 1975; Revelle 1979) may be obtained in energy plantations by raising specific varieties of fast-growing trees on marginal farm land. However, arable land in the developing regions is in short supply; the development of new land for energy plantations must be considered in direct competition with the additional land required to support the food needs of a rapidly increasing population. And the apparent and widely publicized problem of deforestation in these regions leaves little to spur hope of developing energy-producing forests.

In view of these difficulties and those of access, transportation, management, and environmental safeguarding, it is assumed that by 2030 no more than about one-third of the forest areas in regions IV and V could be harvested for energy purposes. Moreover, since wood is also not a convenient fuel in industry or urban areas, most of available wood would have to be converted to charcoal—a relatively more transportable fuel, burned with an efficiency comparable to that of fossil fuels. As the conversion efficiency of wood to charcoal is about 45 percent (Earl 1975), the forests in each of regions IV and V could supply a maximum of about 300 GWyr/yr of fossil fuel replacement. This would be quite adequate for meeting the charcoal/wood demands of region IV in both the High and the Low scenarios as well as the Low scenario demand of region V, but would need to be supplemented by some 150 GWyr/yr by plantation wood or some other means (e.g., crop residues) for meeting the High scenario demand of region V in 2030. If the entire remaining demand were to be met by plantations, the corresponding land requirements would be about 17 million hectares, which is equivalent to about 4 percent of the present arable land in region V.

Agricultural wastes in 1975 in regions IV and V from cereal production alone amounted to about 55 and 200 GWyr/yr (Parikh 1980; Revelle 1979). These figures could be perhaps 50 percent higher if residues from other crops and dung of cattle fed on pastures are also included (Revelle 1979). About one-third of all agricultural and animal wastes was probably used as a noncommercial fuel in these regions in 1975 (Parikh 1980). Over the next fifty years, agricultural production and the consequent usable wastes will likely increase by factors of three to five. Some of these farm and animal wastes will certainly be returned to the fields in order to maintain the soil quality, and some more may find nonenergy applications in industry—for example, as feed material in the paper and pulp industry. Still, if fossil fuels are scarce or if wood supply from forests is inadequate and/or if the plantations are undesirable—as may well be the case in region V—a significant fraction of the agricultural and animal wastes would necessarily become an important fuel source.

In Chapter 16, the requirements for biogas for rural households in region V were estimated as 35 to 40 GWyr/yr in 2030. This implies that by 2030

Table 17-13. Resource utilization[a] of renewable energy sources in regions IV (LA), V (Af/SEA), and VI (ME/NAf) in the High and Low scenarios.

	Maximum Production Capacity (GWyr/yr)	Capacity in 2030	
		High Scenario (GWyr/yr)	Low Scenario (GWyr/yr)
Hydroelectricity[b]			
IV (LA)	583	355	355
V (Af/SEA)	761	426	426
VI (ME/NAf)	68	12	12
Wood from Forests[c]			
IV (LA)	2090	704	458
V (Af/SEA)	1880	673	604
VI (ME/NAf)	55	0	0
Wood from Plantations[c]			
IV (LA)	NA	0	0
V (Af/SEA)	NA	340	0
VI (ME/NAf)	NA	0	0
Agricultural and Animal Wastes[d]			
IV (LA)	291-374	0	0
V (Af/SEA)	1054-1355	67	58
VI (ME/NAf)	98-126	0	0

[a] Commercial energy use only.

[b] The figures refer to primary energy equivalents at an efficiency of about 37 percent.

[c] These data refer to dry wood above ground; it is assumed in the scenarios that the harvested wood will be converted to charcoal with an efficiency of about 0.45 before it is used as a replacement of fossil fuels.

[d] The agricultural and animal wastes are assumed to increase by 2030 to 3.5 to 4.5 times the 1975 value. The commercial use of these wastes is assumed through biogas generation for which the conversion efficiency is taken as 0.60.

NA—Not available.

about 60 to 70 GWyr/yr of agricultural and animal wastes would be used for biogas production, assuming a conversion efficiency of 60 percent (Makhijani and Poole 1975). The charcoal/wood needs (150 GWyr/yr of fossil fuel replacement in the High scenario) not covered by forest biomass in region V may also be met by turning some agricultural wastes into pellets suitable for use as fuel in urban households and industry.

Table 17-13 reports both the assessed maximum production capacity in each of regions IV, V, and VI and the capacity used in the scenarios in 2030. These figures are within the potentials analyzed in a more global fashion in Chapter 6.

It is certainly not possible to prescribe an optimum allocation of biomass sources for meeting the future needs of developing regions. The supply scheme for region V considered here[j] envisages by 2030 an annual supply of

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[j] There are other approaches for using biomass energy that have not been considered here. For example, Brazil in 1976 produced about 0.2 GWyr/yr of fuel alcohol using sugarcane and intends to extend this activity to about 3 GWyr/yr by 1980 (Goldemberg 1979). This would require about 1

272 to 303 GWyr/yr of charcoal[k] from natural forests, 0 to 153 GWyr/yr of charcoal from plantations, and 35 to 40 GWyr/yr of biogas from agricultural and animal wastes. In region IV, biomass fuel supplies are assumed to come solely from forests, at levels of 206 to 317 GWyr/yr of charcoal by 2030.

CARBON DIOXIDE AND FOSSIL FUEL USE[l]

Large-scale exploitation of fossil fuels, as these scenarios project, carries with it the likely buildup of the carbon dioxide content in the atmosphere, and this carries possible implications for the globe's climate (see Chapter 10). Here, the carbon dioxide buildup resulting from the High and the Low scenarios is assessed.

The calculated carbon dioxide emissions into the atmosphere resulting from fossil fuel use in the two scenarios enter the global carbon cycle simulated by a model described in Niehaus (1976, 1978). The following calculations are based on a preindustrial atmospheric carbon dioxide concentration of 298 ppm (by volume), which increased to 335 ppm in 1978 (NOAA 1979). Biomass on land was assumed to grow by 10 percent until about the year 2000.

Estimates of global average temperature changes were taken from Augustsson and Ramanathan (1977). They calculated a nearly linear contribution from the weak bands and a leveling off contribution from the 15 μm bands, which sum to a total increase of the average global temperature in the lower troposphere of about 1.9 K for a doubling of atmospheric carbon dioxide concentration from 300 to 600 ppm. For polar regions an amplifying factor of about three to five times the average temperature would have to be considered.

The results for the High and Low scenarios are given in Figures 17-18A and 17-18B. It is estimated that by the year 2030 atmospheric carbon dioxide concentration would have increased to about 500 ppm for the High scenario and to about 430 ppm for the Low scenario. The temperature changes would then be about 1.1 K and 0.8 K, respectively, above the temperature level of 1967 by 2030, with all other climatic parameters held constant.

It is not yet possible to give a final evaluation of the consequences of such a change in global average temperature; it could result in shifts of climatic zones or rainfall patterns with implications for the world's food production. It is not even possible to give probability estimates of their occurrence or to add uncertainty bands to the concentration and temperature curves

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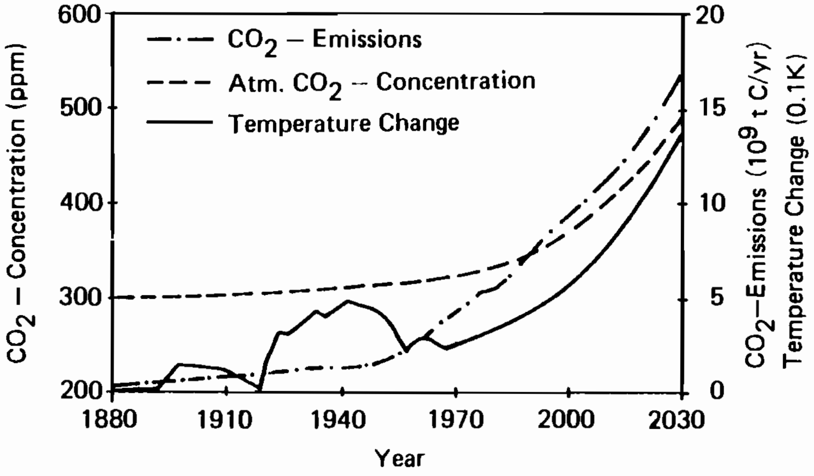
million hectares of arable land (i.e., about 3 percent of Brazil's present arable land area) and $2 to $4 billion of investment. However, in view of the uncertain cost economics of this operation and its strong competition with food production requirements of arable land, alcohol production at several tens of GWyr/yr scale is not considered a viable future option.

[k] Charcoal figures assume 5 percent losses in transportation. Both charcoal and biogas are then equivalent to primary fuels replacement.

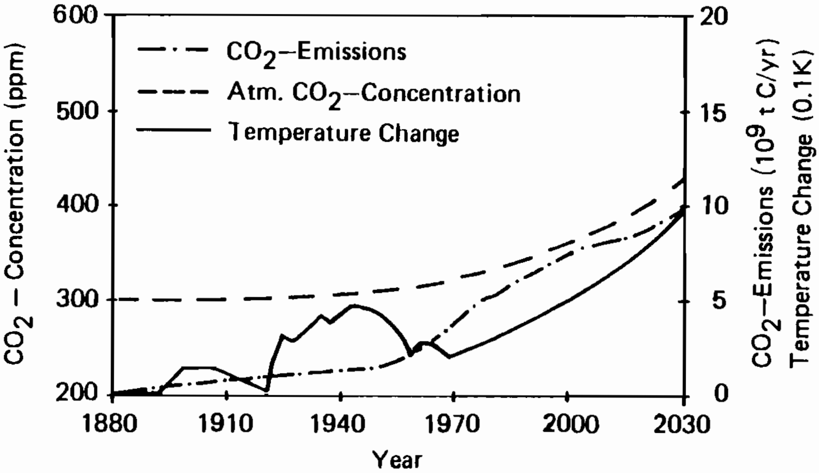
[l] This section is contributed by Friedrich Niehaus.

Figure 17-18. CO_2 emissions, atmospheric CO_2 concentration, and temperature change, High and Low scenarios.

A. High Scenario



B. Low Scenario



of Figures 17-18A and 17-18B. However, a comparison of the estimated changes with the historical trends in the northern hemisphere (Mitchell 1970) demonstrates the magnitude of this problem. Climate is not a stable system, and changes do occur. As has been shown by Flohn (1977), several rapid changes in the order of 2 to 4 K did occur in Central Europe over the past 20,000 years. The time constants of these changes were in the order of decades.

According to the estimates given here, it should be possible to detect a "carbon dioxide signal" before the turn of the century, if the present estimates of the greenhouse effect are correct.

The steep increases in carbon dioxide concentration in the year 2030 also demonstrate that the time period used for these calculations is much too short to evaluate the potential consequences of any large-scale exploitation of fossil fuels. It has been shown (Niehaus 1978) that if a signal were detected around the year 2000 and even if drastic steps were taken to reduce fossil fuel consumption, the atmospheric carbon dioxide concentration would still be expected to increase for at least another forty years.

The remaining rather disturbing uncertainties in this area demonstrate the urgent need for extensive and continuous research. The implications could be great, and the lead times for action are clearly long.

CUMULATIVE FOSSIL FUEL USE

The High and Low supply scenarios detailed here incorporate a number of nonfossil fuel energy sources. Yet as has repeatedly been pointed out, fossil fuel use in these scenarios remains high. Since there is, of course, a finite amount of such resources available for ultimate use, a fair question is: How much of the total resource would be consumed in the scenario projections?

The estimate of this study of total oil resources at costs less than $20/boe is 464 TWyr (327 billion tons or 2400 billion barrels of oil equivalent). This total includes some small amounts of shale resources, rather large amounts (at least 90 TWyr) of heavy crude oils, and much enhanced oil recovery. Of this total, the High scenario uses by 2030 some 317 TWyr (1630 billion barrels of oil equivalent); the Low scenario uses 264 TWyr. Of the assumed 373 TWyr of the unconventional, high cost ($25/boe) oil (mostly shale), only 4.4 TWyr are used in the High scenario, none in the Low scenario.

In Table 17-14 these cumulative oil figures are given, as well as those for natural gas and coal. The world is not running out of resources. But the world is running into expensive, difficult, unconventional fossil resources. We are running uphill and remain rather unsure of what is on the other side. For better or worse, it seems to be a large hill.

Table 17-14 shows that natural gas is not consumed, relative to the available resource base, nearly as much as oil. Only 66 percent of cheap category 1 gas is consumed by 2030 in the High scenario; only 16 percent of category 2 gas is used. This result points to the possibly vast potential for exploiting gas resources (perhaps to produce liquid fuels, as posed in the next chapter), as well as to the restricted uses and difficult transport of gas.

The world's coal resources would not be consumed very severely relative to their total availability. However, coal is produced in tremendous quantities in these scenarios, as has been repeatedly observed. This simply illus-

Table 17-14. Cumulative uses of fossil fuels, 1975 to 2030, High and Low scenarios.[a]

	Total Resource Available[b] (TWyr)	High Scenario		Low Scenario	
		Total consumed (TWyr)	Remaining resource (yrs)[d]	Total consumed (TWyr)	Remaining resource (yrs)[d]
Oil					
Category 1 + 2	464	317	21	264	40
Category 3	373	4	54	0	74
Natural Gas					
Category 1 + 2	408	199	35	145	76
Category 3	130	0	22	0	38
Coal[c]					
Category 1	560	341	18	224	52
Category 2	1019	nil	85	nil	158

[a] For definition of terms and categories, see Tables 17-6 and 17-7.

[b] Total resources, including to be discovered, as of 1975.

[c] Coal use includes coal converted to synthetic liquid fuels and gas.

[d] Number of years the remaining resource would last if it were consumed at the 2030 annual rate of fuel use and if it all came from the designated category.

trates the vastness of the coal resource and the contrasting difficulty of greatly expanded coal production. Even with plenty of coal resources available, there may be many compelling reasons for restraining its exploration, as illustrated by the carbon dioxide considerations of the preceding section.

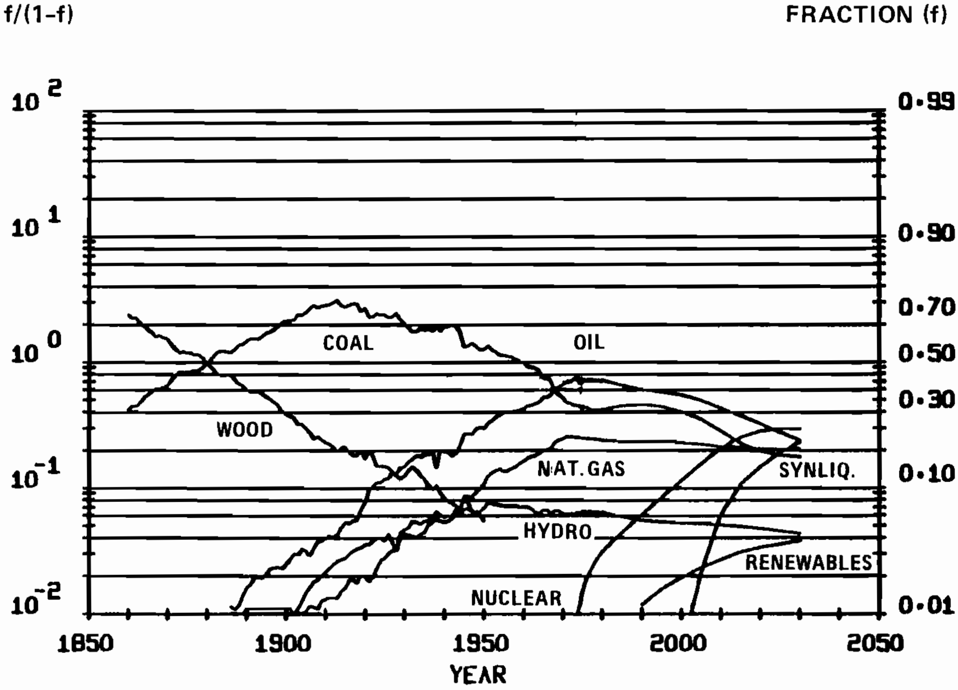
WHERE DO THE SUPPLY SCENARIOS LEAD?

Fifty years is a long time. In this period it is not likely, as shown in this chapter, that the world will "run out" of oil. Or as one energy analyst has put it, it is not so much that we are running out as that we are running. The pace of energy growth, coupled with its large global magnitude, challenges energy supply systems to keep up—even while total resources (perhaps at high cost) are quite abundantly available.

The supply scenarios detailed in this chapter have been built up through consideration of a great many possibilities and constraints. These inputs, based on work reported in earlier chapters of this book, were generated piece by piece and integrated only in these quantitative analyses, using the IIASA set of energy models. Having done this, it may be instructive to step back and look, from a quite different angle, at the total energy supply system development as postulated by the scenarios.

Figure 17-19 presents the scenario-generated global primary energy totals by source in "market penetration" terms (see Chapter 8). The logistic behavior of the market shares of primary fuels in the past is apparent. The decidedly nonlogistic behavior of the market shares of primary energy in the

Figure 17-19. Global primary energy market penetration, High scenario. Logarithmic plot of the transformation of f/(1-f) where f is the fractional market share. From 1860 to 1974 the substitution lines show historical data, from 1975 to 2030 the IIASA High scenario.



scenarios is also apparent. According to our scenarios, the observed market behavior of the past will not occur in the future. In fact, it may be somewhat startling to see the projections, plotted in this way, evidencing such a smooth, almost nondynamic character after all of the detailed wrenching constraints have been aggregated.

Does this imply that the scenarios postulate a violation of some intrinsic behavior or "rules" of energy systems? Does it convey a measure of how drastic are the changes (from the past) in the scenarios? Frankly speaking, perhaps. None of us is a prophet; none of us knows with surety that the logistic substitution process of the past is—or is not—a rigid system rule. But the changes from past behavior, clearly apparent in these projections, offer food for thought.

One mechanism for assessing the possibility of large changes to the High and Low scenarios is to test alternative cases and to perform sensitivity analyses. The next chapter does just this, in hopes of probing the system boundaries and generating insights into both possibilities and implausibilities in the world's energy future.

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18 ALTERNATIVES AND SENSITIVITIES

The High and Low scenarios detailed in the preceding four chapters are not, clearly, the only possible future states of the energy world. (In fact, one can be confident that the real outcome of events will be neither of these scenarios.) In this chapter, a selected few of a great many alternative possibilities are examined.

First, to recapitulate, the High and Low scenarios can be regarded as bounding the middle range of expected economic performance for the world: they are neither "extreme" nor "most likely" conditions. That is, while the structure of global energy systems would change markedly in the scenarios, the input assumptions and judgments underlying them are well within the mainstream of expert opinion. Practical constraints are imposed on resources, economics, information, organization, and technology. (For example, the energy technologies included in the scenarios are either in operation or in an advanced stage of development.) It would seem advisable to explore, at least tentatively, some radical departures from the accepted middle ground of opinion. This, in part, is the purpose of this chapter.

Roughly the same energy demands as in the High and the Low scenarios are used to examine two alternative supply cases through a series of MESSAGE model runs. (The alternative cases were also examined using the IMPACT model, as reported in Chapter 19.) These two alternative cases are specified so as to represent extreme poles of opinion—purposely to reach to the boundaries of conjecture, to pose wide choices, and to assess their consequences. These are labeled here as the "Nuclear Moratorium" and the "Enhanced Nuclear" cases and are defined and described below.

A third case explores the possibility that global energy demand might be very much lower than that projected in the scenarios. In particular, it examines the sorts of changes that would be necessary to bring zero or negative energy growth to developed market economies over the next fifty years (while maintaining the economic growth projection of the Low scenario) so as to have a global 16 TWyr/yr energy use in 2030. This "16 TW" case is also defined and described below.

Still other extreme variations on the scenarios are possible. Some sample "sensitivity" analyses, discussed later in this chapter, probe variations in results following extreme variations in assumptions. This is an attempt to focus on the main factors affecting global energy prospects in the long term and the conceivable global impacts of wide changes in these factors.

A word of caution is necessary for interpreting the results of these alternative cases and sensitivity analyses. The careful and detailed iterative adjustments performed for the scenarios (described in Chapters 13 and 14 and illustrated with specifics in Chapters 15, 16, and 17) have not been done for the cases and analyses of this chapter. That is, these extreme cases contain, inevitably, inconsistencies. They are not put forward here as fully analyzed and consistent cases, but as an instructive probing of limits. They are experiments. Nevertheless, they provide sufficiently interesting and revealing insights so as to be worth reporting here in relatively general and qualitative terms.

TWO ALTERNATIVE SUPPLY CASES

At least two broad and polarized views on future energy supply problems exist today. One view maintains that nuclear energy is unsafe, uneconomical, and/or unnecessary. Another view contends that with long-term oil replacement as the highest priority, nuclear energy—not nuclear energy solely for electricity production—can be called upon to contribute to liquid fuel supply. One view would put a stop to expansion of nuclear capacity (or, at an even greater extreme, close down all existing capacity); the other would accelerate nuclear growth.

The energy supply system implications of these two perspectives are sketched here. First, Table 18-1 summarizes the main defining parameters of the two cases—Nuclear Moratorium and Enhanced Nuclear. The Nuclear Moratorium case is based generally on the Low scenario, [a] with the additional constraint that no new (post-1979) nuclear capacity is ordered. To accommo-

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[a] Advocates of "no nuclear" energy futures generally cite the complementarity and consistency of this with low overall energy growth—that is, greater energy conservation and efficiency of energy use. A nuclear moratorium case with higher total energy demands would simply place even greater pressure on fossil fuel supply.

Table 18-1. Summary definition of two alternative supply cases.

Assumptions	*Nuclear Moratorium Case (based on Low scenario's demand)*	*Enhanced Nuclear Case (based on High scenario's demand)*
FBR[a] buildup	None	1995 onwards (all regions)
LWR[b] buildup	No new installations	Same as High scenario
Oil production limits	Higher than Low scenario	Same as High scenario
Coal production limits	Higher than Low scenario	Coal consumption is "minimized"
Centralized solar electric (STEC)	2000 onwards (all regions)	Unchanged

[a] Fast breeder reactors or other advanced converter reactors.

[b] Light water reactors or other conventional reactors.

date this, the Nuclear Moratorium case allows (by assumption) higher fossil fuel annual production rates than the Low scenario (including higher ceilings on regional coal production) and allows an earlier buildup of centralized solar electricity generation.

The Enhanced Nuclear case is based generally on the High scenario, with a somewhat tighter constraint (by assumption) on fossil fuel supplies (particularly coal) and with a somewhat earlier introduction of breeder reactors. The two cases are further defined and some results are presented in the pages to follow.

The Nuclear Moratorium Case

In spite of the intent in this chapter to confine attention to global aggregate results, certain regional characteristics help to illuminate global phenomena. For example, a nuclear moratorium in the future would almost certainly have its greatest impact in the developed regions (I-NA, II-SU/EE, and III-WE/JANZ), where nuclear energy's contribution is expected to be the largest.

In the developed regions in the Nuclear Moratorium case, annual coal production is allowed to rise to levels of the High scenario (see Table 17-10). This, it turns out, is not a sufficient supply of coal to completely replace nuclear electric capacity, so the balance must be met by central station solar facilities ("hard" solar). By 2030, some 6 percent of total primary energy could come from central solar facilities; this figure matches the maximum penetration rate assessed in the hard solar option (Chapter 5). In the Low scenario, hard solar would not contribute at all to primary energy needs before 2030.

The overall energy supplies for the Nuclear Moratorium case and for the Low scenario are presented in Table 18-2. Coal and solar fill mostly the "nuclear gap"; gas and, especially, oil may have limited capacity for expansion over the Low scenario estimates. Yet natural gas could hold a greater potential for contributing to the liquid fuel problem than is reflected in the Nuclear Moratorium case.

Table 18-2. Primary energy, Nuclear Moratorium case and Low scenario, 2030 (percent of total primary energy).

Energy Form	*Low Scenario*	*Nuclear Moratorium Case*
Coal	29	39
Oil	22	24
Natural gas	15	20
Nuclear	23	
Hydro-geothermal	7	7
Solar and other renewable sources	4	10
Total	100	100

A methane-to-methanol scheme[b], for example, could unlock what are thought to be vast natural gas resources in many regions of the world as a substitute for tight oil supplies. This would be quite apart from simply expanded gas trade—liquefied natural gas (LNG) for example—where the real constraint is thought to be rather limited end use markets for gaseous fuels (see Chapter 16). But gas as a source of liquids more closely meets the market needs. A possible boost to such uses of gas may come if coal production limits are lower than assumed here (with consequently less coal available for liquefaction); this prospect would seem to be quite plausible.

Fossil fuel consumption figures show coal uses increasing significantly from the Low scenario to the Nuclear Moratorium case, with gas uses growing only moderately. Oil production is already near conceivable upper limits in the Low scenario, so little additional capacity can be called upon for the Nuclear Moratorium case. These upper limits (see Chapter 17) are based on price-production profiles and (very generally) on the ability of economies in a low growth scenario to support the requisite investments.

The sources for electricity generation, with no new nuclear capacity, shift moderately among load regions. Coal-fired plants, which would operate in the peak and intermediate load regions in the Low scenario, would take over the nuclear baseload share in the Nuclear Moratorium case. Solar and gas would then provide peak load power.

Coal inputs to power production would be so great under the conditions of the Nuclear Moratorium case that the coal available for liquefaction would actually be less than in the Low scenario—in spite of raised coal production limits in the Nuclear Moratorium case. As a result, the share of synthetic liquids from coal in liquid fuel supply drops from 39 percent (Low scenario) to 33 percent (Nuclear Moratorium case) by 2030.

The amounts of fossil resources remaining in 2030 in the Low scenario and the Nuclear Moratorium case (Table 18-3) show the effects of the larger

[b] Such technologies are coming increasingly under discussion. Still, their technical and economic feasibility remain in some question, and their politics are no less certain. (Most of the world's natural gas resources are in the Middle East.)

Table 18-3. Fossil fuel consumption, Nuclear Moratorium case and Low scenario.

Resource Type and Cost Category[a]	*Low Scenario*	*Nuclear Moratorium Case*
A. Percent of Original Resources Remaining at 2030		
Coal		
Category 1	65	44
Category 2	100	100
Oil		
Category 1	21	14
Category 1A	24	27
Category 2	86	90
Category 3	100	100
Gas		
Category 1	51	32
Category 2	96	96
Category 3	100	100
B. Years of Resource Remaining After 2030 (expressed in 2030 annual production rate)		
Coal		
Category 1	52	30
Category 2	158	136
Oil		
Category 1	11	7
Category 1A	2	2
Category 2	27	25
Category 3	62	54
Gas		
Category 1	30	15
Category 2	39	28
Category 3	38	27

[a] Cost categories represent estimates of costs at or below which the stated volume of resources are recoverable (in constant 1975 US$).

For oil and gas:	Cat. 1:	12$/boe
	Cat. 2:	12-20$/boe
	Cat. 3:	20-25$/boe
For coal:	Cat. 1:	25$/tce
	Cat. 2:	25-50$/tce
For uranium:	Cat. 1:	80$/kgU
	Cat. 2:	80-130$/kgU

A subcategory of oil, 1A, exists only for regions I (NA) and IV (LA) and includes oil available at production costs of $12 to $16/boe. Also, a subcategory of gas, O, exists only for region VI (ME/NAf), with gas available at $2/boe.

fossil consumption of the latter case: resources are seriously depleted, leaving uncomfortably small amounts for post-2030 needs. Time, then, becomes an increasingly constraining factor in this case. Time is required to develop an acceptable, large-scale energy source. If no nuclear capacity were to be built in the coming decades, it may be that fossil fuels would be consumed too rapidly and that the time to develop viable substitutes would be too short.

One observes two main features of these Nuclear Moratorium case results. First, primary energy needs can be met without new nuclear capacity (for a low energy demand). Fossil fuel supplies would be depleted more alarmingly, solar electric would expand at its maximum rate, gas would become a more important fuel of the future (with even greater potential)–but needs could be met. In this context, nuclear power is seen to be not an absolute necessity. But, second, the price is great. Large-scale exploitation of fossil fuels carries environmental, climate, cost, and social burdens. These could be critical. The choices are not easy ones.

The Enhanced Nuclear Case

By allowing a more rapid buildup of nuclear energy supplies than in the High scenario, and by further constraining coal production limits, one can construct another alternative case–an Enhanced Nuclear case. The intent is to introduce nuclear energy at its maximum possible rate–a rate calculated and discussed at some length in Chapter 4 in order to use the generated heat to produce a liquid fuel. This alternative case, then, provides a direct link to the more global limit-probing arguments of Part II of this book.

This expanded nuclear option, which is elaborated in Chapter 4, is conceived as a long-term scheme to make use of an essentially infinite heat supply (from nuclear breeders and/or advanced converter reactors such as high temperature reactors [HTRs]). This heat source could generate hydrogen–through electricity generation and then electrolysis–or directly through thermolysis. The hydrogen could be combined with coal to produce methanol. Thus, breeders could be a source of liquid fuel. This option would be particularly attractive since it would use coal much more efficiently than otherwise for producing synthetic fuels (see Chapter 22 on new old technologies). Such a coal-efficient technology is specified for the Enhanced Nuclear case and is described in Figure 18-1.

The source of heat could, in theory, as easily be the sun as breeder reac-

Figure 18-1. An assumed methanol production technology (schematic) for the Enhanced Nuclear case.

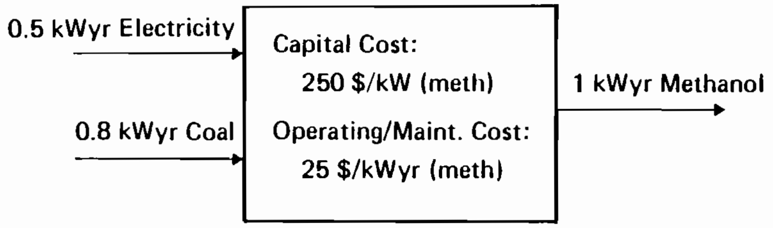

Table 18-4. Primary energy, Enhanced Nuclear case and High scenario, 2030 (percent of total primary energy).

Energy Form	*High Scenario*	*Enhanced Nuclear Case*
Coal	34	29
Oil	19	17
Gas	17	17
Nuclear	23	29
Hydro-geothermal	4	4
Solar and other renewable sources	4	4
Total	100	100

tors. Large, methanol-producing solar facilities in the deserts can be conceived (see Chapter 5). The point here is not to choose between the natural heat "endowments" of breeders or the sun, but simply to envisage a large-scale, sustainable, liquids-producing system.

In addition to supplying an alternative source of liquids, the Enhanced Nuclear case seeks to minimize fossil fuel production in general and coal production in particular. In spite of the increased nuclear capacity in this case, global coal production would be reduced by just 2 TWyr/yr by 2030. This coal production is not unimportant. And the modest size of the reduction somewhat conceals the rather dramatic changes in global coal trade. A reduction of 500 to 1000 million tons per year of coal production and export from each of regions I (NA) and II (SU/EE) could be seen as a major benefit of a regional enhanced nuclear strategy for the otherwise coal-importing region III (WE/JANZ).

The Enhanced Nuclear case increases the role of nuclear energy to 29 percent of total primary energy supply by 2030, compared to 23 percent for the High scenario (see Table 18-4). This seemingly modest increase is all but that; it means very roughly an additional 1000 GW(e) of installed nuclear capacity by 2030. These extra 1000 (or so) power plants need to be sited, built, and integrated into national grids. The analyses of the nuclear option (Chapter 4) indicate that, globally, this expansion (and more) could be done. But regional and national singularities would make the task a challenging one.

The unsettling depletion of fossil resources apparent in the scenarios and in the Nuclear Moratorium case is just slightly abated in the Enhanced Nuclear case. Table 18-5 shows that this case would stretch cheap (category 1) coal resources by just six years, more expensive (category 2) coal by eight years. Gas resources are depleted somewhat faster in the Enhanced Nuclear case than in the High scenario, but their exploitation is in any case regarded as more market limited than supply constrained. The Enhanced Nuclear case adds some six years to the High scenario projections of resources remaining after 2030 for all four categories of oil taken together.

By 2030, the supply of liquid fuels in the Enhanced Nuclear case would

Table 18-5. Fossil fuel consumption, Enhanced Nuclear case and High scenario.

Resource Type and Cost Category[a]	*High Scenario*	*Enhanced Nuclear Case*
A. Percent of Original Resources Remaining at 2030		
Coal		
Category 1	43	51
Category 2	100	100
Oil		
Category 1	11	11
Category 1A	2	1
Category 2	76	81
Category 3	99	99
Gas		
Category 1	39	36
Category 2	84	81
Category 3	100	100
B. Years of Resource Remaining After 2030 (expressed in 2030 annual production rates)		
Coal		
Category 1	18	24
Category 2	85	93
Oil		
Category 1	4	5
Category 1A	0	0
Category 2	17	20
Category 3	54	47
Gas		
Category 1	15	12
Category 2	20	18
Category 3	22	22

[a] For definition of cost categories see footnote to Table 18-3.

be a mix of crude oil, methanol, and synthetic liquids produced from coal using the more "conventional" technology of Chapter 17. Methanol would replace a fraction of the liquid fuel supplies of the High scenario. Instead of secondary liquid fuel demand being met 39 percent by synthetic liquids from coal and 61 percent by crude oil (mostly unconventional) as in the High scenario, the liquid fuel demands of the Enhanced Nuclear case would be supplied 31 percent by synthetic liquids from coal, 55 percent by crude oil (mostly unconventional), and 14 percent by the nuclear-based methanol technology. This case, then, could be seen as a way of speeding the transition away from depletable, nonrenewable crude oil (and coal) and toward some sustainable source of liquid fuels (assuming that the coal needed for methanol production would last a very long time). In a sense, the point of the Enhanced Nuclear case is the phase-out of fossil fuels. The idea here is to exploit capital-intensive, expensive technologies in order to build up a stock (or "endowment") of plutonium (if breeders are the source of heat) that could be drawn upon later.

Methanol in the Enhanced Nuclear case is generated by using off-peak electricity from nuclear breeders. This process allows looser constraints on the maximum fraction of nuclear in total electricity generated, for reasons of load curve characteristics. Nuclear in this case provides as much as 75 percent of all electricity generated. Methanol is assumed to compete economically with coal liquefaction only if off-peak electricity is used as an input. This assumption matches the need for the methanol introduction process to be a slow one—so that energy end use technologies can adjust to using methanol rather than conventional hydrocarbons.

As with the Nuclear Moratorium case, there are perhaps two main features of the Enhanced Nuclear case results. First, one observes that nuclear capacities could be expanded beyond the High scenario estimates and could contribute to the liquids supply problem—pending, of course, the successful development and commercialization of the methanol-producing technology postulated here (Figure 18-1). That is, the gradual buildup of an energy endowment seems to be possible—with all of the caveats about costs, technologies, politics, and other uncertainties.

Second, one observes that this endowment-creating potential could not be as large, by 2030, as one might hope. Nuclear sources would contribute some 29 percent of total primary energy by 2030 and not 40 percent as proposed in Chapter 4. The reasons are legion and have to do with constraints in each region on expected nuclear buildup, availability of cheaper alternatives, and so forth. Global projections of "maximum potential" capacity miss these regional considerations. (For example, the methanol from breeders option may be a very attractive one for region III but less so for coal-rich regions I and II or, particularly, for oil-rich region IV.) Still, 14 percent of liquid fuel supply from an "endowment" source is not inconsequential; it could signal the start of the inevitable transition toward sustainable energy supplies.

The analyses of the two alternative cases can be expanded by considering their investment requirements and comparing these with the High and the Low scenarios. This is done, using the IMPACT model, in Chapter 19.

Other alternative supply cases could be evaluated in the same way as is done here. This requires time. For now, it was thought to be a sufficient minimum to explore and discuss the two polar Nuclear Moratorium and Enhanced Nuclear cases. These extremes may lead, in future IIASA research, to consideration of other, more plausible, alternatives.

AN ALTERNATIVE DEMAND CASE: "16 TW"

Energy supply systems for the scenarios of Chapter 17 or for the alternative supply cases just discussed would be impressively difficult to build. Repeated mention in these pages of the challenges of expanding oil production or coal mining or the synthetic fuels business would lead the skeptic to wonder whether it could be done. While it is maintained here that indeed it could be done—that the necessary energy supply systems could be established—it seems worthwhile to consider a popular and increasingly plausible alternative to large supply schemes—namely, much lower energy consumption than the scenario projections.

Lower energy demand, of course, would ease the pressure on energy supplies. It would also somewhat ameliorate the environmental impacts of ever-increasing energy use, and (perhaps most compellingly) it would offer a bonus of time—time to develop oil alternatives or to discover some viable and sustainable energy source. Lower energy demand, therefore, is worth exploring. Yet one wonders, Is it feasible in the context of continuing global economic growth? What measures would be required to drastically reduce energy consumption growth over the next five decades?

The case examined here was proposed by Dr. Umberto Colombo, a member of the Club of Rome and director of the Italian Atomic Energy Commission. In response to a preliminary presentation of IIASA results (Häfele and Sassin 1979), Colombo (Colombo 1978; Colombo and Bernardini 1979) proposed an alternative scenario—a simple doubling of global energy demand from some 8 TWyr/yr (1975) to some 16 TWyr/yr by 2030. (This proposed doubling of global primary consumption compares to the scenario increases of factors of 2.7 and 4.3 by 2030.) With a doubling of population in the same period, this would lead to a constant global average energy use per capita. But of course, the energy use distribution around the world would change.

In this section, the 16 TW case initiated by Dr. Colombo is evaluated using the MEDEE-2 model (see Chapter 16). The intent is to describe, in modest detail, the sorts of changes required in order to have a 16 TWyr/yr world by the year 2030. This case is presented with somewhat greater specificness than the alternative supply cases just described. This is not necessarily because the 16 TW case is thought to be more plausible or more important, but rather because of the many and inescapable details of energy consumption. The focus is on the demand side.

Definition of the Case

The major premise of the low energy growth (16 TW) case, as specified by Dr. Colombo, is that requirements for energy in the developed regions would saturate—as economies mature and population growth rates decline—while energy growth in developing regions would continue to increase—although it may be slowed there by resource availability difficulties. The next fifty years would be the critical period, after which global energy use may well stabilize.

This hypothesis stems from "general" considerations dealing with the nature of technological development and its effects on the economy and society and not from a detailed modeling exercise.[c]

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[c] This argument is made in explicit terms in Dr. Colombo's specification of the case in a communication to W. Häfele, 13 October 1978.

Table 18-6. Assumptions on GDP growth rates, 16 TW case and IIASA scenarios (percent/yr).

Region	*High Scenario (1975-2030)*	*Low Scenario (1975-2030)*		*16 TW Case*[a] *(1975-2030)*	
I (NA)	2.87	1.68	2.09	1.70	2.00
II (SU/EE)	3.91	2.99		2.37	
III (WE/JANZ)	2.93	1.88		2.04	
IV (LA)	4.37	3.48	3.24	3.94	3.84
V (Af/SEA)	4.32	3.27		3.34	
VI (ME/NAf)	5.09	3.57		4.79	
VII (C/CPA)	3.77	2.64		3.44	
World	3.44	2.37		2.50	

[a] *Source:* U. Colombo communication to W. Häfele, 13 October 1978.

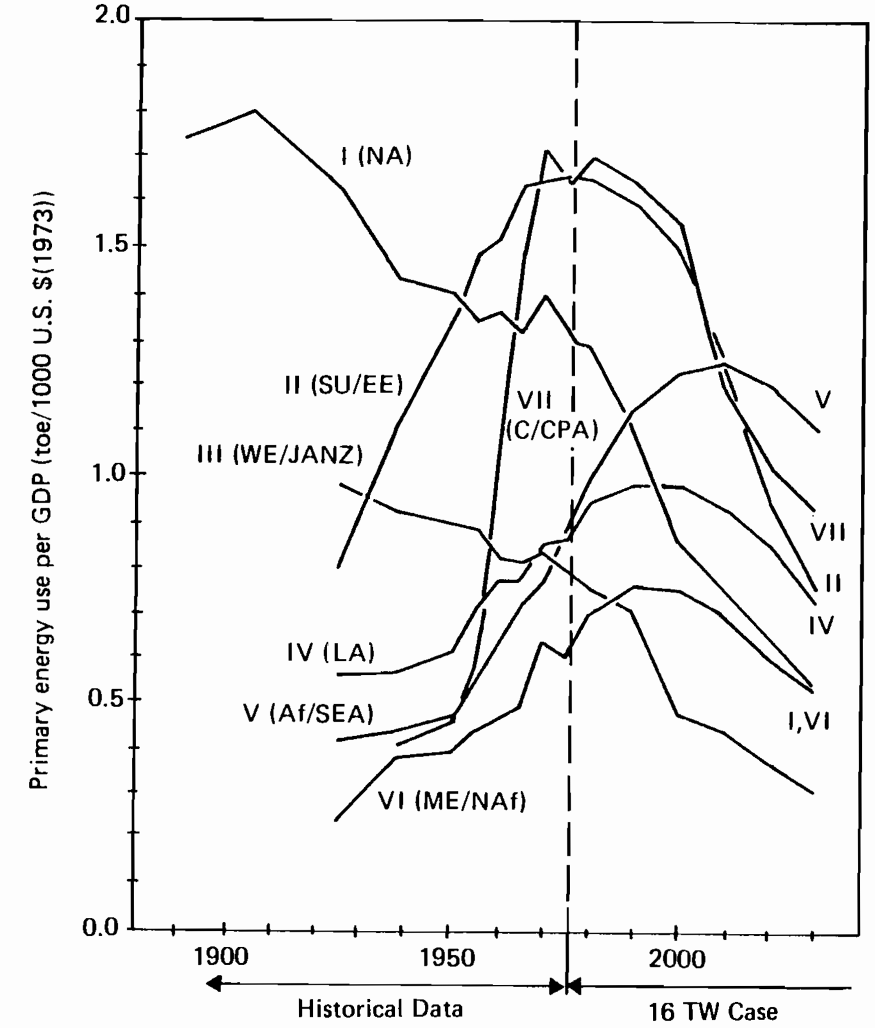
Notes: Figures are average real GDP growth rates over the period 1975-2030. The IIASA scenarios assume declining growth rates; the 16 TW case assumes constant average growth rates over the fifty-five-year period.

The population projection for the 16 TW case is identical to that for the High and the Low scenarios (see Table 14-2). The GDP assumptions differ only slightly between the 16 TW case (Colombo definition) and the Low scenario, as Table 18-6 illustrates. One notices a somewhat greater economic growth assumed for developing regions in the 16 TW case than in the Low scenario and a slightly higher overall global growth as well. But it seems fair to say that the economy in the 16 TW case is, in general terms, like that of the IIASA Low scenario.

The 16 TW case presupposes a substantial decline in the energy-to-GDP ratio in the developed regions. Colombo contends that such decrease, however, does not depart from the historically observed trends—as Figure 18-2 illustrates. For comparison, the IIASA Low scenario primary energy-to-GDP ratios are plotted in Figure 18-3. The higher ratios resulting from the Low scenario assumptions are evident; part of the difference in projections may be due to some apparent and troublesome differences in historical data (particularly for regions II and VII). Also, the region II projections for both the High and the Low scenarios may be relatively more optimistic in assumptions for the success of energy developments in this region than the projections for other regions.

The 16 TW case specifications from Dr. Colombo included regional primary energy use in 2030; these are compared with the Low scenario in Table 18-7. There, clearly the major differences in the two projections are in regions I, II, and III—the developed regions. The 16 TW case projects an absolute decline in energy use over the next five decades in these three regions. This characteristic is evidenced also in the primary energy-to-GDP elasticity, ϵ_p, in Table 18-8. (See Chapter 15 for the definition and discussion of this elasticity.) While the differences are significant for all regions, they are especially vast for the developed regions. In Dr. Colombo's words: "The basic assumption was that the future economic and social

Figure 18-2. Energy-to-GDP ratios in the 16 TW case for the IIASA world regions.



growth in the advanced countries will be largely based on technologies requiring very little energy consumption and characterized by high information-carrying capacity."[d]

Per capita primary energy consumption data, Table 18-9, offer a start to setting targets for MEDEE-2 runs. MEDEE-2 was used to study only regions

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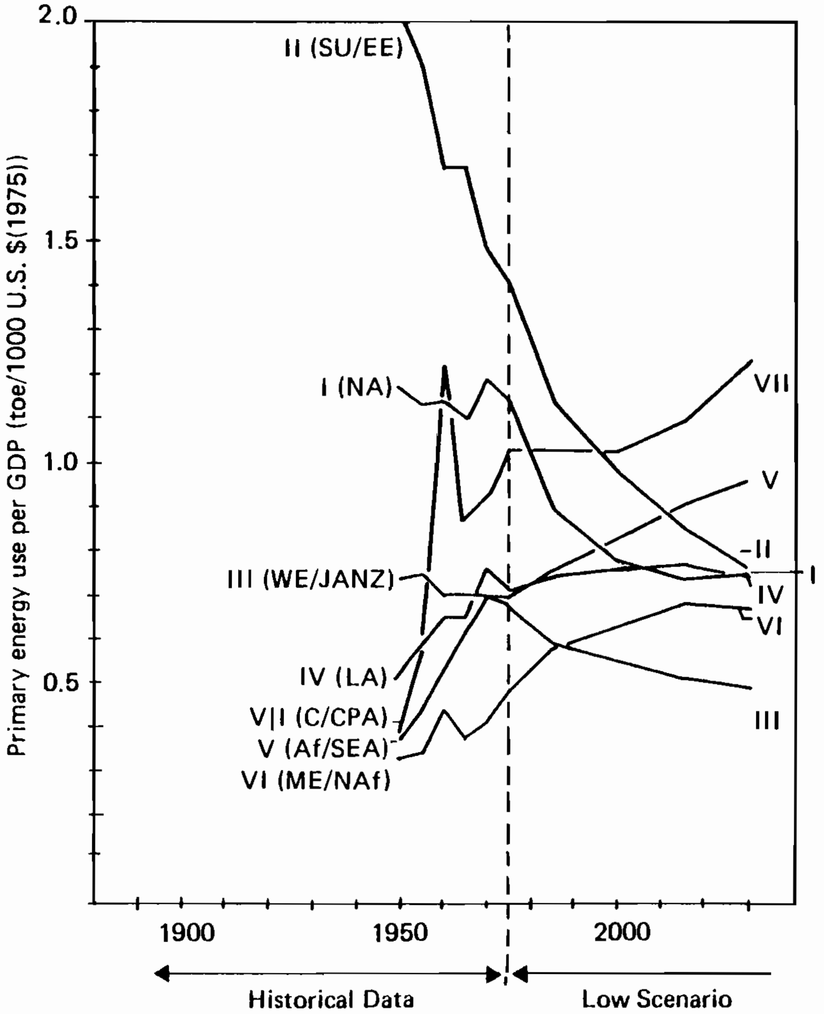
[d] Personal communication with W. Häfele, 13 October 1978.

Figure 18-3. Energy-to-GDP ratios in the IIASA Low scenario for the IIASA world regions.



I and III (together these regions are mostly OECD member countries) for the 16 TW case. Insufficient data for region II and, quite frankly, the extremely unlikely prospect of such low energy futures in this region (in the view of IIASA energy analysts) argued for concentrating on regions I and III. The differences for developing regions between the 16 TW case and the Low scenario were not thought to be sufficiently great to warrant MEDEE-2 analysis.

Table 18-7. Primary energy consumption in the IIASA scenarios and in the 16 TW case (TWyr/yr).

Region	*Base Year* *1975*	*Low Scenario* *2030*	*16 TW Case*[a] *2030*
I (NA)	2.65	4.37	2.52
II (SU/EE)	1.84	5.00	2.98
III (WE/JANZ)	2.26	4.54	2.45
IV (LA)	0.34	2.31	2.23
C (Af/SEA)	0.33	2.66	2.50
VI (ME/NAf)	0.13	1.23	1.27
VII (C/CPA)	0.46	2.29	2.05
Total	8.21[b]	22.39	16.00

[a] *Source:* U. Colombo communication to W. Häfele, 13 October 1978.

[b] This total includes 0.21 TW of bunkers—fuel used in international shipments of fuel.

Note: The Low scenario numbers came from the MESSAGE model analyses reported in Chapter 17.

Target Values

The 16 TW case specifies a global primary energy consumption of 16 TWyr/yr in 2030; of this, 5 TWyr/yr are specified for regions I plus III. The Low scenario projects a global primary energy consumption of 22.4 TWyr/yr in 2030; of this 8.9 TWyr/yr would be used in regions I plus III. Thus, of the global reduction of 6.4 TWyr/yr in 2030 from the Low scenario to the 16

Table 18-8. Primary energy-to-GDP elasticities, ϵ_p[a].

Region	*Historical* *1950–1975*	*Low Scenario* *1975–2000*	*Low Scenario* *2000–2030*	*16 TW Case*[b] *1975–2000*	*16 TW Case*[b] *2000–2030*
I (NA)	1.03	0.36	0.89	-0.20	0.06
II (SU/EE)	0.77	0.62	0.62	0.75	0.01
III (WE/JANZ)	0.96	0.65	0.73	0.04	0.10
IV (LA)	1.28	1.06	0.97	0.96	0.82
V (Af/SEA)	1.52	1.18	1.19	1.38	0.90
VI (ME/NAf)	1.20	1.23	1.10	1.04	0.75
VII (C/CPA)	1.57	0.98	1.27	1.12	0.54
World	0.99	0.67	0.93	0.50	0.34

[a] This elasticity, ϵ, is defined by the following relationship:

$$\frac{E(t_2)}{E(t_1)} = \left\{\frac{GDP(t_2)}{GDP(t_1)}\right\}^{\epsilon},$$

where t_1 and t_2 are two given times, E is energy consumption measured in physical units, and GDP is gross domestic product measured in real noninflated monetary units. This elasticity is calculated with respect to primary energy, ϵ_p.

[b] Derived from U. Colombo's specification of GDP and primary energy consumption growth (U. Colombo communication to W. Häfele, 13 October 1978) and is not consistent with methodology of IIASA scenarios.

Table 18-9. Primary energy consumption per capita in 2030 (kWyr/yr,cap).

Region	*Base Year 1975*	*High Scenario*	*Low Scenario*	*16 TW Case*[a]
I (NA)	11.2	19.1	13.9	8.0
II (SU/EE)	5.1	15.3	10.4	6.2
III (WE/JANZ)	4.0	9.3	5.9	3.2
IV (LA)	1.1	4.6	2.9	2.8
V (Af/SEA)	0.2	1.3	0.7	0.7
VI (ME/NAf)	0.9	6.7	3.5	3.6
VII (C/CPA)	0.5	2.6	1.3	1.2
World	2.1	4.5	2.8	2.0

[a]*Source:* U. Colombo communication to W. Häfele, 13 October 1978.

Note: The High and Low scenario numbers result from energy supply analyses reported in Chapter 17.

TW case, 3.9 TWyr/yr must come from regions I plus III. Analyses with MEDEE-2 can show the kind of detailed assumptions necessary to achieve such a reduction.

But MEDEE-2 calculates final, not primary, energy. And, MEDEE-2 accounts for a great many parameters, including a disaggregation of GDP. In Table 18-10 some final energy target values for MEDEE-2 runs are specified. Setting such targets necessitates some careful consideration of

Table 18-10. "Target" values for MEDEE-2 analysis of the 16 TW case.

	Region I (NA)		*Region III (WE/JANZ)*	
	1975	*2030*	*1975*	*2030*
Low Scenario				
GDP (10^9 1975$)	1670	4170	2385	6656
Primary energy (GWyr/yr)	2654	4367	2256	4542
Low Scenario (Modified)[a]				
GDP (10^9 1975$)	1670	4421	2385	7242
Primary energy (GWyr/yr)	2654	4400	2256	4760
Final energy (GWyr/yr)	1871	2656	1589	3143
16 TW Case				
GDP (10^9 1975$)	1670	4421	2385	7241
Primary energy (GWyr/yr)	2654	2520	2240	2424
Final energy[b] (GWyr/yr)	1871	1840	1589	1745
Difference Between 16 TW Case and Low Scenario (Modified)				
Δ Primary energy (GWyr/yr)		-1880		-2336
Δ Primary energy (percent)		-42.7		-49.1

[a] Using exactly the same GDP evolution as the 16 TW case but keeping all other assumptions identical to the Low scenario produces the Low scenario (modified).

[b] Only primary energy is specified by Dr. Colombo for the 16 TW case. To calculate final energy, losses from primary to final energy are assumed to be the same as for the Low scenario, except that no losses for coal liquefaction are included. This assumes that, because of the lower liquid fuel demands of this 16 TW case, no coal liquefaction would be required.

conversion losses, primary to final, and a careful specification of GDP. The intent is always to produce detailed assessments of the 16 TW case, being as true as possible to the Colombo definition of the case.

For comparative purposes, the Low scenario projections are modified by using the same GDP projections for regions I plus III as specified in the 16 TW case. This means that differences, cited below, between the "Low scenario (modified)" and the 16 TW case will be due solely to detailed MEDEE-2 input assumptions and not to differences in aggregate GDP growth rates.

To achieve the targets for the 16 TW case, primary energy consumption must be 43 percent lower in region I and 49 percent lower in region III than in the Low scenario (modified) by 2030. In the Low scenario (modified), losses from primary to final energy increase from 30 percent in 1975 (for both NA and WE/JANZ) to 40 percent in NA and 34 percent in WE/JANZ by 2030. For the 16 TW case, a reduction to 27-28 percent is expected as a result of lower electricity use and no requirements for high loss synthetic fuels. Thus, the final energy targets for MEDEE-2 runs are 1.8 TWyr/yr for region I and 1.7 TWyr/yr for region III by 2030. Detailed analyses yield results that are slightly below these target figures, as will be described in the next pages.

Assumptions and Results

In order to achieve these targets, changes to the Low scenario assumptions were introduced in several steps. First, electricity penetration into thermal uses was reduced or phased out completely (this was already rather restricted in the Low scenario); efficiency improvements were increased even further than in the Low scenario; the shift in the structure of GDP formation toward services, and within the manufacturing sector away from (energy-intensive) heavy industries and toward (less energy-intensive) construction of machinery and equipment, was accelerated, especially in region III; and finally, activity level projections were reduced, primarily in the transportation sector. These changes are listed in Table 18-11.

A great many changes were made in the Low scenario in order to reach the 16 TWyr/yr target values for regions I and III. Table 18-11 records only a few of them. They were selected so as to reflect, as much as possible, the current thinking on the most "reasonable" or most plausible mix of alterations that would lead to very low energy consumption in the future (see Leach et al. 1979).

In some cases, changes to important energy-using activities were rather modest because, it was felt, sufficiently aggressive changes were already introduced into the Low scenario. For example, automobiles were assumed to reach an average efficiency of 7.4 l/100 km (32 mpg) in region I by 2030 in the Low scenario from a 1975 average of 17.1 l/100 km (14 mpg); this projection to 2030 was unchanged for the 16 TW case runs. In region III, automobile efficiency was assumed to improve from about 9.9 l/100 km in

Table 18-11. Major assumptions for the 16 TW case, compared to the Low scenario.

	Region I (NA)			*Region III (WE/JANZ)*		
		2030			*2030*	
	Base year 1975	*Low scenario*	*16 TW case*	*Base year 1975*	*Low scenario*	*16 TW case*
Macroeconomics, lifestyle						
Manufacturing (% of GDP)	24.5	23.8	20.0	33.6	29.7	20.0
Services (% of GDP)	64.8	65.8	69.6	48.5	55.0	64.7
Basic materials (% of manufacturing–VA)	24.8	23.2	20.0	33.0	29.4	20.0
Machinery and equipment (% of manufacturing–VA)	43.2	47.0	50.2	42.0	47.1	55.0
Intercity passenger transportation						
Distance traveled per person per year (1000 km)	10	15	10	7.5	10	7.5
Persons per car	2.0	1.9	2.0	5.21	3.20	4.0
Distance driven per car per year, intercity (1000 km)	7.0	7.8	5.0	5.0	5.6	5.0
Bus (% of public transportation)	15	12	30	35	29	35
Train (% of public transportation)	5	5	20	50	56	60
Plane (% of public transportation)	80	83	50	5	15	5
Dwellings						
Electrical use for appliances (1000 kWh/dwelling)	3.85	6.25	3.85	1.95	4.50	2.20
Useful energy for air conditioning per dwelling (1000 kcal)	4472	5800	4472		3000	
Dwelling with air conditioning (%)	39	50	20	0	20	0

Note: These assumptions are selected from an array of changes. They both represent the largest changes and have the most energy-reducing impact. In some instances (e.g., automobile efficiency or home insulation) the assumptions for the Low scenario were regarded as sufficiently rigorous so that only rather minor further improvements could be introduced into the 16 TW case.

1975 to about 7.2 l/100 km in 2030 in the Low scenario and to about 5.5 l/100 km in the 16 TW case. Similarly, improvements in the technical efficiency of fossil fuel use from the Low scenario to the 16 TW case could not be too substantial, given the already high efficiencies assumed for the former.

Of course, no one really knows what are "reasonable" or "plausible" assumptions for future changes of these kinds. The intent in making judgments for the 16 TW case was to reach for the potentials for energy-reducing changes. One may (or may not) doubt the likelihood of such changes, but by all evidences they are possible. Such potentials are instructive—for example, one wonders what actions (energy price increases, tax benefits, early amortization allowances, and so forth) would be required to achieve such changes. (The answers could spur earlier and more vigorous measures than might otherwise occur.) But as has already been observed, such potentials may not be the wisest projections of energy demand for use in energy supply planning.

In Table 18-12, the final energy projections resulting from these changes are compared with the Low scenario projections, sector by sector. The household/service sector seems to be the least affected by changes. This is partly because insulation improvements were already extensive in the Low scenario, but also partly because of the reduction of electricity penetration assumed for the 16 TW case. The strong reduction in industry is primarily the result of two changes. First, the value added of heavy industries in these 16 TW case runs is assumed to grow only by a factor of 1.7 in region I and 1.1 in region III, instead of 2.3 and 2.4, respectively, in the Low scenario. Construction of machinery and equipment, on the other hand, would still grow by a factor of 2.4 in both regions, instead of 2.7 and 3, respectively, in the Low scenario, but the value added of the whole manufacturing sector is assumed to grow by only a factor of 2.1 in region I and 1.8 in region III, compared to 2.5 and 2.7, respectively, in the Low scenario. The assumption of a structural shift of GDP formation away from manufacturing toward services, and within the manufacturing sector away from heavy industries toward construction, machinery, and equipment, obviously has a significant impact on energy consumption. (To give a frame of reference: the energy intensiveness of heavy industry is about four to five times higher for electricity use and about eight to ten times higher for thermal energy use than the energy intensiveness of other industrial sectors.)

Table 18-12. Final energy results, 16 TW case and Low scenario (absolute figures are GWyr/yr).

	Region I (NA)				*Region III (WE/JANZ)*			
		2030				*2030*		
	Base year 1975	*Low scenario*	*16 TW case*	*% reduction*[a]	*Base year 1975*	*Low scenario*	*16 TW case*	*% reduction*[a]
Total final energy	1871	2656	1819	-32	1589	3143	1723	-45
By sector								
Transportation	541	688	410	-40	313	716	394	-45
Industry	757	1327	818	-38	805	1588	725	-54
Household-service	573	641	591	-8	417	839	604	-28
By fuel type								
Substitutable fossil fuels[b]	921	964	789	-18	801	1012	607	-40
Centrally supplied heat[c]	0	0	0	n.a.	0	103	68	-34
Soft solar	0	74	61	-18	0	71	46	-35
Electricity	228	547	265	-52	201	640	285	-55
Motor fuel	597	804	510	-37	381	864	518	-40
Coke and feedstocks	125	267	194	-27	206	453	199	-56

[a] Percent reduction is the reduction from the Low scenario to the 16 TW case, as a percentage of the Low scenario.

[b] Substitutable fossil fuels are substitutable (mostly heat) uses of oil, gas, and coal.

[c] Centrally supplied heat is heat produced by district heat and cogeneration facilities.

If this assumption were dropped and structural changes as in the Low scenario were assumed, primary energy consumption would be 300 GWyr/yr higher in region I and 670 GWyr/yr higher in region III in 2030. These are large amounts—some 16 and 29 percent of the total primary energy difference between the Low scenario and the 16 TW case by 2030.

The changes in assumptions concerning the transportation sector (the main ones of which are given in Table 18-11) result in a reduction of energy use (in terms of primary energy) of 270 GWyr/yr in region I and 250 GWyr/yr in region III by 2030. In region I, this difference is mainly attributable to changed assumptions on passenger transportation (135 GWyr/yr), international and military transportation (90 GWyr/yr), and freight transportation (50 GWyr/yr). The latter two components are of minor importance in region III, where the components contributing most to the total difference are again intercity passenger transportation (110 GWyr/yr) and urban passenger transportation (60 GWyr/yr); the remaining components are freight, international and military transportation (40 GWyr/yr), and fuel economy of cars (30 GWyr/yr).

Although the final energy projections for the household/service sector do not change drastically, assumptions of saturation of electricity consumption for specific purposes (lighting, refrigerators, freezers, dishwashers, etc.) at the 1975 level in region I, and only slightly above the 1975 level in region III, make up for 140 GWyr/yr and 330 GWyr/yr in regions I and III, respectively.

In sum, for the 16 TW case, the major factors that succeed in reducing energy use in regions I and III over the Low scenario projections are the following:

- Modifications in assumptions concerning energy use in all buildings save (in primary energy terms) 370 GWyr/yr in region I and 610 GWyr/yr in region III by 2030. In both regions, about 25 percent of this difference is attributable to technological improvements and 75 percent to a reduction of useful specific energy consumption.
- Electric energy intensiveness in manufacturing was assumed to decline by 10 percent and useful thermal energy intensiveness by 20 percent from 1975 to 2030 in the Low scenario and by 35–40 percent and 40 percent, respectively, in the 16 TW case. These changes account for 270 GWyr/yr of primary energy saved in region I and 280 GWyr/yr in region III—or about 65 percent of the combined effect of energy-reducing assumptions introduced in the manufacturing sector in region I and 70 percent in region III.
- Avoiding synthetic fuel production (and its conversion losses) accounts for 9 percent of the total primary energy difference in region I and 3 percent in region III between the Low scenario and the 16 TW case by 2030.

Table 18-13 offers a sector-by-sector listing of energy consumption, economic activity level, and energy intensity. Energy consumption is specified

Table 18-13. Comparison of sectoral energy consumption in the Low scenario and the 16 TW case (in terms of primary energy).

	Region I (NA)			*Region III (WE/JANZ)*		
	Base year 1975	*Low scenario 2030*	*16 TW case 2030*	*Base year 1975*	*Low scenario 2030*	*16 TW case 2030*
Freight transportation[a]						
Energy consumption (GWyr)	76	244	109	114	324	196
Activity level (10^{12} ton-km)	2.4	5.9	3.5	1.4	3.8	2.5
Specific energy consumption (kWh/ton-km)	0.28	0.36	0.27	0.69	0.75	0.68
Passenger transportation						
Energy consumption (GWyr)	431	508	251	217	496	204
Activity level (10^{12} passenger km)	4.1	7.4	5.6	5.2	10.7	7.9
Specific energy consumption (kWh/passenger km)	0.92	0.60	0.40	0.37	0.40	0.23
International and military transportation						
Energy consumption (GWyr)	78	264	107	24	80	56
Activity level (GDP, in 10^{12} \$75)	1.7	4.2		2.4	7.2	
Specific energy consumption (kWh/\$VA)	0.40	0.55	0.22	0.09	0.10	0.07
Agriculture, construction, mining, manufacturing[b]						
Energy consumption (GWyr)	1077	2076	1090	1171	2349	1008
Activity level (VA, in 10^{12} \$75)	0.5	1.3	1.1	1.1	2.9	2.2
Specific energy consumption (kWh/\$VA)	18.0	14.2	8.5	9.2	7.2	4.1
Of which: mining and manufacturing[a]						
Energy consumption (GWyr)	1007	1882	954	1091	2140	856
Activity level (VA, in 10^{12} \$75)	0.4	1.0	0.8	0.8	2.2	1.4
Specific energy consumption (kWh/\$VA)	21.6	16.4	9.9	11.9	8.7	5.2
Dwellings						
Energy consumption (GWyr)	680	968	643	617	1222	760
Population (10^6 persons)	237	315		560	767	
Dwellings (10^6 units)	79	141		187	300	
Specific energy consumption (10^3 kWh/person)	25.1	26.9	17.9	9.6	14.0	8.7
Specific energy consumption (10^3 kWh/dwelling)	75.0	60.3	40.0	28.9	35.7	22.2
Service sector						
Energy consumption (GWyr)	310	341	305	116	290	171
Number of workers (10^6 persons)	62	84	90	107	187	228
Floor area (10^9 m^2)	2.7	3.8	3.9	3.0	6.0	6.1
Specific energy consumption (kWh/worker)	43.7	35.5	29.6	9.6	13.5	6.6
Specific energy consumption (kWh/m^2 area)	998	788	681	340	423	243

[a] Excluding pipeline transportation.

[b] Excluding mining, refining, and conversion of energy products.

in terms of primary energy equivalent to avoid creating trends because of different fuel mix. The table shows that the Low scenario projects a significant decline of specific energy consumption in nearly all sectors. However, for the transportation sector, the shift to synthetic fuels projected in the Low scenario tends to increase the sector's energy intensiveness. In passenger transportation, the shift to synthetic fuels, coupled with an expected strong shift to automobiles (in region III) and to airplanes (in both regions I and III) leads to a reduction in energy intensiveness of only 35 percent in region I and to an increase of 8 percent in region III.

A decline in energy intensiveness in the manufacturing sector of 24 percent in region I and 27 percent in region III was projected in the Low scenario while a reduction of more than 50 percent would be required to reach the 16 TW case. The study by Leach et al. (1979) projects savings in final energy in manufacturing for the United Kingdom to be 22 to 35 percent by 2010, depending on the sector. Whether this is likely or not, and whether such potential savings really could be realized by the wide array of countries in the whole of region III (for example), is worth further study.

In the household and service sector, improvements in energy use have impacts only in region I, while energy intensiveness is expected to increase in region III. This development in region III is because of the region's nonhomogeneity: while one can expect a saturation effect like that in region I for the north and northwestern part of Europe, substantial improvements in living standards have to be achieved in the southern part, and it is this area that evidences the highest population growth.

A critical point raised in the 16 TW case is the projection of activity levels, for which a comprehensive view of the whole economy would be necessary. The assumed shift in the structure of GDP formation toward services can hardly be expected to occur simultaneously in all countries of such a macroregion, where a number of countries (e.g., Japan, the FRG, France) have to export manufactured goods to pay for raw material imports. Nevertheless, a final judgment on these scenarios could be made only if the costs of a reduction in energy use were compared with the costs of increased supplies. While this can be done for individual countries, it does not seem feasible for a still-evolving global energy study.

With this detailed presentation, an attempt was made to reveal some of the impressive dimensions of sharply reducing energy growth. All of the assumptions made here could occur; the question remains whether they will—or should—occur. But it is important, at least, to explore such a low future energy demand: the difficulty of energy supply underscored in Chapter 17 may lead the world to such a future.

SOME SENSITIVITY ANALYSES

At least one intent of the alternative cases presented thus far has been to provide some "sensitivity" insights. These have hopefully revealed a few of the consequences of changes in certain crucial assumptions. Yet the alternative cases described so far certainly do not exhaust the conceivable variations in crucial assumptions. Changes in other key inputs can be tested, and the sensitivity of results to such changes can be assessed.

Here, just three such "sensitivity analyses" are offered. They are posed as "what if" possibilities of alterations in assumptions.

- *What if* the ceiling on region VI (ME/NAf) oil production were to be much less (or much more) than assumed here, for example, because of political instabilities, vast new discoveries, or policy changes?
- *What if* technological breakthroughs in energy research (e.g., solar cells, fusion) were to occur?
- *What if* cost estimates for energy sources and technologies were significantly greater than assumed?

Obviously, any list of such questions could be indefinitely long. One is forced, then, to explore only a few examples—examples that offer important and generalizable insights. Together, the scenarios, the alternative cases, and the sensitivity analyses should build both a broad enough understanding of the vital characteristics of the energy problem and a set of sufficiently specific facts so that conclusions and recommendations for the energy transition can be formulated.

The sensitivity analyses to follow are not formal results of the complete, iterative, quantitative approach described in Chapters 13 through 17. Rather, they are largely the judgments of those who, through much experience with the formal analytical approach, have gained some insights into the sensitivity of results to changes in certain inputs. Therefore, these sensitivity analyses are best characterized as informed and experienced opinion, based on other quantitative analyses. They are illustrative, not conclusive. They should convey a "feeling" for the dimensions and texture of energy's future, rather than a prescription for its activities. And of course, these sensitivity analyses do not necessarily deal with events thought to be likely; they do deal with possibilities that are thought to be among the most instructive ones for analysis. The likelihood (or implausibility) of the events treated below is not a subject of discussion in this chapter.

An Altered Region VI Oil Ceiling

The High and Low scenarios of Chapter 17 are shaped in no small measure by a critical and admittedly highly arbitrary assumption—an annual oil production ceiling of 33.6 mbd (2380 GWyr/yr) for region VI (ME/NAf). This ceiling is exactly 50 percent greater than the 1975 oil production of this region and about 30 percent above their 1977 production rate. (The section entitled "The Special Case of Region VI" in Chapter 17 presents some of the reasoning behind this assumption.)

In one sense, the assumed ceiling on oil production is a small number. The resource base in the region could support a much higher production rate in the near term. Globally, demands may face higher production rates.

But in another (perhaps more realistic) sense, the assumed ceiling is a large number. Region VI would not reach the assumed ceiling (in response to rising world liquid fuel demands) until 2010 in the High scenario (2025 in the Low) and would have, after 2030, just eleven years of category 1 (<\$12 per barrel) oil remaining at 2030; they would have twenty-one years of category 1 oil left in the Low scenario. Another eleven years of production after 2030 could come from category 2 oil (<\$20 per barrel). But considering any reasonable reserve-to-production ratio constraints, it becomes clear that region VI's production would be forced rapidly downward from the ceiling rate—even before 2030 in the High scenario.

Also, it must be recognized that the region is, has long been, and will likely remain a politically unstable one. A number of possible terrorist actions, or national revolutions, or acts of political defiance could easily eliminate planned oil production increases. The events in Iran in 1978 and the resultant oil market dislocations of 1979 are a painfully obvious example.

The situation is highly uncertain. Thus, one is led to wonder, What if the oil production ceiling were lower than assumed? What would be the impact on global energy balances? What would be the replacement source of liquid fuels?

Assume a simple (and, on the face of it, small) 10 percent reduction in the previously imposed ceiling of 33.6 mbd, for a new ceiling of 30 mbd (2124 GWyr/yr). In the High scenario, this would extend the category 1 oil resource remaining at 2030 by a total of just over 4950 GWyr, or 25.5 billion (10^9) barrels. At the new production ceiling, this would mean just four years additional production from category 1 and no more than two years more from category 2. Yet even this requires oil production in region VI to increase by 15 percent over 1977 rates.

The reduced ceiling implies a shortfall of some 3.6 mbd of exports. What options would be available to fill the gap? In both scenarios, only regions III (WE/JANZ) and V (Af/SEA) would be net oil importers by 2030. Assume, first, that these two regions share the shortfall in proportion to their imports. Thus, region III would have to absorb 73 percent of the shortfall (or about 2.6 mbd) in 2010 and 46 percent (1.7 mbd) in 2030 in the High scenario. If the region III would (or could) increase its coal liquefaction to meet its share of the shortfall, this would require more than 330 million tons of additional coal production in 2010 and over 200 million additional tons in 2030. These increases over the High scenario coal production constraint of 1150 million tons for this region seem most unlikely. Indeed in the High scenario, region III would be a coal importer (1700 million tons in 2030) for liquefaction.

Region V (Af/SEA) is also unlikely to be able to expand its domestic coal production for liquefaction. Coal resources are probably not sufficient for growth above that of the High scenario, and the technological capability of the region to support such expansion may also be questionable. The region would need an alternative source for its liquids.

These considerations may lead regions III and V to turn to region I (NA) and/or region II (SU/EE) for extra coal-based liquid fuels. Coal resources in these latter two regions are more than ample. But High scenario production in the year 2030 would be 2.9 billion tons in region I and 3.8 billion tons in region II. The two regions might share the extra 458 million tons per year of coal required to fill the oil shortfall with synthetic liquids; but this extra production is nearly 75 percent of the total coal production in region I today.

Suppose such coal production (and export) increases in regions I and II were not possible. An alternative would be more higher cost, unconventional crude oil production outside of region VI. Perhaps this could be shale oil from region I—a required export of 3.6 mbd to meet the global shortfall. This would be the necessary increase over the High scenario oil production projections of 11.8 mbd (in 2030). Concerns about the environmental implications of large-scale shale production in the United States, coupled with uncertain economics, dim the prospects for such a solution.

Another potential non-region VI source of oil could be region IV. (LA). But in spite of large unconventional oil resources in this region, it seems unreasonable to expect the region to be a net oil exporter. The High scenario projects some 25.5 mbd of oil production in region IV by 2030 (from less than 5 mbd today), solely for internal use. It is unlikely that the region will want to expand production much farther or faster; too rapid expansion and income generation lead to economic and social instability and resource depletion.

Any answer to a lowering of the oil production ceiling for region VI would have to be a combination of partial solutions. And any answer would have some component of oil demand reduction, following the higher prices resulting from reduced region VI exports. The explanations of Chapter 16 and the explorations of the 16 TW case in this chapter illustrate the difficulties of further liquids demand reduction.

Yet the demand reduction possibility may be the inevitable one. If the 10 percent reduction in region VI oil production were applied to the Low scenario, for example, the new 30 mbd ceiling would be reached around 2020, just ten to fifteen years later than in the High scenario. This buys some time—time that should be used to develop the requisite oil alternatives and to shift uses more and more away from liquid fuels. But the Low scenario is also lower economic growth. This may inhibit rapid investment in and development of new sources.

And if the reduction in region VI oil production were more than the 10 percent postulated here, the situation for the world could be proportionately worse. One is left with speculation about how quickly the world could adapt to restricted oil supplies. Some measures of adaptation would surely be less difficult than others—and the preferred choices would vary from region to region. Still, it remains clear that there are no easy pathways under a low oil ceiling.

Technological Breakthroughs

What if technological breakthroughs in energy research were to occur? What if some new source of energy such as fusion or solar photovoltaic cells or a new liquids from coal (or garbage?) scheme were to become technically and economically attractive well before expected? How would the future energy paths so far described be redirected?

In Chapter 4 mention is made of the fusion option (see also Häfele et al. 1977). Even if fusion were commercially available as early as the year 2000 (an unthinkable notion to nearly all experts), it would likely only replace some foreseen nuclear fission electric capacity. (Fusion is planned as a source of electricity.) Even if it unexpectedly becomes available at modest costs, it seems implausible that any country would rapidly expand both fusion and fission power supplies. Thus, a fusion breakthrough would probably not alter the scenarios noticeably; one could simply replace "FBR" in the energy supply system graphs with "fusion" and perhaps modestly increase electricity demand estimates.

Solar technologies will, ultimately, provide a major—if not the major—portion of the world's energy needs (see Chapter 5). The solar estimates for the next fifty years in the scenarios assume the application of solar collectors for a certain fraction of the low temperature heat market. They also assume very optimistic costs for central station solar electric facilities. Yet direct solar technologies contribute a mere 0.3 to 0.4 TWyr/yr to total primary energy by 2030—not more than 1 percent of total demand. (Other renewable, solar-derived, technologies—biogas, wood, hydroelectric, and so forth—contribute somewhat more in the scenarios, so that all renewable (nonfossil, nonnuclear) sources would provide some 2 to 3 TWyr/yr or 8 to 10 percent of primary energy by 2030.) What if a technological breakthrough occurred to possibly increase this figure greatly?

If rapid technological advances do occur, as many experts expect they will, the relative contribution of high technology solar devices could be significantly greater than the scenario projections. Technological innovations and mass production techniques could be stimulated by government incentives. The overall scenario results might then change noticeably—but this would demand a careful matching of appropriate solar technology to appropriate end use market.

Solar cells, if conveniently—and relatively cheaply—produced, could replace many now stationary sources of energy and alter economic activities markedly. In particular, if such cells could be an attractive power source for transport (small urban automobiles, for instance), this could have an important effect on liquid fuel demand. And highly efficient solar conversion devices could conceivably penetrate the urban market, where presently solar collectors are all but excluded because of the high energy density requirements of tall buildings.

But one must consider "market penetration" constraints: How quickly could new solar devices contribute? (see Chapter 5). And one must consider the potential markets for each energy source, recognizing that consumers might be willing to pay a high price for assumed backup supplies to supplement primary solar devices. It is not clear that solar energy, even if suddenly much cheaper, could easily contribute much more than in the scenario projections. The best possibility may be the one already noted: photovoltaics offering a dispersed and mobile power source.

Any new technology that supplies an alternative liquid fuel to crude oil can substantially alter the scenario projections. Liquid fuels are the problem in the long term. If some process using wood or garbage (at least potentially abundant and renewable raw materials) could make a competitively priced liquid fuel, this would certainly lessen the pressure on oil supplies. Crude oil and the new source of liquids could then together help developing regions develop more comfortably; they could ease the requisite rapid buildup of new electricity generation facilities, and they could perhaps lessen the need for massive coal production (necessary otherwise as a liquids substitute or as a source of synthetic liquid fuel).

In short, some conceivable technological breakthroughs could ameliorate the liquid fuel dilemma, while others would attack the wrong problem. The sensitivity of scenario results to such possibilities is not easy to gauge; it seems most likely that the result would be simply the substitution of one new technology for one old, scenario-assumed technology. The new idea, if it is to significantly change the oil results, would probably have to contribute more than the coal liquefaction amounts—up to 4000 GWyr/yr (or over 55 million barrels per day) by 2030. And the new technology would need to produce liquid fuels far under $25 per barrel (1975 U.S. dollars) to compete with oil from shales. This would be a sobering challenge indeed for a technology not yet developed.

Escalations in Energy Costs

The costs of energy resources and of energy supply and conversion technologies used in the scenarios are based on a modest survey of existing studies. It may be that these cost estimates will be found to drastically understate reality; the world is not unused to rapid cost escalations even today. What then?

What if, for example, synthetic liquids from coal were to cost, say, $60 per barrel instead of the scenario estimate here of $21.50 per barrel (1975 U.S. dollars)? One (or both) of two things would happen. Either some alternative source of liquid fuel (e.g., oil from shales) would replace liquids from coal in the scenarios (and coal production would be reduced), or demands for liquid fuels would plummet as (less expensive) substitutes are found, or as consumers use less, or both. If, in general, alternatives to conventional crude oil are found to be much more expensive than anticipated, then one could expect increased liquid fuel conservation, shifts to electric modes of transport, and probably depressed economic growth rates. The High scenario growth rates, for example, would be quite unrealistically high.

In these broad considerations, the preference for synthetic liquid fuels from coal over oil from shale is moot. The scenario assumptions of Chapter 17 favor coal liquefaction; vast increases in coal production result. If, instead, oil shales were favored, then the exploitation of shale in the United States (for example) would replace the mining of coal, and the same export of synthetic liquid fuels as in the scenarios could occur. The environmental implications of both coal and shale production are severe. In either case, it would be a large, complex, and expensive undertaking to produce the liquid fuel.

Still, the globe's energy future is not insensitive to energy costs. If the costs of all sources were to grow in real terms, then, surely, there would be more serious impacts on economies than are assumed here. The international balances of trade and aid could easily be upset (one is tempted to observe that they already are); national development goals would not be met. This, to a certain degree, is a likely prospect: the economic growth rates of the scenarios were reduced from historical rates for just this reason. But the more instructive consideration, perhaps, is that of the possible variations among the relative price changes of new sources of energy.

Imagine three possibilities: (1) that all electricity generation costs doubled (in real terms); (2) that all fossil fuel production costs doubled; or (3) that both electricity and fossil fuel costs doubled. Number (1) perhaps reflects a currently popular view that nuclear costs, for example, are widely underestimated—or that, in general, the electricity generation technologies used in this study have too low cost estimates. Number (2), analogously, may represent the view that unconventional fossil fuels—whose cost estimates have continually risen in real terms—will ultimately be much more expensive than current estimates. With number (3) one can test both given prospects.

For sensitivity analyses of these three possibilities, select region I (NA). Take the High scenario year 2030 costs, escalate them according to the three possibilities, assume the same "add ons" of costs as in Chapter 15 to get final energy (consumer) prices, then use the implicit price elasticity (Chapter 15) of the High scenario to calculate the resultant implied changes in energy demands. The relevant figures for this simple analysis are given in Table 18-14.

Assumed electricity production cost doubling would reduce demand by 8.4 percent in 2030 from the High scenario, as Table 18-14 shows ("2030 demand factor" 0.916). Fossil fuel cost doubling would cut demand in 2030 by 18.2 percent, and doubling of all costs would reduce demand by almost 24 percent. These reductions, less than those of the 16 TW case described above, would surely ease the supply squeeze—with the extent of relief depending on how much of the savings would be liquid fuels.

One can debate the validity of such use of price elasticities. Still, the analysis does reveal that savings do not come easily beyond a certain point (i.e., there are a lot of savings already assumed for the scenarios). Rising prices may not be the panacea that many expect. Indeed, a sizable number of analysts contend that many conservation measures are cost effective now. It could be argued that the scenario assumptions of Chapter 16 concur with this. Even if energy savings beyond the scenario assumptions were to occur,

Table 18-14. Sensitivity analysis of energy supply cost assumptions.

		Production Costs 2030			
Energy Source	*GWyr/yr*	*High scenario ($/kWyr)*	*(1)[a] ($/kWyr)*	*(2)[a] ($/kWyr)*	*(3)[a] ($/kWyr)*
A. Region I (NA), High Scenario					
Fossil fuel	2832	117	117	234	234
Electricity	749	161	322	161	322
Total	3581	126	160	219	252

High Scenario Possibilities[a]	*Product Cost ($/kWyr) 2030*	*"Other" Costs ($/kWyr) 2030*	*Price ($/kWyr) 2030*	*Price (P) Relative to 1972*	$P^{-0.58}$[b]	*Demand[c] Factor 2030*
B. Prices and Demand Reduction						
	126	84	210	3.0	0.53	1.0
(1)	160	84	244	3.49	0.48	0.916
(2)	219	84	303	4.33	0.43	0.818
(3)	252	84	336	4.80	0.40	0.761

[a] Possibilities: (1) Assume all electricity production costs double in the High scenario. (2) Assume all fossil fuel production costs double in the High scenario. (3) Assume both (1) and (2) in the High scenario.

[b] ϵ_p for High scenario, region I is -0.58.

[c] 2030 demand factor is the fraction of primary energy in 2030 that would result from each possibility.

one should maintain an healthy skepticism about their potential in developing regions. Energy-saving measures often require sophistication—technical, political, and societal sophistication. In developed economies, large energy savings may be feasible; in developing economies, it seems much less likely. The world, under almost any conceivable circumstance, will face increasing demand for energy—and, more importantly, for liquid fuels.

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19 ECONOMIC IMPACTS: COMPARISON OF ENERGY SCENARIOS AND ALTERNATIVE CASES

Quantitative analyses of scenarios and alternative cases can go farther than the simple comparisons of Chapter 18. One can also evaluate the economic implications of these futures; to an extent Chapter 15 dealt with such evaluations, or interpretations, for the scenarios. But an additional consideration is the level of investments necessary for various energy projections. This chapter investigates the capital investments as well as the manpower and material and equipment requirements of the High and Low scenarios (Chapter 17) and of the Nuclear Moratorium and the Enhanced Nuclear cases (Chapter 18).

Capital investments may be particularly worth calculating if, as seems likely, energy supply systems become increasingly capital intensive. The projected growth in real energy production costs for the scenarios was described in Chapter 15. Indeed, the suspicion that energy may become increasingly capital intensive is based on observations of cost escalations of new sources of liquid and gaseous fuels. Table 19-1 offers some indicative costs that support this argument.

The shift to more capital-intensive energy sources would probably occur concurrently with expected increases in capital costs of many other resources. New technologies in agriculture and many industrial sectors also tend to be capital intensive. And capital would be required for environmental protection, particularly if present industrial practices of "fixing" pollution by add on technologies persist. All of these would compete for investment capital, which may thereby become a serious constraint on the rates of introduction

Table 19-1. Expected production and investment costs for sources of liquid and gaseous fuels (1975 US$).

Energy Source	*Production Cost ($/boe)*	*Investment Cost (10^3 $/boe/day)*	
		Liquid fuel	*Gaseous fuel*
Natural fuel			
Giant fields (Saudi Arabia, Libya, Algeria)	1-3	4-5.5	1.6-3.2
Relatively favorable conditions (present U.S. and North Sea deposits)	4-7	7.5-10	6.5-10
Unfavorable conditions and enhanced recovery (U.S. and North Sea deposits)	10-12	15-18.5	16-20
Extreme conditions (deep offshore and polar areas)	20-25	28-38	33-40
Synthetic fuel			
Tar sands, heavy oils	10-20	15-20	
Shale oils	15-25	19-26	
Coal liquefaction and gasification	17-28	20-29	19-26
Hydrogen (electrolytic)	> 25	> 100	> 70

Notes: The data for synthetic fuels include not only costs of conversion but also costs of primary energy production. Investment costs means constructor's plus owner's costs and includes the cost of refining. To reflect the uncertainties in cost estimates, figures are given here as ranges. Such uncertainties force judgments to rely more on criteria other than cost. They also imply that over reliance on purely economic models for finding "precise" or "optimal" energy solutions for forty to fifty years ahead is meaningless. Still, this does not diminish the utility of models as tools for exposing new trends and problems in energy futures.

of new energy sources. In short, it seems worthwhile and important to calculate all energy investments likely in the future.

Implementation of energy scenarios may face bottlenecks not only of shortages of capital but also of constraints of some other essential resources (manpower, raw materials, land, water). Therefore, in these comparisons of the scenarios and alternative cases an attempt is made to give rough assessment of their WELMM requirements. (WELMM analyses are described in Chapter 9.)

In this chapter, both direct and indirect requirements for energy supply systems of the future are considered. Direct requirements are energy system investments and WELMM needs. Indirect requirements refer to resources and investment requirements of nonenergy sectors, the additional development of which is induced by energy supply system development. For example, if a rapid transition to new capital-intensive energy sources were to occur, additional (indirect) investments in machinery, metallurgy, construction, and other energy-related industrial sectors could amount to 25 percent or more of direct investment in the energy supply system. (This assessment is based on work performed at the Siberian Power Institute and reported in Kononov and Makarov [1975].)

A word of caution: the numbers presented in this chapter should not be interpreted literally. Fifty-year economic analysis is a risky business. The studies here are intended simply to present some general and dominant trends and to search for order of magnitude estimates of future investment (and WELMM) requirements for energy supply systems. If anything, the numbers here may be too low; the discussion in Chapter 17 of cost estimation pointed to the assumption made here of constant (in real terms) capital costs for energy technologies and the admitted possibility that the assumed costs reflect resource and technological optimism that may yet prove to be unwarranted.

SOME INPUT ASSUMPTIONS

The primary tool used for these economic analyses is the IMPACT model. IMPACT describes dynamic production relations between the energy supply system and economic sectors that are particularly relevant to energy system development. (The IIASA version of the model includes fifty-eight energy activities and thirty-six energy-related sectors and aggregated kinds of materials and equipment.)

First, IMPACT evaluates the direct requirements of a given energy strategy in terms of investments for industrial goods and services. Then the model assesses the required additional development of energy-related sectors of the economy (taking into account exogenously given imports of equipment and materials). Finally, the model estimates investment in energy-related sectors—direct and indirect WELMM expenses. (IMPACT is described in Chapter 13 and in Kononov and Por [1979].)

Each activity is characterized in IMPACT by the following indexes:

- Input coefficients per unit of output (operation and maintenance requirements for materials, equipment, and services);
- WELMM coefficients (specific expenditures of water, energy, land, manpower, and some limited materials for operation and construction;
- Capital coefficients (material and equipment requirements per unit of new capacity or per dollar of capital investment);
- Incremental capital-output ratios (specific investment per unit of new capacity);
- Typical construction time and a pattern of lags between construction and completion of the plant.

In an energy-oriented model such as IMPACT, the accuracy required of the data for energy activities must be higher than that required of data for the energy-related sectors. Many different data sources were analyzed and used. The data received from the Bechtel Corporation (1978) were particularly valuable.

Yet one should not rely too much on cost data. A multicriteria approach to long-term economic problems is to be preferred to modeling approaches that seek "least cost, optimal" solutions.

A special task that had to be completed before IMPACT could be used was to evaluate the capital costs of extraction of different categories of oil, natural gas, and coal in different world regions, taking into account present marginal capital costs, known resources and their distribution by price category, anticipated time of exhaustion of these resources, and other factors. Some of these estimations are given in Table 19-2. The generalized material structure of the capital investments for fuels extraction is shown in Table 19-3. These figures were used for estimating corresponding capital coefficients in IMPACT.

Capital cost and other economic indexes for power plants and energy conversion technologies do not depend so strongly on local conditions as do the indexes for primary energy resources. Therefore, they were assumed to be identical for all regions and based on U.S. prospective data. The values used, as in the IMPACT model, are shown in Tables 17-4 and 19-1.

The evaluation of input-output and capital coefficients for energy-related sectors for separate world regions and for a perspective of thirty to fifty years can be, inevitably, only very rough and aggregated. It is impossible to obtain average regional indexes by means of conventional procedures because of the lack of corresponding information for all countries of each of the regions. Therefore, for each region, one representative country is selected, its coefficients are aggregated, and the results are then generalized for the entire region. Thus, for example, the United States was considered the representative country for region I (NA), the FRG for region III (WE/JANZ), and India for region V (Af/SEA).

Table 19-2. Capital costs of fuels used in the IMPACT model (1975 $/kW).

	Regions				
Resource Cost Category	*I (NA) and II (SU/EE)*	*III (WE/JANZ)*	*IV (LA)*	*VI (ME/NAf)*	*V (Af/SEA) and VII (C/CPA)*
Oil 1	110	135	130	35	110
1A	205	205	185	110	190
2	305	330	260	270	290
3	410	410	410		410
Gas 1	100	160	85	25	100
1A	280	315	250	80	270
2	455	455	420	250	435
3	665	668	665		668
Coal 1	32	74	70		37
1A	74	150	95		74
2	160	225	190		115

Note: These resources are defined in Tables 17-6 and 17-7. They cover fuel resources from present marginal production cost (category 1) to $25/boe (category 3). The regional differences in capital cost of the same resource categories reflect differences in known resources, present capital cost of their extraction, and time of exhaustion of given resource category (in accordance with the scenarios). The data do not include intraregional transportation costs for moving energy from resource site to end user.

Table 19-3. Composition of costs of energy production and conversion facilities as used in the IMPACT model (percent).

	Oil		*Gas*		*Coal*	
	On-shore	*Off-shore*	*On-shore*	*Off-shore*	*Under-ground*	*Surface*
Materials	33	30	36	33	15	5
Primary iron and steel	15	12	14	17	3	1
Nonferrous metals					1	0.5
Fabricated metal products	3	12	2	9.5	7.5	1.5
Glass, clay, and stone products	7	2	13	3	1	1
Chemical and allied products	6	3	7	3	1.5	0.2
Miscellaneous materials	2	1		0.5	2	0.8
Equipment	31	41	18	31	49	61
Electrical	1	1	1	1	3.5	1.5
Oil field	20	34	9	24		
Mining					32	52
Transportation and material handling					7.5	4.2
Fabricated plate products	4	1	3	1	2.5	2
General industry	3	1	2	1	1	0.3
Miscellaneous	3	4	3	4	2.5	1.0
Manpower	26	13	28	18.5	22	19
Services and other constructor costs	10	16	18	17.5	14	15
Total constructor's costs	100	100	100	100	100	100
Owner's costs as % of constructor's costs	51	96	51	94	76	29

Note: These figures are based on Bechtel data. They reflect the conditions of the United States but are used in IMPACT with small corrections for other regions because of lack of data. Owner's costs include interest during construction, land lease, and so forth.

CAPITAL REQUIREMENTS

This section presents the IMPACT model assessment of the capital requirements associated with the energy supply scenarios of Chapter 17 and the alternative supply cases of Chapter 18. All capital costs are expressed in constant (1975) U.S. dollars without discounting.

High and Low Scenarios[a]

Global investments for exploration, production, conversion, transportation, and distribution of primary and secondary energy under the assumptions in

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[a] The two scenarios evaluated here differ slightly from the supply scenarios of Chapter 17, the former being somewhat earlier versions of the final IIASA scenarios. The gross, almost qualitative, evaluations given here would not be affected in any important way by the minor differences actually obtained.

the two (High and Low) scenarios would be very large. Even in the Low scenario, the global energy supply system would need about \$7 trillion (10^{12}) of direct energy investment during the period 1975 to 2000 and about \$20 trillion during 2000 to 2030. These investments would represent about 2.9 and 3.8 percent of cumulative gross world product (GWP) during the two periods. The High scenario would require \$2 trillion more than the Low over the first twenty-five-year period and \$13 trillion more over the next thirty years. These High scenario energy investments would be about 3.1 and 3.9 percent of cumulative GWP during the two periods.

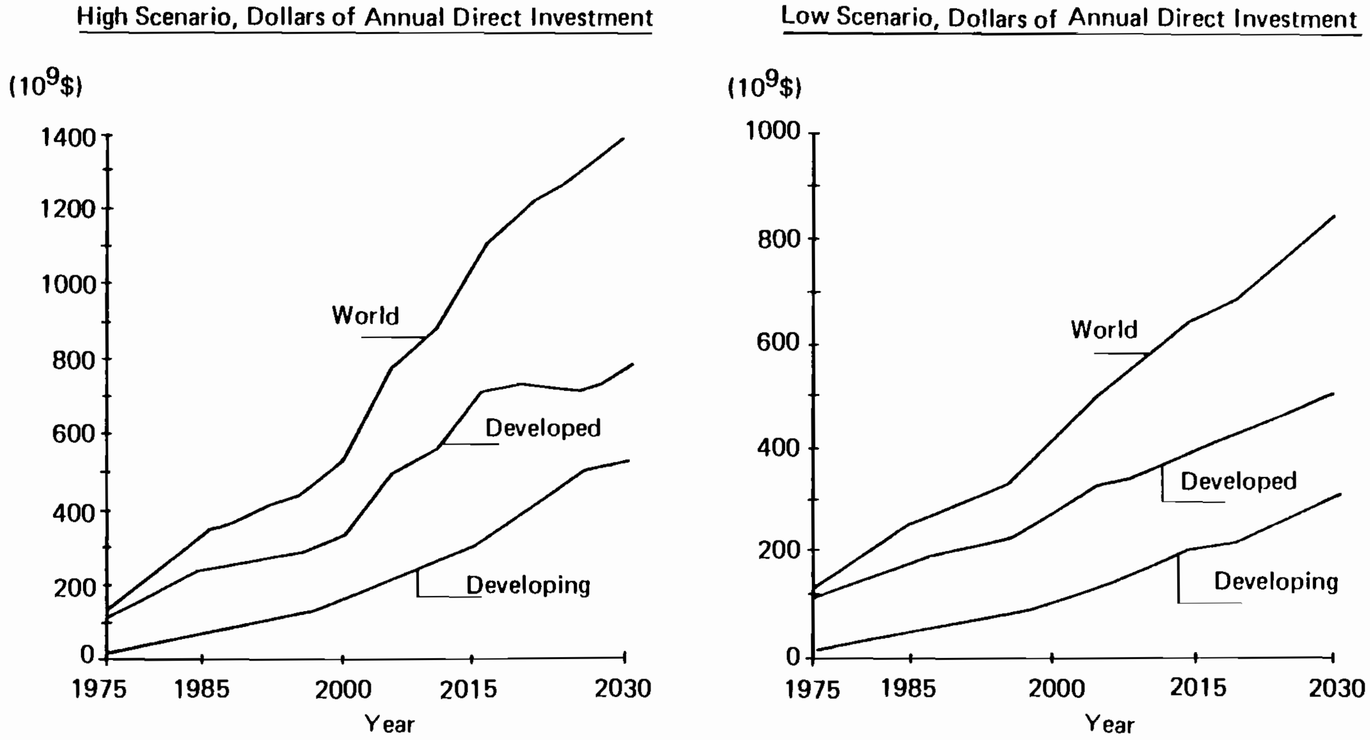
The dynamics of global annual direct investment requirements for energy supply systems are illustrated in Figure 19-1. They would start from about \$135 billion (10^9) in 1975 (2.2 percent GWP) and would increase up to \$840 billion by 2030 in the Low scenario and up to \$1400 billion in the High scenario (3.7 to 3.5 percent of GWP in the two scenarios, respectively, by 2030). The direct energy investments obviously would be more and more important in macroeconomic terms. Still, the increase of these investments as a share of total gross economic product does not appear alarming, on a globally aggregated scale. Regional differences may reveal considerable capital-generating difficulties. Greater and greater energy capital needs occur in developing regions (regions IV-LA, V-Af/SEA, VI-ME/NAf, and VII-C/CPA) in the scenarios. These regions now spend only about 15 percent of the global energy investment; in the year 2000 their share would increase to 32 to 38 percent in these scenarios, and later it would reach 40 to 44 percent or more.

Energy capital requirements, this analysis shows, would grow more rapidly than energy consumption (Table 19-4). This is mainly because of the exhaustion of cheap oil and gas resources in these scenarios and because of the greater role in the global energy balance of more and more capital-intensive energy sources (Figure 19-2). Appreciable changes in the industrial structure of energy investments occur in the scenarios (Table 19-5).

Two important scenario results must be mentioned—the rapid growth in the share of investment in synthetic fuels (from 1 to 12 percent) during the period of 1980 to 2030 and in nuclear power plants and the nuclear fuel cycle (from 14 to 25 percent). At the same time, one can observe (Table 19-5) that total electricity generation investment is projected to drop as a percentage of total (direct plus indirect) energy investment, while electricity increases its contribution to energy supply. This follows from the assumption of relatively less expensive sources of electricity compared to unconventional fossil fuels. Large-scale development in many countries of solar heating and cooling, district heating, and various small-scale energy technologies would lead to an increasing share of these items ("other" investment in Table 19-5) in total energy investment—from 6 percent in 1980 to 12 percent after 2000.

The development of new capital-intensive energy sources on a large scale necessitates the additional development of the metallurgy, engineering, chemical, and building industries and other sectors of the economy. The dynamics of such indirect investments are reflected in Figure 19-3. At the present time, global indirect investments to the energy supply system equal

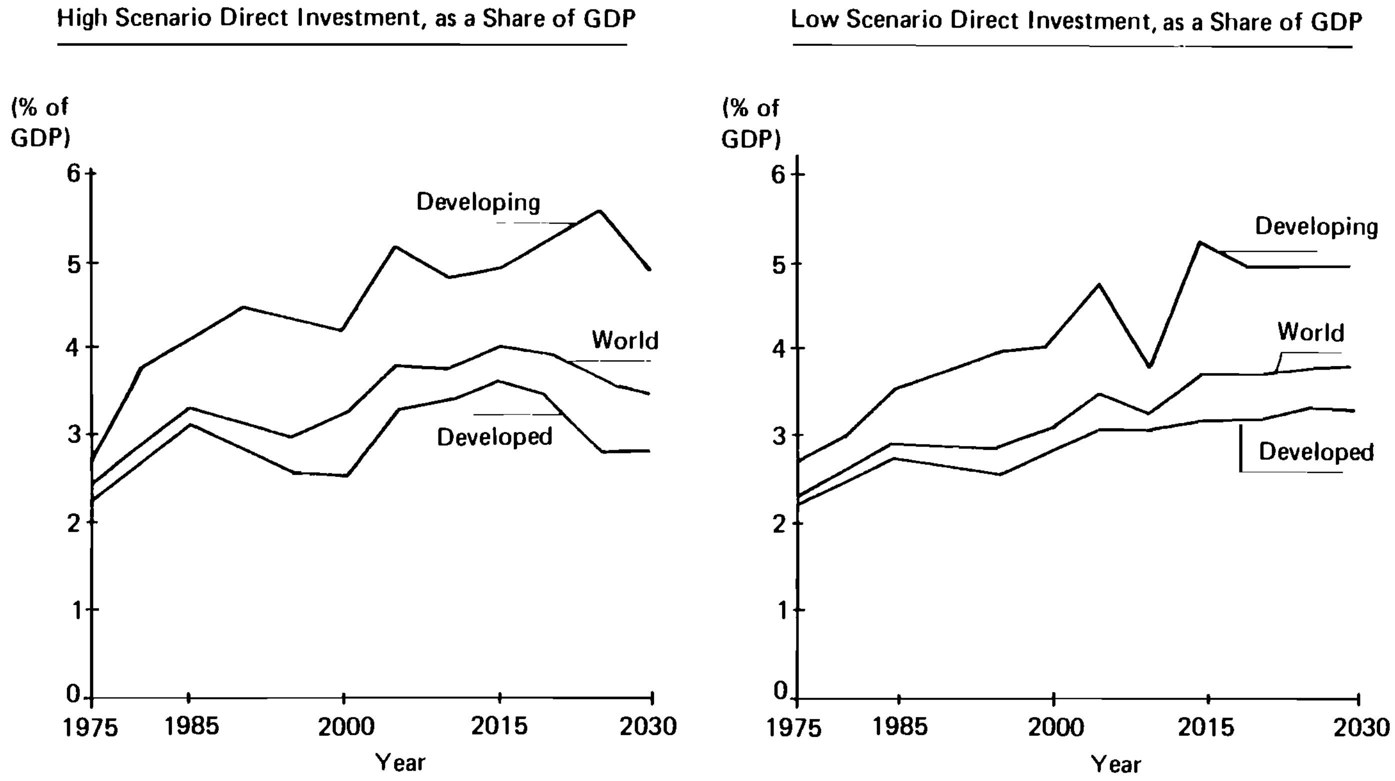
Figure 19-1. Direct annual investment requirements for energy supply systems for the two scenarios. These figures include requirements for energy supply and transportation facilities; they do not include investments in final energy consumption and investments in energy conservation.



High Scenario, Dollars of Annual Direct Investment

Low Scenario, Dollars of Annual Direct Investment

Figure 19-1 continued.



High Scenario Direct Investment, as a Share of GDP

Low Scenario Direct Investment, as a Share of GDP

Table 19-4. Annual growth rates of energy and capital requirements (percent/year).

	High Scenario		*Low Scenario*	
	1975–2000	*2000–2025*	*1975–2000*	*2000–2025*
Developed regions[a]				
Primary energy	2.3	1.8	1.6	1.1
Final energy	2.1	1.4	1.5	0.8
Direct capital investment	4.6	3.5	3.3	2.5
Developing regions[b]				
Primary energy	5.7	3.8	4.3	2.9
Final energy	5.5	3.4	4.2	2.6
Direct capital investment	9.6	5.0	8.7	3.5
World				
Primary energy	3.0	2.5	2.1	1.7
Final energy	3.0	2.2	2.1	1.4
Direct capital investment	5.9	3.7	4.7	2.9

[a] Regions I (NA), II (SU/EE), III (WE/JANZ).
[b] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

roughly \$22 billion per year. During the period under consideration, annual indirect investments would increase to \$90 billion for the Low scenario and to \$150 billion for the High scenario. The absolute maximum of indirect investment could occur between 2010 and 2020 by this analysis and precede by ten to twenty years the maximum of direct investment.

Maximum ratios of indirect to direct investment resulting from calculations for the High scenario are region I (NA), 28 percent (in the period 1995-2000); region II (SU/EE), 21 percent (1995-2000); region III (WE/JANZ), 15 percent (1990-1995); region IV (LA), 24 percent (1995-2000);

Table 19-5. Structure of direct global energy investment, High scenario (percent).

	1980	*2000*	*2000*
Natural fuels	22	22	19
Synthetic fuels	1	3	12
Fuel transportation and distribution	13	9.5	8
Nuclear power plants	14	22	25
Other power plants	19	11	9
Electricity transmission and distribution	25	20.5	15
Other[a]	6	12	12
Total	100	100	100
Total (10^9 \$/yr)	238	580	1330

[a] "Other" consists of decentralized energy sources and certain others not listed (i.e., solar heating and cooling systems, district heat and cogeneration systems, and renewable small-scale heat or power supply systems).

Figure 19-2. Trends in marginal investment cost of fuels (1975 $/kW of primary energy). The projection of the global trends was made on the basis of regional analysis (the trends for separate regions are contained inside the intervals shown for the world or for aggregated regions). In so doing, the following were taken into account: 1) present and perspective investment costs for marginal energy resources; 2) timing of synthetic fuels contributions and different price categories of fossil fuels; and 3) the exponential character of investment cost growth inside each price category.

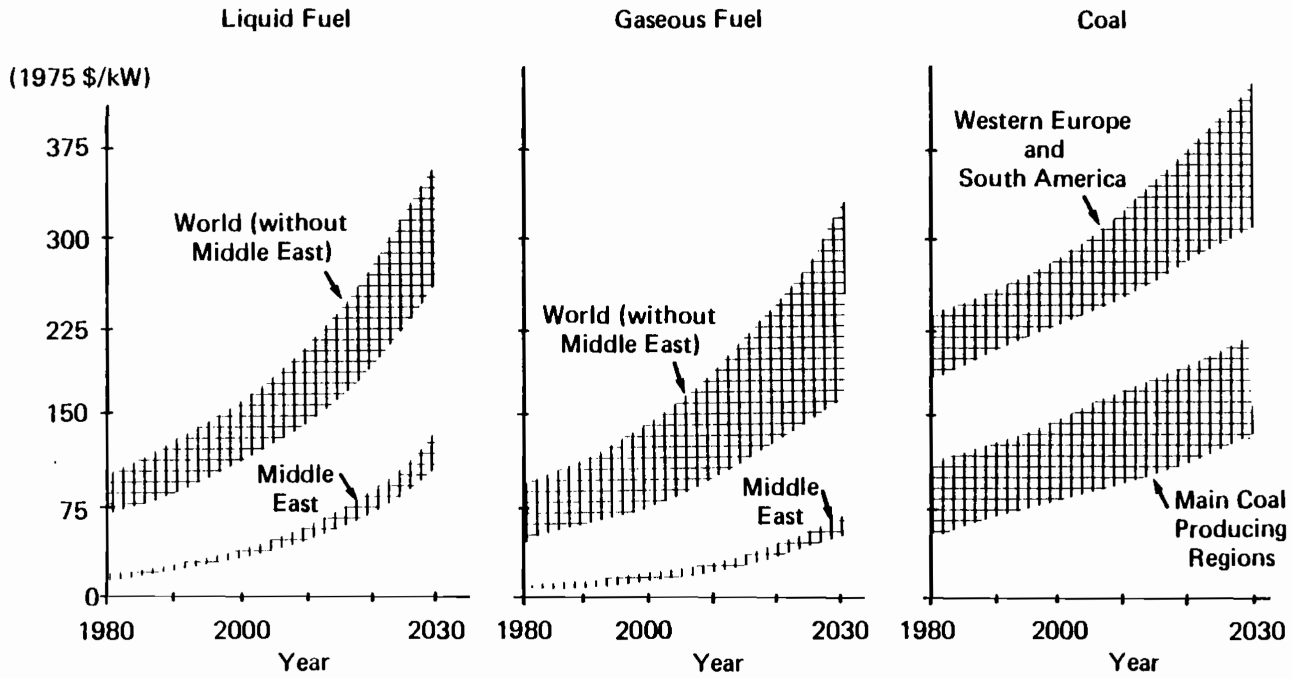
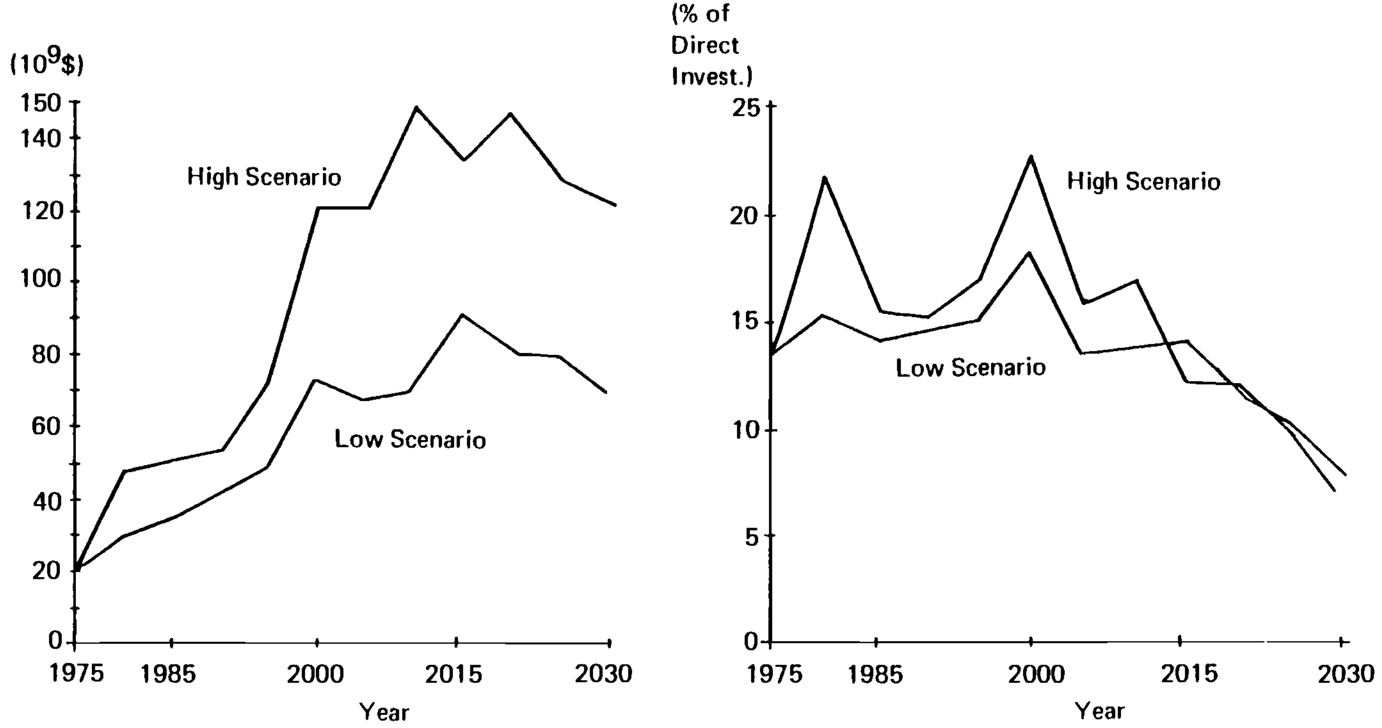


Figure 19-3. Global indirect investment. These figures include capital requirements for additional development of metallurgy, engineering, chemical, and other industries associated with implementation of the energy supply scenarios.



region V (Af/SEA), 21 percent (2000-2005); region VI (ME/NAf), 20 percent (1995-2000); and region VII (C/CPA), 36 percent (1995-2000 and 2005-2010). Indirect investments, while rather small compared to direct investment requirements, should not be neglected. In the developing regions (IV, V, VI, VII), 35 to 50 percent of indirect investment would be spent for the development of engineering and chemical industries. In the developed regions (I, II, III), the largest part of indirect investments would be needed for ferrous metallurgy (30 to 35 percent).

The Low scenario requires \$3.5 trillion and the High scenario \$5.7 trillion of indirect investment to the energy system during 1980 to 2030. These figures are 13 and 14 percent, respectively, of cumulative direct investment.

The sum of direct plus indirect capital investment requirements (Table 19-6) during 1980-2030 could amount to \$30 trillion for the Low scenario and \$46.5 trillion for the High scenario. These figures are 3.9 and 4.1 percent, respectively, of cumulative GWP during this period. Total (direct plus indirect) investment in the scenarios grows faster than does GWP. The share of annual GWP used for total energy investments would increase from 2.2 percent in 1975 to 4 percent by 2030 in the Low scenario and to 4.3 percent in the High scenario. This doubling of the share of total energy investment in GWP is striking; whether it reveals an alarming problem, or simply a challenging shift of economic resources, remains to be seen. Regional differences in this context are revealing.

Table 19-6. Total (direct and indirect) cumulative energy investment requirements, 1980-2030.

	Developed Regions[a]		*Developing Regions*[b]		*World*	
Period	*High scenario*	*Low scenario*	*High scenario*	*Low scenario*	*High scenario*	*Low sceanrio*
1980-1990						
(10^{12} \$/period)	2.8	2.3	1.4	0.8	4.2	3.1
(as % of GDP)	3.6	3.3	6.0	4.2	4.0	3.5
1990-2000						
(10^{12} \$/period)	3.6	2.9	2.1	1.4	5.7	4.3
(as % of GDP)	3.3	3.2	6.0	5.2	3.9	3.7
2000-2010						
(10^{12} \$/period)	6.1	3.8	3.4	2.2	9.5	6.0
(as % of GDP)	4.1	3.5	6.4	5.9	4.6	4.1
2010-2020						
(10^{12} \$/period)	7.7	4.6	5.1	2.9	12.8	7.5
(as % of GDP)	4.0	3.6	6.6	6.0	4.7	4.3
2020-2030						
(10^{12} \$/period)	7.8	5.2	6.6	3.6	14.4	8.8
(as % of GDP)	3.2	3.6	6.1	5.8	4.1	4.2
Total 1980-2030						
(10^{12} \$/period)	28.0	18.8	18.5	10.9	46.5	29.7

[a] Regions I (NA), II (SU/EE), III (WE/JANZ).

[b] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

The developing regions, which in 1975 spent about 2 percent of their GDP on energy investment, would have to drastically increase this figure by 2030 (see Figure 19-4) under the conditions of the scenarios. The maximum share of total energy investment in GDP in these regions would reach 6.1 percent in the Low scenario and 6.7 percent in the High scenario.

For region IV and region VI, the maximum share of total energy investment in GDP fluctuates between 6.5 and 8 percent in the scenarios. For region V, this index would not exceed 6 percent in the Low scenario and 7 percent in the High scenario. But the economic problems of this region become complicated by the need for hard currency to pay for oil imports (Figure 19-5).

In the developed regions, the growth of total energy investment as a fraction of GDP would not be as high as in the developing regions in the scenarios. In the Low scenario, this index would be close to historical figures (2 to 3.5 percent). It would appear that this would not present serious difficulties in providing the required capital. But this may not hold true for the High scenario. In regions I and II, the share of total energy investment in GDP may increase to 5 percent in the High scenario. For region III, energy investments in GDP would not exceed 3 percent. But this reflects the continued dependence of this region on imported energy resources; the figures cited here do not include investments in increased production of some export goods to compensate for required energy imports. Such additional investments could be substantial. The costs of energy imports to region III would grow from $80 billion in 1980 to $220 billion in the scenarios by 2030 (Figure 19-5).

Alternative Supply Cases

The Nuclear Moratorium and Enhanced Nuclear cases of Chapter 18 are extreme cases, but their analysis gives some indication of the possible economic consequences of deviations from the conditions and constraints contained in the scenarios. It should be remembered in this context that one of the criteria of energy supply source selection for the High and the Low scenarios was minimizing capital costs. Because of this, the alternative cases should be expected to have higher investment requirements than the scenarios against which they are compared. As will be seen shortly, this is indeed the situation.

In the Nuclear Moratorium case, constraints on coal production were removed, and as a result, its share in global primary energy consumption was increased in 2030 from 29 to 39 percent. This step would actually contribute to a decreasing of the capital intensiveness of the energy supply system. But simultaneously, additional resources of expensive categories of oil and gas would be involved in the energy balance—thereby increasing the energy capital intensiveness.

As a result, the Nuclear Moratorium case would require some $4600 billion more (cumulative) direct investment for the global energy supply system up to the year 2030 than in the Low scenario (i.e., about 19 percent more). The major part of these additional investments ($3300 billion) would have

Figure 19-4. Total (direct plus indirect) energy investment as a share of GDP for the High and Low scenarios.

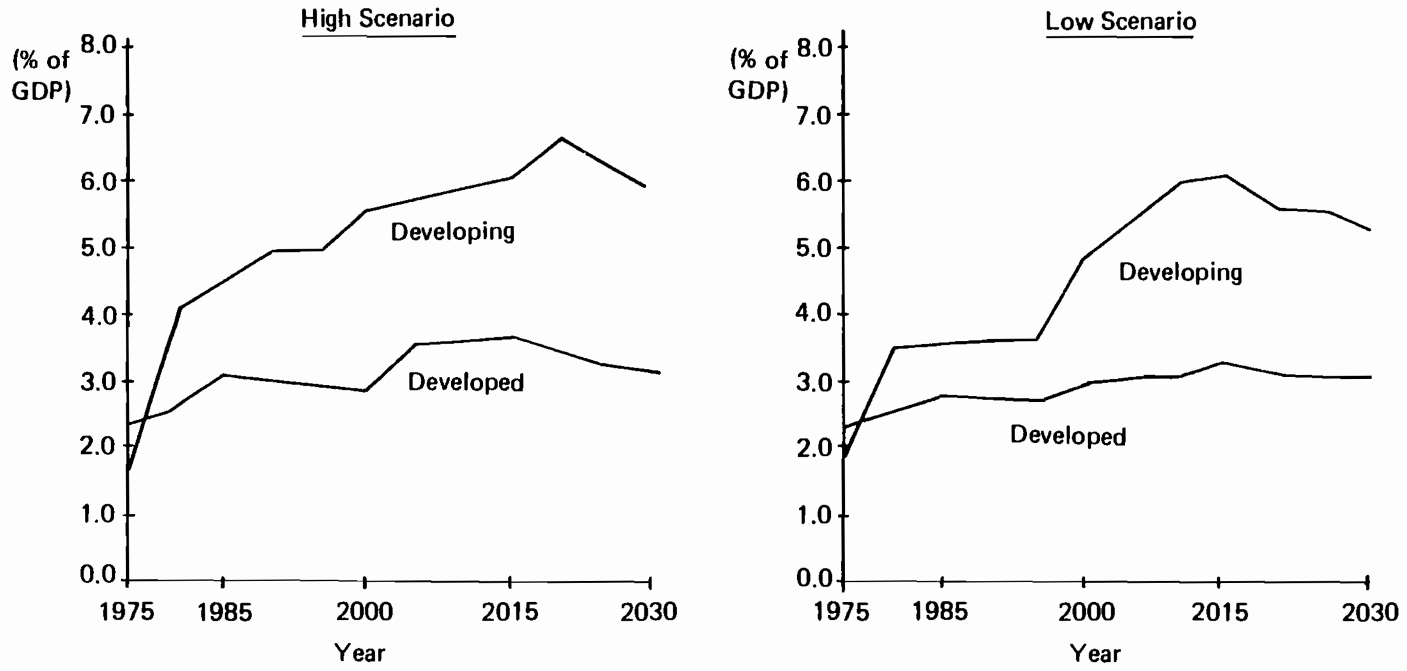
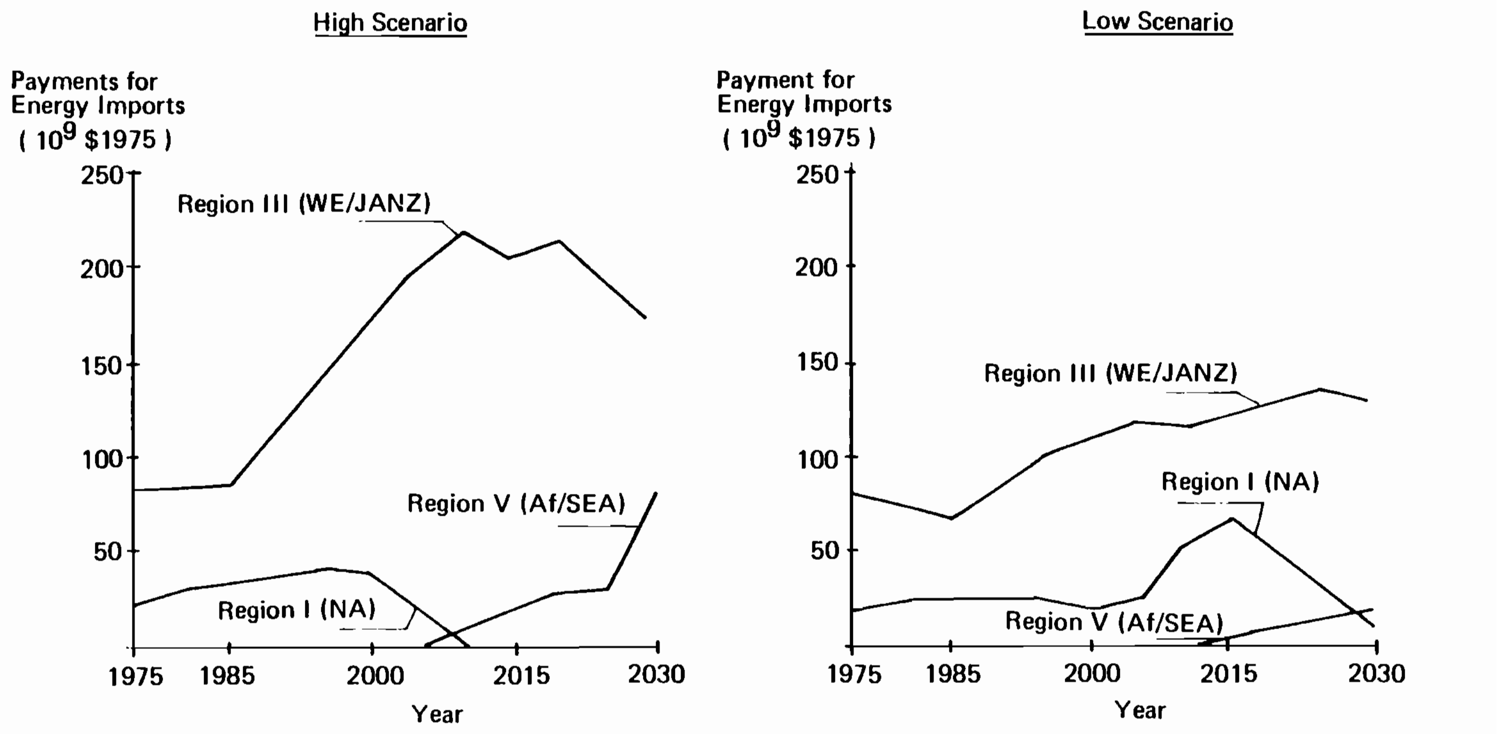


Figure 19-5. Costs of energy imports for the High and Low scenarios.



to be accumulated in the developed regions. If one compares the dynamics of direct investment requirements for the Nuclear Moratorium case and for the Low scenario (Figures 19-1 and 19-6), then one can see that all additional investments are needed after the year 2000. In the beginning of the period under consideration (i.e., the next fifteen to twenty years), the Nuclear Moratorium case is less capital intensive.

The indirect investment requirements of the Nuclear Moratorium case are higher than for the Low scenario during the whole period. The indirect investments of the Nuclear Moratorium case exceed those of the Low scenario by 24 percent or about $880 billion. During the period of peak global annual investment (direct and indirect) for development of energy-related branches of the economy and infrastructure, indirect investment would amount to 26 percent of direct investment. This peak period would be 1995-2000 (Figure 19-6). Over the entire period of 1975-2030, indirect investments average 16 percent of direct investments.

Total (direct and indirect) global investments for the Nuclear Moratorium case are 17 percent higher than for the Low scenario (Table 19-7). The Nuclear Moratorium case results in an increase in the share of total energy investments in GWP—to as high as 6.8 percent, compared to 6.1 percent for the Low scenario.

In the Enhanced Nuclear case, nuclear power plants would provide 75 percent of total global electricity production. (This share was 61 percent in the High scenario.) This, together with breeder reactor capacity as part of the methanol production technology (Chapter 18), would lead to additional capital requirements. In comparison with the High scenario, the Enhanced Nuclear case would require 8 percent more direct capital investment for the developed regions and 10 percent more for the developing regions (excluding region VI). For the world, additional direct energy investment in the period 1980-2030 for the Enhanced Nuclear case would come to about $3400 bil-

Table 19-7. Total (direct and indirect) capital requirements of the Nuclear Moratorium case (10^{12} $/period).

	1980–1990	*1990–2000*	*2000–2010*	*2010–2020*	*2020–2030*	*Total 1980–2030*
Nuclear Moratorium case						
Developed regions (I-NA, II-SU/EE, III-WE/JANZ)	2.2	2.9	4.5	5.7	6.7	22
Developing regions (IV-LA, V-Af/SEA, VI-ME/NAf, VII-C/CPA)	0.7	1.3	2.3	3.3	4.4	12
World	2.9	4.2	6.8	9.0	1.1	34
Deviation from Low scenario						
Developed regions			0.7	1.1	1.5	3.3
Developing regions[a]			0.1	0.4	0.8	1.3
World			0.8	1.4	2.2	4.6

[a] Excluding region VI (ME/NAf).

Figure 19-6. Direct and indirect annual investment requirements for energy supply systems for the two alternative cases. (See Figure 19-1 for comparable figures for the High and Low scenarios.)

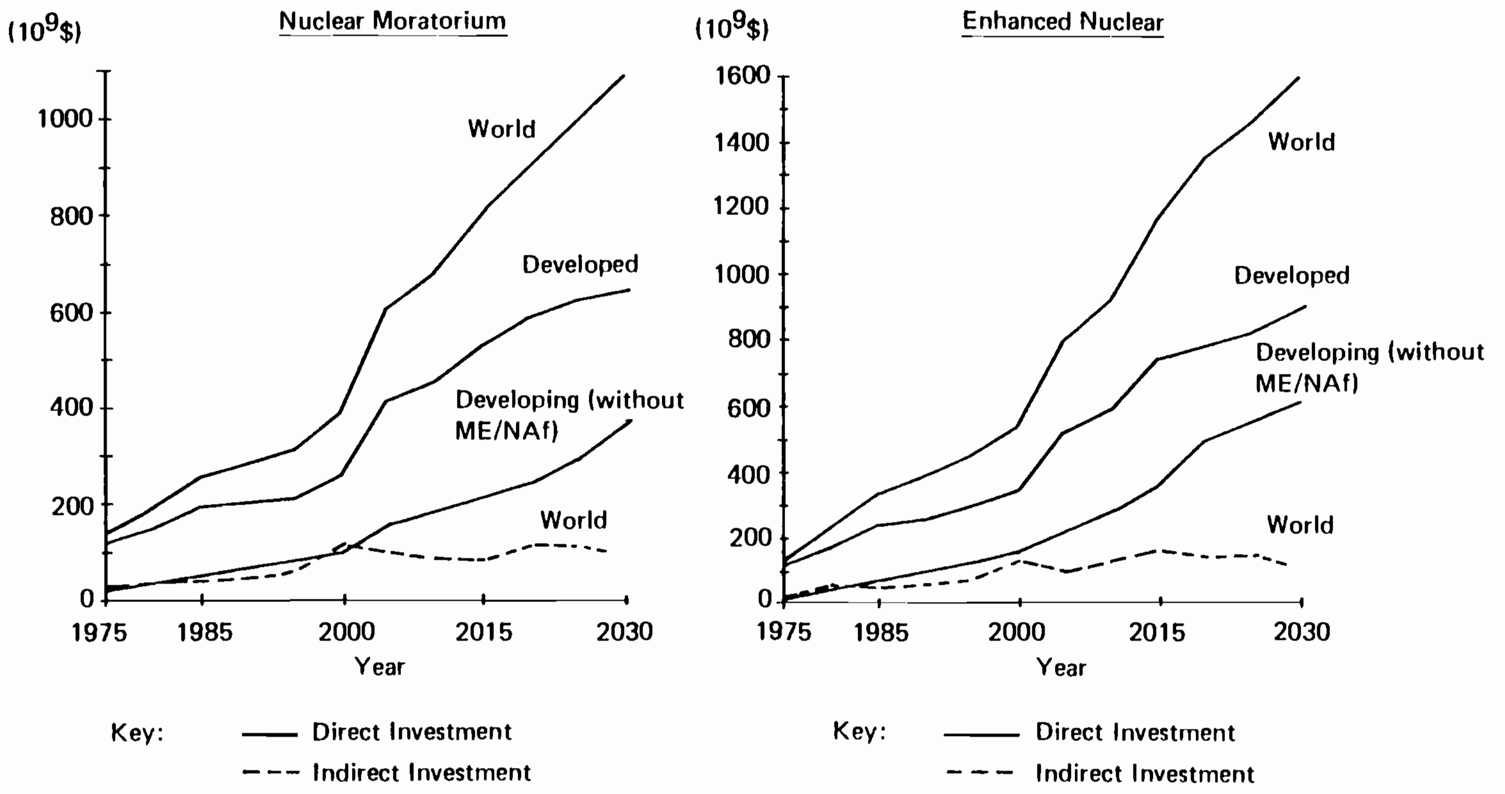


Table 19-8. Total (direct and indirect) capital requirements for the Enhanced Nuclear case (10^{12} \$/period).

	1980–1990	*1990–2000*	*2000–2010*	*2010–2020*	*2020–2030*	*Total 1980–2030*
Enhanced Nuclear case						
Developed regions (I-NA, II-SU/EE, III-WE/JANZ)	2.9	3.7	6.3	8.2	8.8	29.9
Developing regions (IV-LA, V-Af/SEA, VI-ME/NAf, VII-C/CPA)	1.3	2.1	3.45	5.55	7.35	19.75
World	4.2	5.8	9.75	12.75	16.15	49.65
Deviations from the High scenario						
Developed regions	0.1	0.1	0.2	0.5	1.0	1.9
Developing regions[a]			0.05	0.45	0.75	1.2
World	0.1	0.1	0.25	0.95	1.75	3.1

[a] Excluding region VI (ME/NAf).

lion or about 8 percent higher than the High scenario. About 60 percent of this sum would be required after the year 2015, when the introduction of fast breeder reactors would occur rapidly and on a large scale.

Indirect investments for the Enhanced Nuclear case are, on average, 9 percent of direct investments or about \$390 billion. Both the relative and absolute values of indirect investments for the Enhanced Nuclear case are less than those for the High scenario. To provide for the Enhanced Nuclear case, global investments in energy-related sectors would have to be, on average, \$70 billion per year before 2000 and \$120 billion per year after 2000 (Figure 19-6).

Total energy investment requirements for the Enhanced Nuclear case in the period 1980–2030 would equal some \$29.9 trillion for the developed regions and some \$19.75 trillion for the developing regions (Table 19-8). These figures are just 6.5 and 8 percent higher than the corresponding figures for the High scenario. The share of GWP taken up by total energy investments in the Enhanced Nuclear case would be (at maximum) 7.4 percent, compared to 6.7 percent for the High scenario. The technology cost assumptions for the Enhanced Nuclear case are sufficiently optimistic so that the increased capital burden would be relatively light.

These capital investment requirements for the scenarios and alternative cases do not yet deal with the problem of capital availability. This issue will be discussed briefly at the end of this chapter, after an evaluation of the WELMM requirements for the scenarios and alternative cases.

WELMM ANALYSIS

This section presents some generalized results of the IMPACT model's assessment of the requirements for manpower, materials, energy, land, and water in the scenarios and alternative cases. Two rather similar studies were made recently—in the United States by the Bechtel Corporation (Gallagher et al. 1978) and in the USSR by the Siberian Power Institute (Kononov and Makarov 1975)—for WELMM type conditions in these two countries over the medium term. The results of these works were used here for examination of IMPACT results for regions I and II.

The assessments provided here are inevitably very rough; they give only the order of magnitude of possible WELMM requirements. This is especially true for the developing regions. But it is felt that they reasonably reflect the major impacts of alternative energy strategies on the requirements for limited resources, and they may help to better understand some of the economic problems to come during the transition to new energy sources.

Manpower Requirements

In calculating the manpower requirements of the scenarios and alternative cases, an average growth of 1.5 to 2 percent per year in labor productivity in energy industries and in energy-related sectors of the economy was anticipated. Under this condition, direct requirements for manpower for operation and construction of the global energy supply system would grow by 0.4 percent per year from 1975 to 2000 and by 0.7 percent per year over the following thirty years for the Low scenario. The High scenario would require more rapid growth of labor forces—1 percent before and 2.3 percent after the year 2000 (see Figure 19-7). In 2030, about 24 million people in the world would be involved in fuel and electricity production and transportation[b] in the High scenario—that is, 13 million more than at present and 8.6 million more than for the Low scenario.

The largest part of the labor force would be employed in the coal industry—25 percent in the developed regions and 38 percent in developing regions (Table 19-9). Manpower requirements for synthetic fuel production would reach, by 2030, levels comparable with those for electricity generation. About a quarter of the total required labor force would be engaged in fuel transportation and distribution.

Indirect manpower requirements, which at present exceed direct requirements, would grow at 1.2 percent per year on average during 1980-2030 for the High scenario and at 0.3 percent for the Low scenario (Figure 19-7). About eleven to nineteen million people would be employed in energy-related sectors of the world in 2030. Total (direct and indirect) annual manpower requirements by 2030 would equal about twenty-six million people for the Low scenario and forty-two and a half million for the High scenario.

The Nuclear Moratorium case would require in the year 2030 some 14 percent more workers than the Low scenario, while the Enhanced Nuclear case would require 13 percent less manpower than the High scenario (Table 19-10). And the labor savings in the Enhanced Nuclear "endowment" case would come after 2000, when labor might be in short supply.

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[b] These figures do not include manpower requirements for production of noncommercial sources of energy.

Figure 19-7. Total manpower requirements.

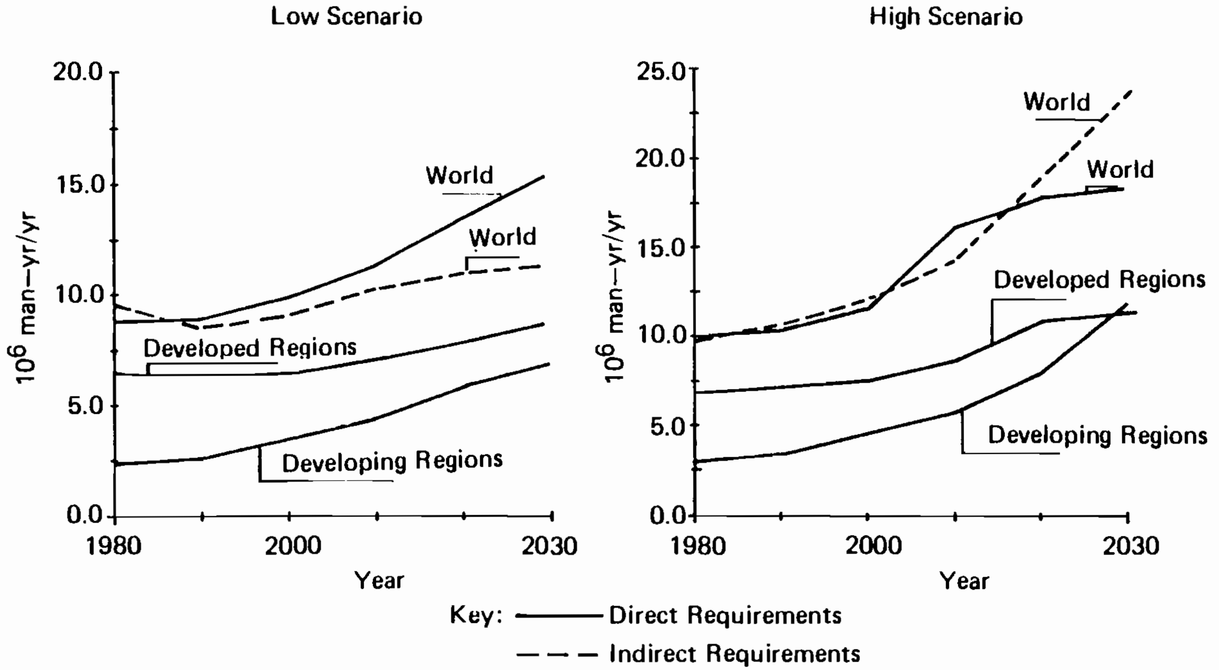

Table 19-9. Structure of direct energy manpower requirements for the High scenario, 2030 (percent).

	Developed Regions[a]	*Developing Regions*[b]	*World*
Oil and gas industry	5.5	11.5	9
Coal industry	25	37.5	31
Synthetic fuels production	14	8	11
Fuel transportation	14	25	24.5
Electricity generation	17.5	11	14.5
Electricity transmission and distribution	14	7	10
Total	100	100	100
of which unskilled labor	9.5	11	10.4

[a] Regions I (NA), II (SU/EE), III (WE/JANZ).
[b] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

Table 19-10. Comparison of total (direct and indirect) global manpower requirements.

	(10^6 person-yr/yr)				
Low scenario	17.4	18.8	21.3	24.1	26.3
Nuclear Moratorium case	17.8	21.0	25.3	27.2	30.1
Difference	0.4	2.2	4.0	3.1	3.8
High scenario	21.1	23.9	30.8	37.1	42.5
Enhanced Nuclear case	20.8	24.4	29.1	35.0	37.2
Difference	-0.3	0.5	-1.7	-2.1	-5.3

With these considerations, it would appear that manpower requirements during the next fifty years may not be serious for the world as a whole. The problem of labor force quality is much more serious. This is especially true for the developing regions where, for the High scenario, the energy sector alone would require in 2030 some nine to ten million more skilled workers, technicians, and engineers than at present.

Material and Equipment Requirements

Energy supply systems strongly affect the development of many branches of industry by requiring the output of these branches.[c] Conversely, lack of some materials or equipment can negatively influence the rates of development of energy supply systems.

For the High scenario the total (direct and indirect) basic materials re-

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[c] For example, in both the United States and the USSR, development of the energy supply system requires, directly or indirectly, up to 20 percent of metallurgical products, approximately 10 to 20 percent of copper and aluminum, 11 to 16 percent of cement, and more than 10 percent of the gross machine-building production.

quirements of the global energy supply system would increase by a factor of 5.9 over the period 1975 to 2030. This is 36 percent higher than the growth in world primary energy production. Requirements for chemical products would increase particularly rapidly (Figure 19-8).

Global energy supply needs for industrial equipment would be higher than needs for basic materials. The requirements for equipment for fields, coal mines, and other primary energy extraction facilities may increase over the period by a factor of seven to twelve.

The Low scenario would require 30 to 40 percent less material and equipment than the High scenario. But even for the Low scenario, the total costs of materials directly or indirectly used for operating and developing the global energy supply system would be about $400 billion per year in 2000 and about $760 billion per year in 2030. The cost of equipment required annually is estimated at $3000 billion in 2000 and $520 billion in 2030.

The Nuclear Moratorium case would lead to a 25 percent increase (over the Low scenario) in total (direct and indirect) material and equipment requirements by 2030 (Figure 19-9). The Enhanced Nuclear case, on the contrary, would save 12 to 14 percent of the materials and equipment required by the High scenario.

The considerably increased requirements for materials and equipment in the scenarios and alternative cases leads one to wonder how difficult this might be. A sense of the problem can be gained by comparing these requirements with projections of the total global outputs of two very aggregated industrial sectors—basic materials (ferrous and nonferrous metals, building materials and chemical products) and machinery and equipment.[d]

The analysis shows (Figure 19-10) that at present some 10 percent of total global production of basic materials and some 6.5 percent of total equipment output are used for the development of the energy supply system. These figures would increase slightly in both scenarios. In neither scenario do materials and equipment needs seem unreachable, although the relative ease or difficulty of meeting the needs cannot now be known with any confidence.

The Nuclear Moratorium case materials and equipment situation may be more serious: after 2000 the ratio between the energy supply system requirements and world production of these commodities would rise to 13.9 percent for basic materials and to 9 percent for equipment.

The problem of providing energy requirements in basic materials and equipment may become more challenging in the developing regions. Availability of hard currency in the developing regions may be a serious obstacle to expanded imports of materials and equipment on a scale large enough for requisite development of domestic energy systems.

Energy Requirements

Production materials and equipment for energy and energy-related sectors of the economy require fuel and electricity. The energy content of industrial

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[d] Chapter 16 describes the procedure used in calculating the output of these sectors.

Figure 19-8. Global materials and equipment requirements, High scenario (1975 = 100%).

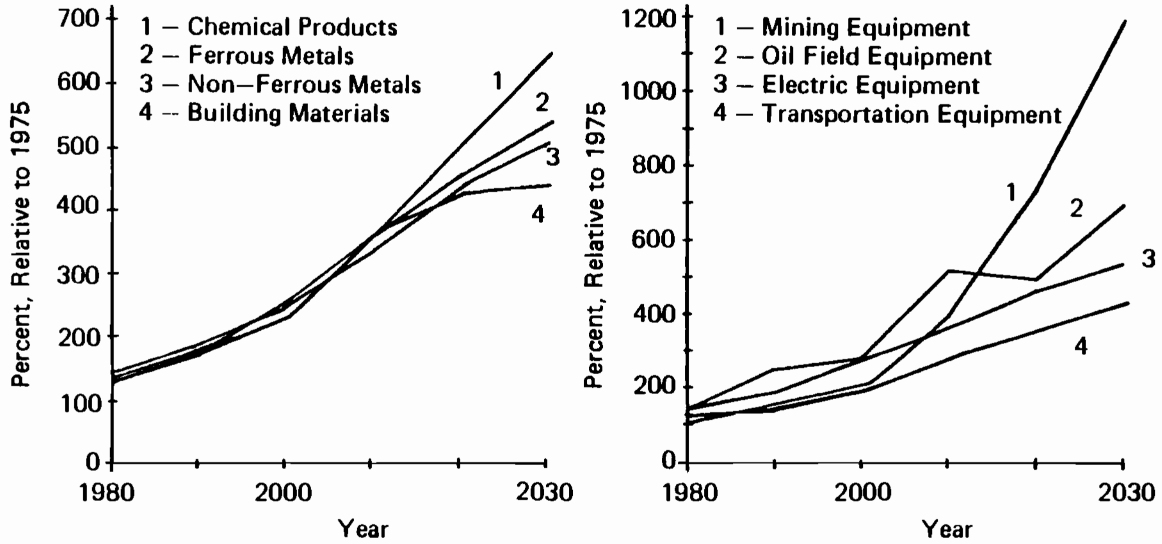
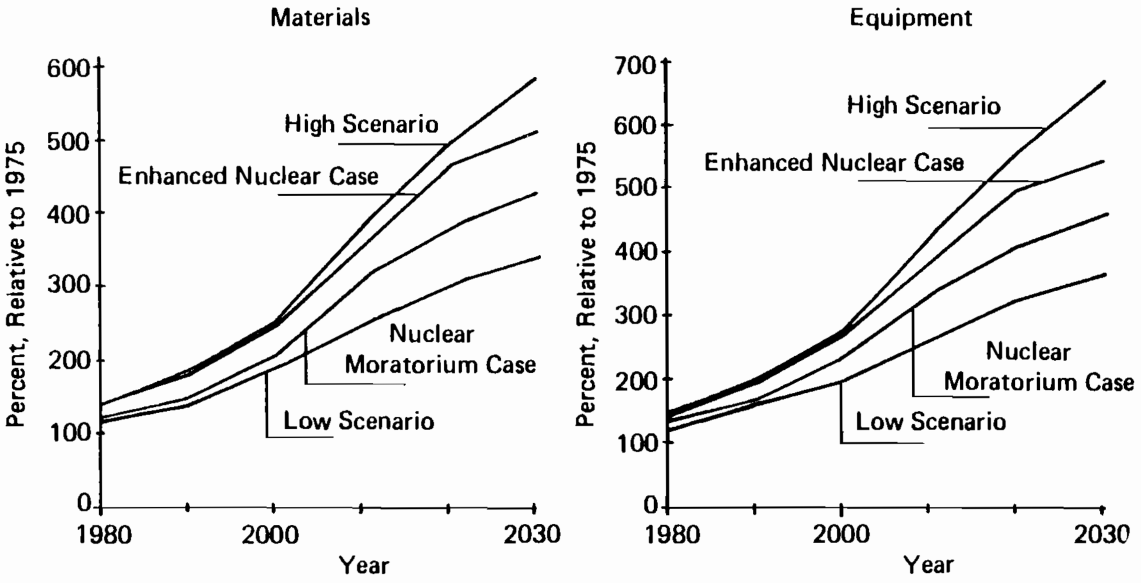


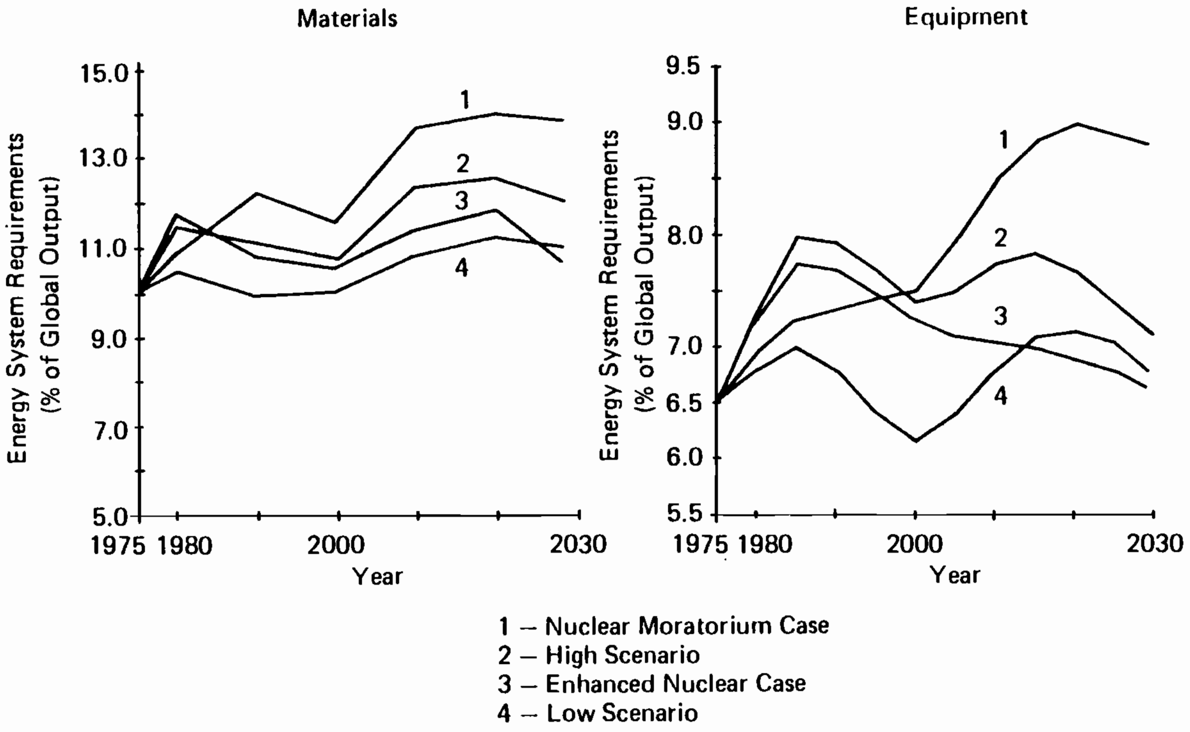
Figure 19-9. Aggregated global materials and equipment requirements for the scenarios and alternative cases.



Materials

Equipment

Figure 19-10. Energy supply system requirements as share of global output of materials and equipment.



goods used for construction and operation of energy facilities represent the indirect energy requirements of energy supply systems.

Results of IMPACT model runs show that the global indirect requirements for fuel and electricity are equivalent by 2030 to 1.1 TWyr/yr of primary energy for the Low scenario and 1.85 TWyr/yr for the High scenario. These figures would be approximately 4.2 and 4.6 percent of total primary energy demand.

The Nuclear Moratorium case, which requires additional development of some energy-related sectors, would increase indirect energy needs by 0.4 TWyr/yr over the Low scenario. The amount of this direct requirement seems small, yet its financial impact could be nonnegligible. Additional development of expensive, alternative energy sources (synthetic fuel, solar power plants) to meet the increased energy needs would require some $300 billion. The Enhanced Nuclear case provides a saving of 0.25 TWyr/yr of primary energy in energy-related sectors.

Land and Water Requirements

If the global energy supply system were to develop in accordance with the Low scenario, it would require in the next fifty years the extension of land occupied by energy facilities and energy-related enterprises during their life by about 330,000 km^2. In addition, about 400,000 km^2 would be needed for nonexclusive energy use (for instance, aerial electric corridors do not exclude farming). The High scenario would require about 500,000 km^2 of fixed land and about 750,000 km^2 of "right of way" land.

The land requirements in the scenarios and alternative cases would be distributed between the developed and the developing regions rather equally (Table 19-11). Some 20 percent of total fixed land requirements in the developed regions concern the energy-related enterprises that provide energy development. In comparison with the scenarios the Nuclear Moratorium case

Table 19-11. Land and water requirements.

	Fixed Land (10^3 km^2)[a]			*Water (10^9 m^3/year)*[b]		
	Developed regions[c]	*Developing regions*[d]	*World*	*Developed regions*[c]	*Developing regions*[d]	*World*
Low scenario	170	160	330	143	34	177
Nuclear Moratorium case	240	175	415	123	33	156
Difference	70	15	85	-20	-1	-21
High scenario	260	240	500	210	60	270
Enhanced Nuclear case	250	220	470	215	70	285
Difference	-10	-20	-30	5	10	15

[a] Cumulative (1980-2030) direct and indirect requirements.

[b] Average (2010-2030) annual total consumption.

[c] Regions I (NA), II (SU/EE), III (WE/JANZ).

[d] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

requires 25 percent more fixed land and the Enhanced Nuclear case 6 percent less fixed land.

The average annual water consumption requirements (including the water supply of the energy-related branches) are estimated by the IMPACT model to be 177 billion m^3 for the Low scenario and 270 billion m^3 for the High scenario (Table 19-11). This estimation does not consider the availability or nonavailability of sources of water and, in particular, the possibility of repeated use of the water in closed systems of water supply. The latter could reduce the stated water requirements substantially in these scenarios and cases. About 80 percent of water demand would be concentrated in the developed regions, where the problem of water is expected to become one of the most crucial ones.

The Enhanced Nuclear case would require 5 percent more water than the High scenario. This is because a large part of the water consumption is concerned with electricity production. Nuclear power plants require 30 percent more water than fossil-fuel-fired power plants. For this reason, the Nuclear Moratorium case needs less water than the other case and the scenarios and saves about 11 percent in comparison to the Low scenario.

SUMMARY OBSERVATIONS

The scenarios and alternative cases evaluated here seem to indicate that the transition to new energy sources would be characterized by a definite increase in energy costs. The investment costs of unconventional fossil resources may increase in many regions by a factor of four to five for crude oil and natural gas and by a factor of two to two and a half for coal by the year 2030. Simultaneously, the sharpness of competition among the energy sector and other sectors of the economy for limited national and natural resources would heighten. Of course, the progress of development would generate a good deal of capital for energy purposes. Nevertheless, under these conditions even a rough assessment of future capital and WELMM requirements and their availability becomes an important consideration for the energy transition.

Here, direct and indirect resource requirements have to be taken into account. From the IMPACT model runs of the IIASA energy scenarios, one finds that ratios of indirect to direct requirements would (with the array of assumptions made) amount to 20 to 25 percent for capital investment, 200 to 300 percent for basic materials and nonenergy equipment, 160 to 200 percent for manpower, 20 to 25 percent for land, and 12 to 18 percent for water.

The comparative analysis of the scenarios at the global level shows the following:

- The Low scenario would not create any serious and additional difficulties in providing capital and other scarce resources for energy systems. The more stretched transition to new, capital-intensive energy sources shifts the related economic problems beyond the year 2030.

- The High scenario envisages elevated rates of economic development (especially for the developing regions) and more rapid exhaustion of relatively cheap energy resources. Its cumulative direct and indirect requirements in capital are $17 trillion (55 percent) higher than for the Low scenario. The largest difficulties in providing for energy capital needs may arise in the period 2005-2020.
- The Enhanced Nuclear case, in comparison with the High scenario, would require $5 trillion (12 percent) more cumulative direct capital investment but $0.2 trillion (4 percent) less indirect investment. It would exert less influence on other sectors of the economy and seem to be more favorable than the other cases regarding the total (direct and indirect) material and equipment requirements.
- The Nuclear Moratorium case is the most capital, labor, and material intensive case. While before 2000 its total (direct and indirect) requirements in capital investment are about the same as for the Low scenario (less direct but more indirect investment), after 2000 it would require $5.7 trillion (20 percent) in addition. Additional annual total requirements in other resources by 2030 would be 15 percent for manpower, 20 to 25 percent for total materials and equipment, 36 percent for energy (indirect), and 25 percent for land.

A summary of the total cumulative energy sector capital investment requirements of the scenarios and alternative cases is given in Table 19-12.

The observations concerning the regional features of the scenarios and alternative cases indicate the following:

- In all scenarios and cases the requirements of the developing regions for capital, investment goods, and manpower would rise much faster than

Table 19-12. Cumulative energy sector capital investment requirements, 1980-2030 (10^{12} $).

	Developed Regions[a]	*Developing Regions*[b]	*World*
High scenario	28.0	18.5	46.5
Low scenario	18.8	10.9	29.7
Nuclear Moratorium case	22.0	12.0	34.0
Enhanced Nuclear case	29.9	19.75	49.65

Note: These figures are the composite of Tables 19-6, 19-7, and 19-8. They are highly approximate and are meant to convey no more than the relative magnitudes of total (direct and indirect) investment requirements for quite different energy futures.

[a] Regions I (NA), II (SU/EE), III (WE/JANZ).

[b] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

those of the developed regions. As a result, their share of the global requirements would increase from 20 to 25 percent at present to up to 42 to 50 percent by the year 2030.

- The developing regions, which in 1975 spent about 2 percent of GDP on development of their own energy resources, would have to increase this figure to 6.1 to 7.4 percent by 2030. Availability of capital and investment goods would be a key factor in the future energy strategies of nonindustrial countries. A shortage of capital could create serious economic problems, complicated by skilled manpower requirements. Hard currency shortages for imports of energy equipment and energy resources may have to be faced.
- The developed regions would increase the share of GDP that goes into energy and energy-related investments from 2.3 percent at present to 3.3 to 3.8 percent by 2030 in the scenarios and as high as 4.6 percent in the Nuclear Moratorium case.

Each of the scenarios and alternative cases has highlighted potentially serious problems of energy supply and/or trade. Yet it may be that the investment and financing requirements of energy systems would be binding earlier than the physical availability of fuels. The calculations of this chapter are intended as a start toward consideration of just this possibility.

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20 BALANCING SUPPLY AND DEMAND: THE SUMMARY

A DOMINANT THEME

The central observation of the preceding seven chapters is simply that over the next five decades, even with vigorous conservation measures in industrialized regions, increasing needs for liquid fuels throughout the world may exceed the capabilities of global energy supply systems. The "energy problem," viewed with a sufficiently long-term and global perspective, is not an energy problem, strictly speaking; it is an oil problem or, more precisely, a liquid fuels problem.

A great deal of information and a good many insights lie behind this analysis of the globe's long-term energy future. Different regions of the world face widely different economic and energy prospects, with widely different potentials and constraints. Some energy end use markets can be more easily supplied than others. And different energy supply options carry different economic, environmental, political, and institutional implications.

Energy systems are complex. They are closely linked with our economies and our lives. Because of this, definitive statements on energy futures must be greeted with skepticism. No one yet fully understands the intricate workings of energy in the world, and no one is a prophet of the future. The uncertainties are great; but at the same time, they are not infinite.

Based on several years of analysis at IIASA, with contributions from many international experts, a number of compelling observations can be made. A few of them are presented here. (The following numbers, as throughout Part IV, are meant to be indicators, not predictors. They result from the specific and carefully designed and analyzed High and Low scenarios.)

- The supply analyses show world crude oil production peaking in about 2010, at nearly 7 TWyr/yr in the High scenario (or in 2015 at 5.5 TWyr/yr in the Low scenario), and declining thereafter. Only large-scale exploitation of oil shales and tar sands seems capable of reversing this decline, because these unconventional sources are the only ones of sufficient global magnitude identified so far.
- Indeed, by 2030, only 61 percent of liquid fuel demands would (under the assumptions of the High scenario) be met by produced crude oil. The remainder (39 percent) must come from synthetic liquid fuels made from coal. The level of demand for liquid fuels is the engine for change in these scenarios, especially after the year 2000 when most of the major changes in energy supply patterns are expected. In combination with this, the ceiling assumed on oil production in region VI (2380 GWyr/yr or 33.6 mbd) would have a great impact on the extent and timing of oil alternatives: as imports become restricted, alternatives appear sooner and to a greater extent.
- Coal would be required in tremendous quantities—7 to 13 billion tons per year in 2030 under the conditions of the scenarios. Some 56 percent of these amounts would be required for the production of synthetic fuels. Whether this amount of coal can be mined in the world is open to serious question.
- Efficiency improvements and "substitutions" of less energy-intensive economic activities for more energy-intensive ones would reap substantial energy savings in the developed regions. There, technical and economic sophistication and saturation effects could reduce growth in final energy from the 3.8 percent per year values of the past two or three decades to 1.1 to 1.7 percent per year over the next five decades.
- Development needs, expanding populations, and increasing urbanization would lead to continued energy growth in the developing regions. The prospects for saving energy—reducing energy growth relative to economic growth—seem dim for these regions; there, energy-to-GDP elasticities are expected to be greater than one, while they are likely to be less than one in the developed regions.
- The mix of sources for electricity are likely to undergo great transformation. By 2030, if liquid fuels are to be reserved for transportation and petrochemicals, then some 60 percent (in the High scenario) of all electricity generation would be from nuclear. The share of electricity generated by coal would decline from 40 percent in 1975 to about 15 percent by 2030 in the High scenario. This decline would occur as demands for coal to produce liquid fuels increase rapidly. In general, oil and gas would be withdrawn from power plants in the near future; yet gas may be forced to return later as a source of electricity (as other sources become supply constrained).

- Production of natural gas would increase moderately throughout the study period under the conditions of the scenarios, reaching 3.5 to 6 TWyr/yr in 2030 (compared to 1.5 TWyr/yr in 1975). There is plenty of natural gas in the world; the problem is transporting it economically to where it is needed. With this resolved (and several solutions are in development), gas could become a truly global-scale fuel in the coming decades.
- Hydroelectric power, exploited to essentially its full potential in the scenarios, would meet from 4.1 to 6.5 percent of primary energy demand by 2030; this would represent 11.3 to 17.8 percent of total electricity demand, depending on the scenario. Over 60 percent of the world's total hydroelectric potential capacity is in the developing regions; exploitation of this potential would meet 17 to 31 percent of electricity demand of the developing regions by 2030 in the scenarios.
- Soft solar, geothermal, and other renewable energy sources would make important, although usually local and relatively small-scale, contributions to the supply mix by 2030. (The potential in developing regions may be considerably higher than in the developed regions.) Together, in the High scenario, they would account for as much as 1.3 TWyr/yr (about 3.7 percent) of primary energy. All renewables (including hydroelectricity) would account for just 5 to 7 percent of primary energy by the year 2000 in the developed regions (6 to 7 percent in region I, NA); by 2030, the share still would not exceed 8 percent.

The energy system of the future would be a mix of many sources—some small, some large, some conventional, some unconventional. The mix would be the product of an intricate balancing act, allocating limited supplies of each fuel to meet the varied and, in the aggregate, relatively inelastic preferences of consumers. The mix of sources would become more heterogeneous in the future than it has been or is now. International dependencies would increase; energy systems would become increasingly complex.

By 2030, substantial shares of the (estimated) available fossil resources would be consumed. By 2030, some 68 percent (in the High scenario) of crude oil resources available at a cost of less than $20 per barrel[a] and 49 percent of equivalent cost gas resources would be exhausted. By far the largest resources available for future use after 2030 would be expensive, unconventional oil (principally oil shales and tar sands), unconventional gas, and high cost coal.

This chapter summarizes the assumptions and findings of the IIASA Energy Systems Program's quantitative analysis. The summary does not necessarily represent equitably the various pieces of the work reported in detail in the preceding seven chapters. Nor does the summary purport to state the unequivocable "most important" findings. It does claim to summarize the main threads of the analysis and to highlight many of the key issues. The probing reader is urged to consider the preceding seven chapters and to refer to the lists of references provided at the end of these chapters.

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[a] Prices are given in constant (1975) U.S. dollars.

TWO SCENARIOS OF THE FUTURE

As has been described in Part I and in Chapter 13, the goal of the quantitative analysis of the IIASA Energy Systems Program is synthesis—the integration of many special studies into a global, long-term, energy supply and demand whole. The synthesis is meant to explore the dimensions of a foreseen energy transition away from cheap oil and gas and toward a sustainable energy system. A highly iterative procedure (Chapter 13) is adopted for this purpose.

Two scenarios (the High and the Low) are constructed as a means of spanning the conceivable evolutions of global energy systems over the next fifty years. Criteria for the development and acceptance of these scenarios include, foremost, consistency and reasonableness. The scenarios also must have continuity—they must recognize the inherent lead times and inertia of economic and energy systems. Finally, the scenarios must span a sufficiently wide range so that a spread of plausible outcomes is encompassed.

Two basic development variables define the scenarios—population growth and economic development (measured in growth of gross domestic product). Chapter 14 presents the scenario definitions in detail. Table 20-1 summarizes some of the key assumptions.

The scenarios, by assumption, are moderate departures from observed trends. They postulate no major surprises—disasters or bonuses—and no sweeping political or economic overhaul in any world region. In a high-low range of such scenario futures, there is thought to be considerable learning.

Economic growth rates gradually decline in these scenarios, by assumptions, and are iteratively adjusted based on analytical results, because among other things higher cost and more difficult to supply energy restrain economic growth. In the High scenario, growth rates are halved in the developed regions and nearly halved in the developing regions from average rates over the past twenty-five years; the rates in the Low scenario are, of course, even

Table 20-1. Two global scenarios, major assumptions.

	High Scenario	*Low Scenario*
Population		
Factor increase, by 2030	2	2
To, in 2030	8×10^9 inhabitants	8×10^9 inhabitants
GWP (gross world product)		
	Declining Growth	
Factor increase, by 2030	6.5	3.6
For average annual growth (percent)	3.4[a]	2.4[a]
GRP (gross regional product)		
Per capita		
Increases from (1975$/cap)	240-7050	
To (1975$/cap) by 2030	1000-25,000	550-13,000

[a] The numbers here are not meant to indicate constant and, by implication, ongoing growth rates; rather, they link the years 1975 and 2030.

lower. Per capita growth rates in OECD countries by 2030 are 1 percent or less than 1 percent per year; in other regions per capita growth rates by 2030 are 1 or 2 percent per year. In short, by any recent historical perspective, the economic growth rates of both scenarios are quite low.

Still, some have argued that the recent past was an extraordinary period in economic history and that economic growth rates should be expected to decline. Energy problems and maturation of economies will combine to hold down growth, it is said. The scenario projections already reflect this to an extent. Yet no one has yet satisfactorily described a viable no growth economy. Still, a stronger reflection of this view would contend that the scenario growth rates here might be too high; the energy supply analyses (Chapter 17) might tend to substantiate the contention. Lower economic growth rates than those projected here would surely ease the energy problem, but would almost equally surely exacerbate other problems.

For example, for some regions, the scenario projections might be discouragingly low relative to hoped for economic development. In GDP per capita terms, only the Middle East/Northern Africa (region VI) is projected to reach average 1975 OECD levels by 2030. In the High scenario, Latin America (region IV) reaches \$4480 per capita; region III (WE/JANZ) in 1975 was \$4259 per capita. The scenarios, which presume an important dependence of the developing regions on the developed regions, hardly reflect a "new international economic order."

At the same time, even with very low economic growth rates in the developed regions, very low population growth rates in these regions would combine to produce hard to imagine average GDP per capita figures by 2030. Region I, for example, would reach over \$25,000 per capita by 2030 in the High scenario (or \$13,000 per capita in the Low scenario), compared to \$7046 per capita in 1975. Region III would reach \$8700 to \$15,200 per capita by 2030. Region II would have levels of GDP per capita comparable to region III in 2030—or 50 to 100 percent higher than those of region I today. At the same time, the poorest of the poor, region V, would reach less than \$1000 per capita in the High scenario by 2030.

In the scenarios, economic growth rates are projected to be higher in the developing regions than in the developed regions; but per capita GDP levels by 2030 remain very high in the North and disturbingly low in the South. Political and economic relationships—North/South and East/West—seem sure to change under such conditions.

Without further exploration of these dimensions, the scenarios as described here are evaluated in energy terms; the richness of the analysis can lead then to the study of a fuller set of possible implications.

HOW MUCH ENERGY WILL BE NEEDED?

Over the previous twenty-five years, global primary energy demand has grown at a surprisingly consistent 4.8 percent per year. This cannot continue indefinitely. It is a simple fact that, in a finite world, exponential growth must ultimately stop. A 5 percent per year growth in energy use, if continued over the next five decades, for example, would necessitate an increase in one year (2030) of 75 percent of today's total annual energy use. Seven years later the required annual growth would exceed today's total annual use. The question is not whether energy growth will slow down, but when, at what level, in which world regions? With what implications will it slow down?

In the scenario analysis process, the implicit assumption is made that there will be no drastic sociopolitical or economic evolutions over the next five decades. The developed regions, it is assumed, would shift economies more to services and more to less energy-intensive industries and would adopt a broad array of more efficient energy practices—thus altering lifestyles to an extent. Developing regions' economies would grow at relatively high rates, would industrialize extensively, and would (in some cases) be nearing "developed" status. But these tendencies are more like observed or expected trends than they are like radical changes of economies or lifestyles. If truly radical departures from trends were to occur, they could change energy demand prospects markedly.

Radical changes of two kinds, especially, could alter energy demand futures significantly.[b] First, a very rapid and extreme shift to service-sector-dominated economies could save appreciable amounts of energy. But, one must question the extent to which such shifts could occur and viable global economies could still exist. (Someone has to produce concrete for office buildings.)

Second, a strong decoupling of transportation activity from economic growth could lower energy demand significantly. Over the last two decades in the United Kingdom, for example, two-thirds of all energy use increases have been due to transportation activities; one-half of the total increase has been due to private automobile travel alone (Leach et al. 1979). Does this reflect an inviolable pattern of development? Can economies—mature or developing—grow without attendant large increases in transportation?

The assumptions made for the scenarios here reflect the need—and the expectation—of a slowdown in energy demand growth in the developed regions. For example, the scenarios project that total global primary energy growth over the next fifty-five years would be just 1.9 to 2.8 percent per year. They project large improvements in the developed regions in automobile efficiency, home insulation levels, and efficiency of energy use in industry. They project, for some regions, saturation of many energy-intensive activities and the introduction of new, fossil-fuel-saving energy sources and uses. For the High scenario, solar systems would cover 13 percent of all household/service sector space heat and hot water needs in OECD countries by 2030; renewable energy sources would meet 36 percent of heat and hot water needs in dwellings in the developing regions. Electric automobiles could account for 20 percent of all urban automobile travel in the developed regions by 2030.

These and other measures are introduced in the scenarios not so much to

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[b] See the discussion of the 16 TW case in Chapter 18 for a quantitative exploration of such changes.

reduce energy growth as to reduce the demand for liquid fuels. Liquid fuels in the scenarios come to be used more and more for their essential purposes only—for motor fuel and as feedstocks for petrochemical industries. In 1975, some 64 percent of total liquid fuel use went to these purposes; the scenario assumptions lead to 88 to 92 percent of all liquid fuel use being for either motor fuel or feedstocks by 2030 (see Table 20-2). Liquid fuels, as the supply analyses here show, are almost too dear to burn.

In spite of vigorous measures to conserve liquid fuels, these fuels still represent the major component of energy use in the scenarios in 2030 (Table 20-2). Liquid fuel use would grow at 1.6 to 2.4 percent per year over the next fifty years, compared to a growth of 1.7 to 2.5 percent per year for all final energy. It is relatively more difficult, in many instances, to conserve motor fuel and feedstocks than it is to use energy in other demand sectors. And it is relatively more difficult to conserve liquid fuels in the developing regions than it is in the developed regions. This last point deserves elaboration.

Whereas liquid fuel use, as a share of total final energy, is projected to decline (from 56 to 46 percent) by 2030 in the developed regions, its share would increase slightly (from 48 to 50-54 percent) in the developing regions. Liquid fuels are easy to use. They meet flexible demands and are easily transported. In short, they serve the purposes of development and industrialization rather well. The developing regions need liquid fuels. Wherever possible, the developed regions should conserve liquid fuels by using them only where essential, and there more efficiently, and thus leave the world's oil supplies for the developing regions.

Table 20-2. Shares of electricity and liquid fuels in final energy.

	Base Year 1975	*High Scenario 2030*	*Low Scenario 2030*
Regions I (NA) and III (WE/JANZ)			
Final energy (TWyr/yr)	3.5	8.0	5.6
Electricity (%)	12	21	21
Liquids (%)	56	46	46
Region II (SU/EE)			
Final energy (TWyr/yr)	1.3	3.7	2.6
Electricity (%)	10	23	20
Liquids (%)	34	32	30
Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA)			
Final energy (TWyr/yr)	1.0	10.6	6.0
Electricity (%)	6	13	13
Liquids (%)	48	50	54
World			
Final energy (TWyr/yr)	5.7	22.8	14.6
Electricity (%)	11	17	17
Liquids (%)	50	45	46
Motor fuel and feedstocks in liquid fuel			
Final demand (%)	64	92	88

This critical dimension of difference between the developed and the developing regions might be restated in the following way. Energy can be "conserved" in three ways—by doing better, by doing differently, or by doing without. Doing better means introducing new, more efficient energy-using devices—a technical fix. It means doing the same things more efficiently. Doing differently means altering the mix of economic activities—having fewer energy-intensive activities. It means doing a different set of things without reducing total economic activity. Doing without means saving energy by cutting out some economic activities.

Of course, most energy-saving measures are combinations of these three. And it is sometimes difficult to say whether, for example, driving a smaller automobile is doing better or doing differently. Still, these categories are instructive: the first two require some sophistication (technical and/or societal), while the last one is generally unacceptable. The developing regions, by definition in the midst of the challenges of development, lack sufficient sophistication for either of the first two options. And for them, "doing without" means not developing. It is in the developed regions where energy can be saved; it is in the developing regions where energy will be needed in increasing quantities and where liquid fuels must be available.

Total primary energy can be saved by minimizing the extent of electrification. But electricity serves many useful purposes, is nonpolluting at the end use side, and can even be energy conserving if off-peak electricity is used or if the end use device is a highly efficient heat pump. The potentials in this direction seem rather limited according to the analysis here; electricity generally is assumed to be restricted to its essential uses.

HOW CAN NEEDED ENERGY BE SUPPLIED?

Unless the preceding considerations of future energy demand are very wrong, they would lead quickly to a simple but far-reaching observation: energy—and particularly liquid fuels—must be supplied in prodigious amounts over the next fifty years. Globally, the challenge looks immense but not insurmountable. When examined regionally, the situation may be worse.

The scenario assumptions lead to primary liquid fuel demands of 1.9 to 2.9 times the 1975 level—or 102 to 157 mbd—by 2030 (see Table 20-3). These amounts would exceed, by 44 and 64 percent, the global oil production levels thought to be the maximum possible and consistent with the scenario assumptions. The difference would have to be made up by coal liquefaction—amounting to 31 to 61 mbd by 2030 in the scenarios (Table 20-3). The latter figure is nearly equal to the 1978 total world crude oil production.

Chapter 17 details these and many other observations about global energy supply systems in the long term. The analyses demonstrate the severe supply pressure on liquid fuel sources. They show the potentially vast exploitation of coal (as a source of liquid fuels), the underutilization of gas, and the relatively limited potential (globally) of some other energy supply alternatives

Table 20-3. Two global scenarios: 2030 liquids demand and supply.

	High Scenario	*Low Scenario*
Assuming		
Population factor increase	2	2
GWP factor increase	6.4	3.6
Shift away from liquid fuel demands	Strong Shifts	
Result in		
Primary energy factor increase	4.5X	2.8X
Primary liquid fuel[a] demand factor increase	2.9X	1.9X
Primary liquid fuel demands level	157 mbd	102 mbd
Assuming		
Potential oil resources[b]	4300 X 10^9 bbl	4300 X 10^9 bbl
R/P ratio[c]	15:1 to 30:1	15:1 to 30:1
Result in		
Oil production level	96 mbd	71 mbd
Coal liquefaction (primary energy equivalent)	61 mbd	31 mbd

[a] Primary liquid fuels are all liquid fuel uses counted at crude oil equivalent.
[b] See Tables 17-6 and 17-7 for definitions of resource categories.
[c] Reserve-to-production ratio varies from region to region; see discussion in Chapter 17.
Note: mbd = millions of barrels per day.

over the next five decades. The supply analyses of the High and the Low scenarios, in short, paint a grim picture.

Part of the grimness of the picture reflects the absence of a true energy transition in the scenarios to 2030. The scenario assumptions produce a transition not from cheap, conventional oil and gas to some renewable, sustainable sources, but a transition from cheap oil and gas to expensive, unconventional oil and gas. In the scenarios, the oil and gas era would not be over by 2030: in that year, some 12.8 TWyr/yr (181 mbdoe) of oil and gas would be produced in the High scenario (8.5 TWyr/yr, 120 mbdoe, in the Low scenario). The 1975 global production of oil and gas was 5.46 TWyr/yr (77 mbdoe).

For the world, excluding the centrally planned economies, the "transition," in these terms, is quite striking (Figures 20-1 and 20-2). Known conventional reserves of oil become rapidly depleted in the next twenty to thirty years, while new sources of both conventional and unconventional oil are called upon to meet growing liquid fuel demands. With oil production and exports from the Middle East (or from all of region VI) held about constant, oil sources—including synthetic liquid fuels from coal—from outside of this region are needed more and more.

Oil resources, even in these shift away from oil wherever possible situations, would continue to be exploited in the next five decades. Cheap, accessible, environmentally acceptable resources would be disappearing and would be rather rapidly replaced by expensive, remote, environmentally disagreeable resources. These include poorer fields requiring more intensive drilling and expensive recovery techniques; continental shelves, deep basins and polar areas; and difficult to extract heavy oil and oil trapped in shale rock and so-

Figure 20-1. Oil supply and demand, 1975-2030, world (excluding centrally planned economies), High scenario.

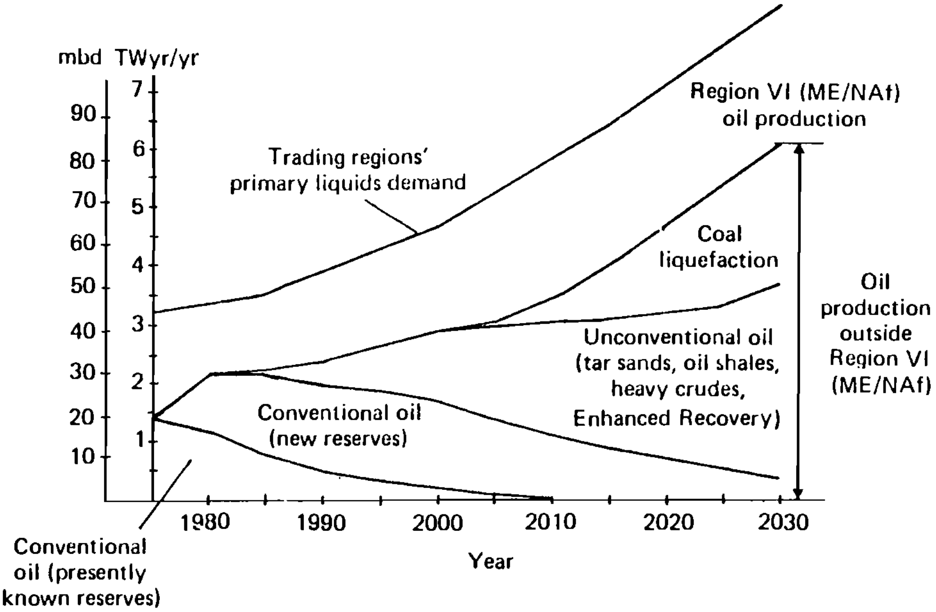
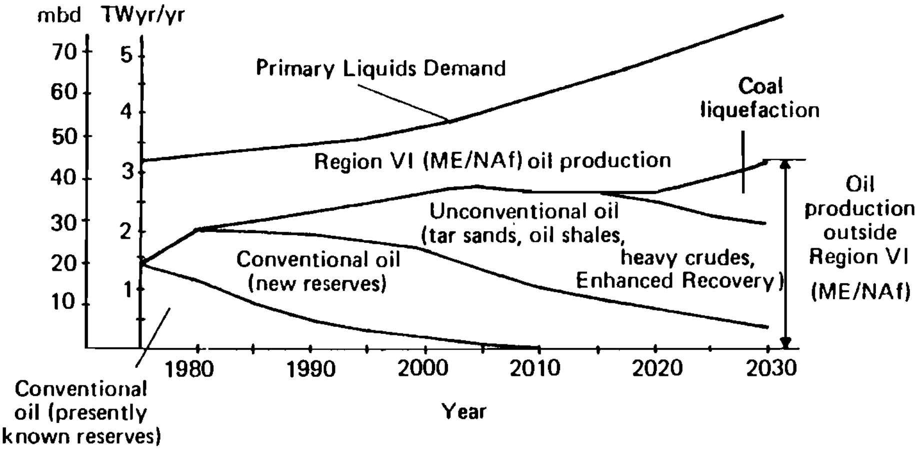


Figure 20-2. Oil supply and demand, 1975-2030, world (excluding centrally planned economies), Low scenario.



called tar sands. The world is already witnessing the lack of new sources of easily accessible oil. Today, oil is drilled in the frozen shores of North Alaska and the hot liquid is sent through more than 1200 km of a $10 billion pipeline. Oil is extracted from the North Sea via rigs whose size dwarfs New York's United Nations Headquarters building. Exploration in remote areas of Siberia is vigorous.

More—many more—oil resources are presently physically available: the world is not yet running out. But the price to be paid—in dollars, in land use, in air quality, and in carbon dioxide buildup—may be too great, for example, to exploit U.S. oil shales or Canadian tar sands at production levels that rival those of the Middle East today. Alternatives to "more oil at whatever costs" are imperative.

The heavy reliance on unconventional fossil fuels and on coal in the scenarios makes their sustainability beyond 2030 doubtful. Some day the world will likely become resource short. Yet the inducements to avoid that day have more to do, in the medium term, with constraints on the maximum rates of oil production than on resource limits. A production ceiling of 33.6 mbd is imposed on region VI in the scenarios—reflecting the explicit desires of that region to stretch out the lifetime of its oil wealth. In other regions, the challenges of starting and/or building up large-scale oil production capabilities are mirrored in the lead times required for such undertakings. The assumptions here allow coal liquefaction capacity in each of the world regions to double every five years (for fifteen to twenty years) after startup. This generous "constraint" does, in fact, become binding in the computer model runs: even more liquefaction is desired in the scenarios.

The international oil trade implications of the continuing tight liquid fuel supply problem could be important. In these scenarios, North America and the Soviet Union become major global energy exporters, particularly after about the year 2020. They would export coal, or synthetic liquids produced from coal, in these scenarios. But what if they chose not to do so—or were unable to do so? Analysis shows that the next available source would be unconventional oils—shale oils, heavy crude oils, and tar sands. Most of these sources are located in North America.[c] In a broad, long-term, and global sense, it may not matter whether synthetic liquid fuels from coal or from shales are cheaper. In either instance, the world would look to the Americas for its extra oil. And in either instance, it may be difficult for the exports to be forthcoming.

These very sweeping global observations are not meant to imply that such "details" as costs do not matter. Quite the contrary, different relative costs than have been assumed here could matter a great deal in many regions of the world. Generally, the energy supply cost assumptions behind these analyses are optimistic—both for resource extraction methods and energy conver-

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[c] A notable exception is the heavy crude oil deposits in Venezuela. But Latin America as a whole is forced, in these scenarios, to increase oil production for domestic needs at a rate sufficiently high as to cast doubt on any net export prospects.

sion technologies. High real costs could lead to very different energy supply mixes or to rather low energy demands. Chapter 18 briefly explores this possibility.

As it is, the global primary energy supply mix in the scenarios seems to stretch almost every source to its logical maximum (see Table 17-2). Coal production would grow by 2.9 to 5.3 times in fifty-five years in the scenarios; oil production by 1.4 to 1.9 times; natural gas by 2.3 to 4. Nuclear power would contribute some 23 percent of primary energy in the High scenario; in 1975 it was just over 1 percent. Solar and other renewables seem to fall far short of their hoped for potentials five decades from now. The potential of each supply source is discussed at length in Chapter 17. And Chapter 18 explores some ways in which different utilizations of gas, nuclear, and solar could change the global supply picture.

Natural gas resources could, conceivably, augment liquid fuel supplies by, for example, direct conversion of methane to methanol. Globally, this would make fuller use of relatively abundant natural gas resources. Viewed regionally, this answer to the liquid fuel problem is a less than perfect one. Natural gas resources of the world are largest in region VI, where conversion to liquids for export would simply compete with intentionally restricted oil exports. Natural gas is also rather plentiful in North America and the Soviet Union, which are also both endowed with vast coal resources. Thus, greater use of available gas resources to make liquid fuels (generally a good idea) may simply be a replacement of one abundant primary source (coal) by another (gas).

The global uncertainties over nuclear capacities induced the creation and examination of two "alternative cases" (Chapter 18)—the Nuclear Moratorium and the Enhanced Nuclear cases. The Nuclear Moratorium case postulates no new nuclear capacity in the world, starting now; the solution would use more coal than that predicted in the Low scenario, upon which this case is based, and some solar electricity production. The Enhanced Nuclear case postulates a more rapid buildup of nuclear capacity than that projected in the High scenario, for the purpose of generating a liquid secondary energy carrier (methanol) through use of the heat of breeder reactors. Particular regional situations preclude an overwhelming nuclear buildup; some regions simply have better options.

These analyses of energy supply systems for the scenarios and the alternative cases have sobering implications. The challenges to be faced, if energy is to be supplied for worthy development needs, are not small. One way of assessing whether the scenarios and alternative cases represent feasible energy systems evolutions is by interpreting their results in economic terms.

Economic Interpretations

A fundamental uncertainty (if not the fundamental uncertainty) in projections of energy consumption is captured by the question: Must energy use and gross economic activity go lock step into the future, inflexibly bound by history and/or "the system"? The answer offered by this study is "partly yes and partly no."

Energy as a productive input to the economy is strongly tied to economic production. The only ways to loosen the tie are through technological development (do better)—a slow, steady process if history offers a lesson here—and through substitution of nonenergy inputs such as more capital or more labor for less energy (do differently). In general, interpretation of the scenario results indicates (as expected) that the developed regions would have significantly greater potential for reducing energy use per unit of economic output by means of technological development and substitution than would the developing regions. Sophistication is required. In particular, it turns out that region II, having a very industry-intensive economy, shows the greatest potential for saving energy in this way.

But energy is not only a productive input to the economy; it is also a "final demand" item—it is consumed like other final products. And energy as a final demand item is probably not strongly tied to economic production. Consumers could spend disposable income on less energy-intensive instead of more energy-intensive goods and services. (This would be a departure from past behavior.) And even the energy-intensive items that are purchased (automobiles, appliances, travel) might become considerably more energy efficient, and the energy-economy fetter would loosen.

Chapter 15 deals in depth with these energy-economy issues. And it presents an evaluation of the overall scenario results for primary and final energy demand in terms of income and price elasticities. In this way, one observes a definite reduction in the growth of total energy use relative to economic growth in the developed regions. In the developing regions, income elasticities would be lower than in the past, but would still be greater than unity: it takes more than a 10 percent increase in energy use to give a 10 percent increase in GDP.

The projected decline in income elasticities for the developed regions is significant (see Chapter 15), particularly for North America (region I)—implying that strong energy saving measures are, indeed, incorporated in the scenarios. Price elasticities are expected to be generally high in the developed regions and much lower in the developing regions. This signals that the potentials for technological development and substitution (as relative prices for energy rise) in the developed regions would be considerably greater than in the developing regions. Faced with higher prices for an essential commodity (energy), the developing poor are hard pressed to do better or to do differently: to do without is only a last resort.

One could calculate all energy savings as if they were price induced, and many economists do just that. For the very long term, this seems inadequate—and various government mandates and energy-saving innovations are only questionably "price induced." Still, prices are important in both the long and the short term. Energy prices for the scenarios are calculated here (Chapter 15) from energy production costs—which would increase by between three and four times in various world regions over the next fifty years. By 2010, the scenarios give price increases for final energy prices (paid by consumers) of 2.4 to 3 times 1972 prices; by 1975, real consumer prices had risen by just 40 percent (i.e., a factor of 1.4) since 1972, so an additional increase of 1.7 to 2.1 times is expected by 2010. Part of the reason for this price rise is the projected growth in the international crude oil price to $19 and $21 per barrel in the two scenarios reached by 1990. (These figures are 1975 dollars; in 1980 dollars the same prices would be $28 and $31 per barrel.)

One final observation is worth making here about energy prices. Increased payments for energy—energy prices multiplied by energy use—reflect a potentially unsettling trend. In the developed regions, the scenarios would increase energy payments as a share of GDP by some 18 to 35 percent by 2030. In the developing regions, the increase would be 300 percent and more. Such indicators dim hopes for more rapid economic development in the future.

Another cut through the energy payments issue is to consider energy investments. These, discussed in some depth in Chapter 19 for both the scenarios and the alternative cases, are projected to double as a share of GDP in the developed regions and to more than triple in the developing regions by 2030 (Figure 20-3). The alternative cases, in very aggregate terms, differ only slightly from the scenarios in this regard.

These various economic interpretations of scenario results perhaps raise more questions than they answer. At this stage of analysis, this is good. The potential impacts on economies of rising energy costs is already a primary concern of governments; by these projections, it is likely to remain so for quite some time to come.

REGIONAL AND INTERREGIONAL PROSPECTS

Regions Are Different

On the surface, it would seem that region VI (ME/NAf) would be the most resource rich of the world regions, while region III (WE/JANZ), for example, would be noticeably resource poor. A closer scrutiny offers some surprises.

In conventional oil,[d] region VI is rich, with 159 TWyr of resource compared to 100 TWyr for region IV or just 20 TWyr for region III. But if all (conventional and unconventional) crude oil resources are counted, region VI places third (almost fourth) among the regions; the heavy oils of region IV and the oil shales and tar sands of region I give each of those regions more total oil resource than region VI. Of course, the issue is extracting and using the unconventionals. Regions are different.

Consider total fossil resources. If one sums the total resource estimates of Tables 17-6 and 17-7 for each of the regions, the richest fossil resource regions are found to be regions I and II. Region V is found to be relatively resource poor. All other regions are about the same—for example, regions III

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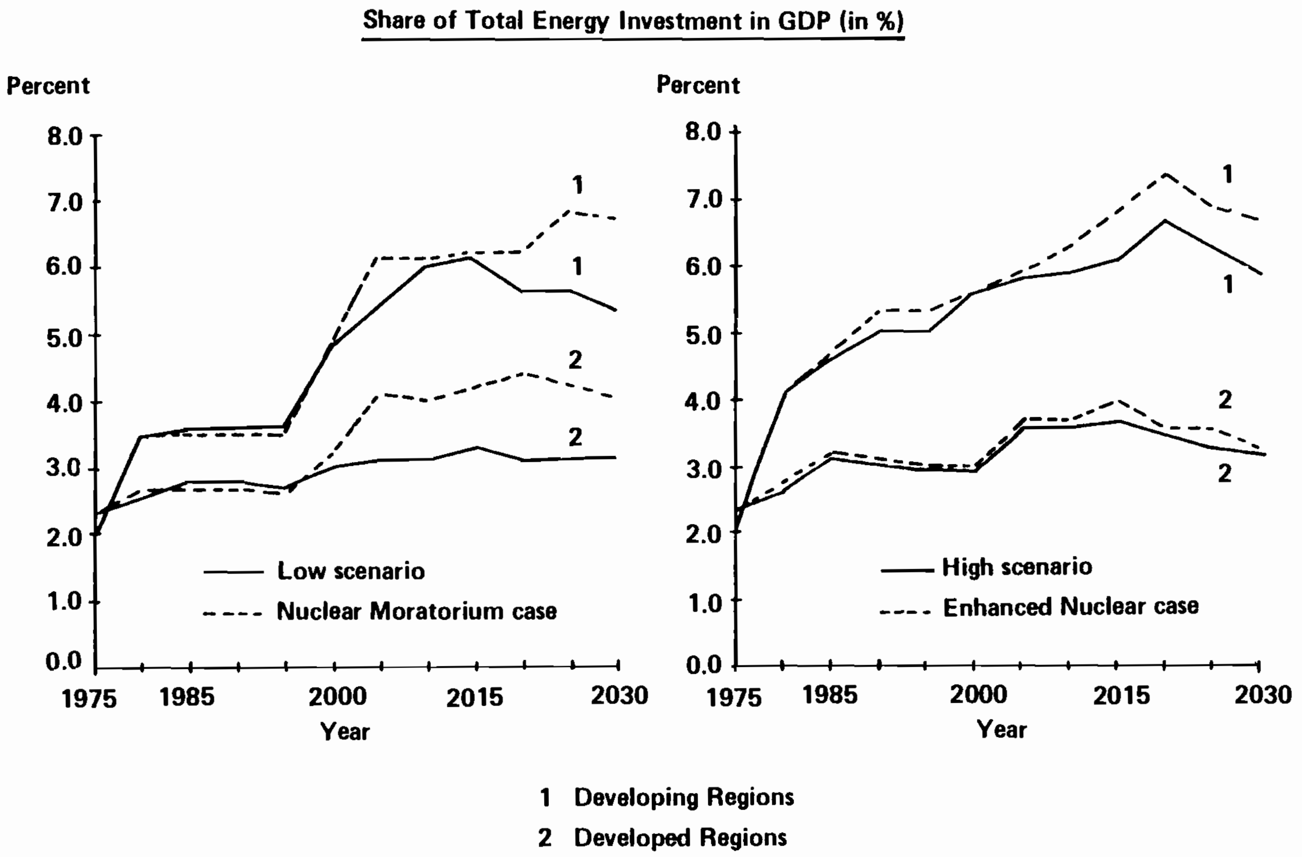
[d] Conventional oil here is oil estimated to be producible for less than $20 per barrel (1975 U.S. dollars); oil categories 1 and 2 are defined in Table 17-6.

Figure 20-3. Share of total energy investment in GDP (in percent).



Share of Total Energy Investment in GDP (in %)

and VI have about the same total fossil resources! The reason is coal. Regions I, II, III, and VII have over 90 percent of the world's coal resources, by the estimates here. But the difficulties of using such large resources tend to dampen enthusiasm about their size.

In the end, resource richness or poorness has more to do with the size of domestic resource pools relative to internal demand for fuels. The resource rich, it seems logical to believe, are those who can export energy. Consider, then, resources per capita (using 1975 population data).

Region VI obviously leads in conventional oil resources per capita; the same is true for gas. The region is blessed with relatively large volumes of cheap to produce oil and gas and a very small population. The apparently high oil resources of region I and region IV shrink somewhat when divided by their large populations. And in terms of all fossil resources, the high coal resources in regions I and II reduce in significance when confronted with large populations; in total fossil resources per capita, region VI still appears resource rich. And the most resource poor, by far, is seen to be region V. The spread is from over 2000 kWyr per capita for regions I, II, and VI to 115 kWyr per capita for region V.

These resource comparisons reveal some of the many differences among regions. The next sections summarize briefly the peculiarities of each region. Of course, it is impossible to capture the richness of diversity among the regions and the depth of considerations important in each region. What follows is illustrative of the analyses and findings of this part, organized now by region rather than by topic.

There are hazards in this approach. The necessary regional grouping of countries necessitates some simplifying assumptions. For example, it is assumed here that there would be completely free energy trade within a region—that is, that domestic, regionally aggregated resources would be used first and that then a net import or export (but not both) could occur. Clearly this violates reality. Today region IV is a net exporter of oil, but Venezuela exports to the United States, and Brazil imports from the Middle East.

Also, one must recognize that the decisionmaking entities of the world are—and are likely to remain—countries, not regions. Each country within a region would find that its own energy prospects would differ from those of the region as a whole. Sometimes regional aggregates are dominated by just one or two countries. But generally, regional trends are instructive, and regions do differ from one another.

The presentations that follow have been extracted from the preceding seven chapters, where fuller elaborations for each of the regions can be found under topical headings.

Region I, North America (NA)

In these projections, the character of the North American energy future is dominated by three considerations—a postindustrial, mature economy "slowdown"; substantial energy savings because of technological advances and some restructuring of economic activities; and a rapid buildup of a coal liquefaction industry to replace domestic and imported oil. None of these changes, except possibly the last, is expected to produce profound or sweeping changes in lifestyles of North Americans.

The North American economy is projected here to grow at real rates declining to 1 and 2 percent per year after 2015, from more than 3 percent per year in the 1950s and 1960s. Per capita GDP growth rates would, of course, be somewhat lower. People's traveling and other energy-consuming activities are expected to saturate—meaning that aggregate growth would be slower. But growth is still expected. People, in these projections, would use public transit more, would live in better insulated homes, would live (on average) more in apartments or townhouses, and would consume a less energy-intensive mix of industrial products. But still, they would commute to their jobs, take vacations, drive automobiles. These scenarios do not postulate an all bicycle or an all high rise apartment future.

The well-publicized "fat" in the North American energy system would be substantially cut out in the scenario projections. Automobiles averaging 35 mpg in 2030, homes 40 percent more efficient in terms of heat loss, and solar collectors attached to 50 percent of all post-1975 single family homes are assumptions that contribute to the diet.

Oil would be avoided wherever possible. Still, liquid fuel demands would grow sufficiently to require a major exploitation of synthetic liquid fuels—from shales or from coal. Coal production in region I is projected to reach 1.5 to 2.7 TWyr/yr by 2030, 3.1 to 5.6 times its 1975 level. In the High scenario, some 55 percent of this production would go to a synthetic liquid fuel industry.

The environmental, labor, water, and transportation issues surrounding coal production in the United States cast some doubt over rapid coal production increases. Yet the liquid fuel demands seem irreducible, and the coal resource is available. The world would need the coal-based liquid fuel supply that region I could export. (In the High scenario by 2030, region I would produce 750 GWyr/yr of coal for export, either as coal to produce synthetic liquid fuels elsewhere or as synthetic liquid fuels produced in region I.) The major global alternative to coal liquids would seem to be shale oil—also a region I export.

Primary energy use in region I would grow from some 2.65 TWyr/yr in 1975 to more than 6 TWyr/yr in the High scenario (4.4 TWyr/yr in the Low) by 2030. Of this, the dominant sources would be nuclear and coal (see Figure 20-4). In 1975, nuclear and coal together were 0.55 TWyr/yr (21 percent), while oil and gas together provided 1.93 TWyr/yr (73 percent); in 2030, nuclear and coal together would give 2.9 to 3.9 TWyr/yr—65 percent—while primary oil and gas together would total just 1.2 to 1.8 TWyr/yr (27-30 percent), given the assumptions of these scenarios. The supply mix of the future seems to be driven toward coal and nuclear, based on the aggregate of supply constraints and market restrictions. With greater flexibility in these

Figure 20-4. Primary energy consumption by source for region I (NA), 1975-2030.

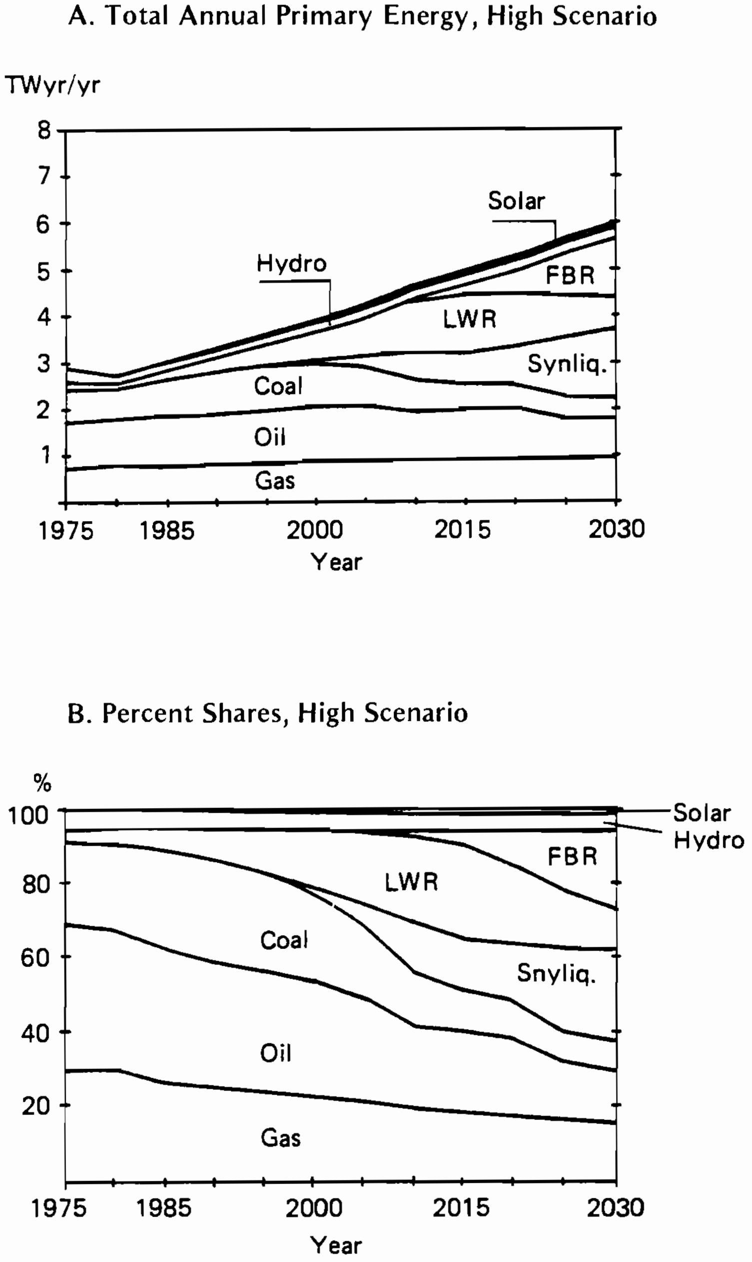
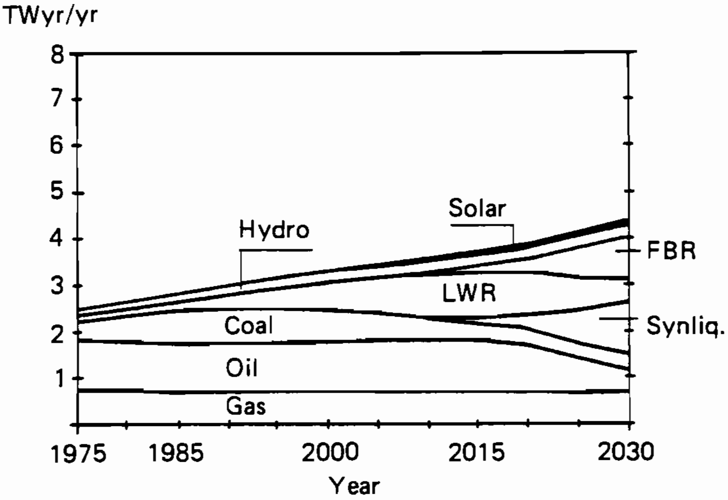
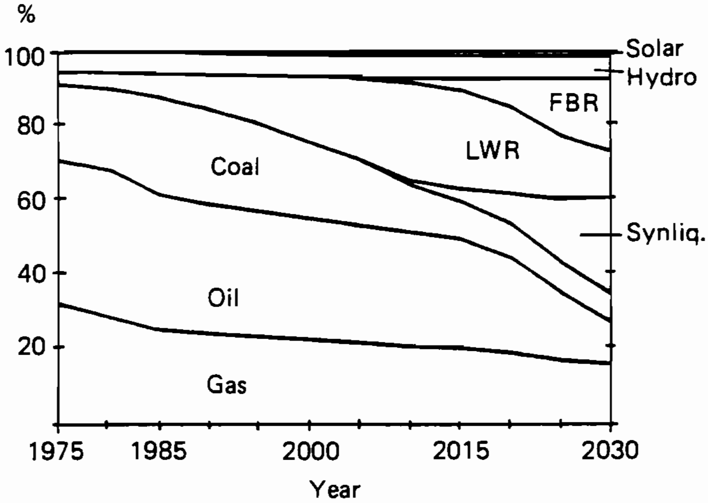


Figure 20-4 continued.

C. Total Annual Primary Energy, Low Scenario



D. Percent Shares, Low Scenario



constraints than assumed here, a conceivably big energy source for the future in NA could well be natural gas.

Region II, The Soviet Union and Eastern Europe (SU/EE)

In the centrally planned economies of region II, the energy future is shaped by a clear intent to expand industrial production and productivity while minimizing oil use wherever possible. Central economic management would seem necessary to do this, as would successful development of the energy riches in inhospitable Asian portions of the region.

Economic growth rates are expected to be high in this region—higher than in other developed regions, yet lower than the rates of the 1950s and 1960s. The growth rates of the scenarios would give GDP per capita levels 40 to 100 percent higher in this region than today's region I level. Much of the GDP would be industrial output, as it is today, and slow population growth in the region would keep labor supply as a major constraint on economic growth prospects.

Industrial productivity gains are expected to be the main source of energy savings. Soviets and East Europeans already drive small, fuel-efficient cars (and relatively few cars) and generally do not lead as energy-intensive lifestyles as do consumers in region I or in region III.

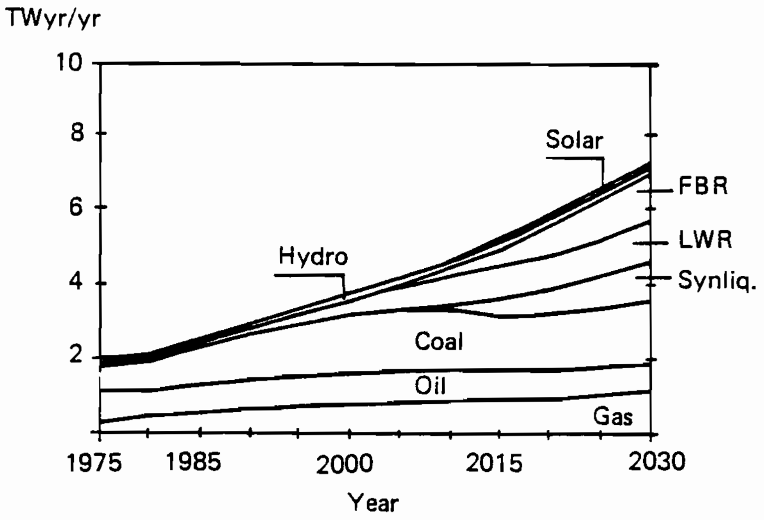
The shift away from a reliance on oil has three main elements. First, communities would be sited so as to maximize public transit use and minimize automobile travel. Second, oil would not be used in power plants—these shifting more to gas (now), coal, and (eventually) nuclear. And third, district heat and combined heat and power capacity would be rapidly expanded for buildings and industrial heat supplies.

The intent thus to minimize liquid fuel use and to exploit the vast gas and coal resources of Soviet Asia for district heat and power supplies leads to the conclusion here that the Soviet Union would not become an oil importer in the foreseeable future. Some oil exporting from the Soviet Union to Eastern Europe would continue, and expanded net exports of gas and coal from the region as a whole could occur.

The greatest shift in region II's among primary energy sources would be toward nuclear and, to a certain extent, toward coal (see Figure 20-5). In the High scenario nuclear power would provide 33 percent of total primary energy by 2030; coal would add 38 percent. Oil production, as a share of total liquid fuel supply, would decline substantially in these estimates as coal liquefaction largely takes over liquid fuel supply. Gas production would remain high, at over 1 TWyr/yr in 2030 or 16 percent of total primary energy, in the High scenario. These primary energy trends look, in the aggregate, very much like those of region I. This is particularly interesting since the underlying energy demand structure and mix of economic activities in the two regions are very different.

Figure 20-5. Primary energy consumption by source for region II (SU/EE), 1975-2030.

A. Total Annual Primary Energy, High Scenario



B. Percent Shares, High Scenario

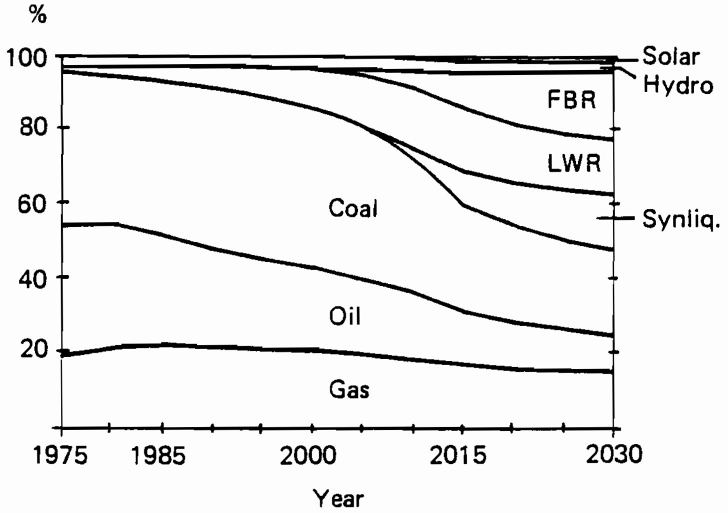
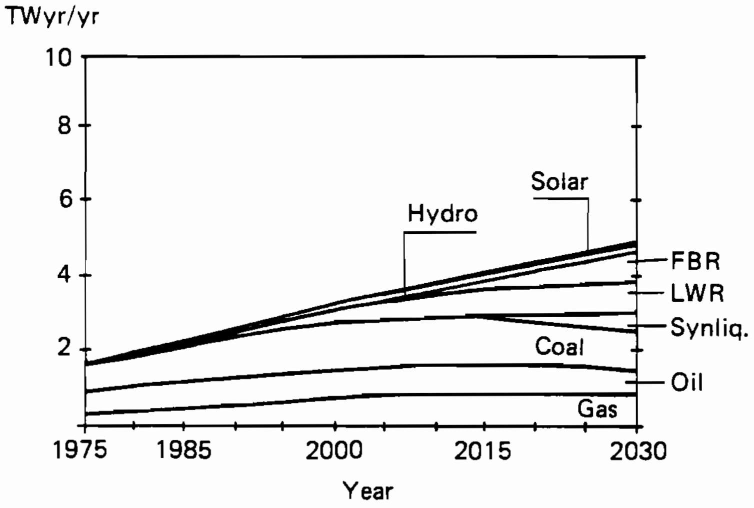
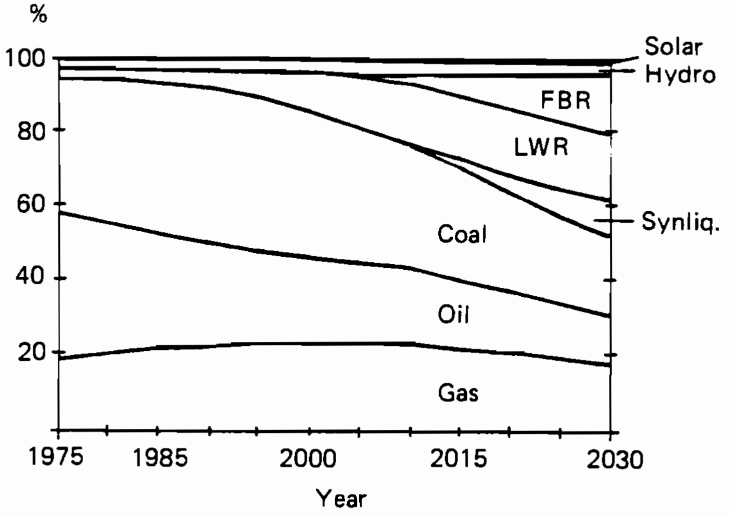


Figure 20-5 continued.

C. Total Annual Primary Energy, Low Scenario



D. Percent Shares, Low Scenario



Region III, Western Europe, Japan, Australia, New Zealand, South Africa, Israel (WE/JANZ)

Region III is a highly heterogeneous region. All countries in the region can be considered "industrialized," but to varying degrees, and countries differ considerably in their energy resource endowments. Today the region as a whole depends extensively on imported oil. This dependence is likely to continue in the coming decades, even as the region's economic growth slows and indigenous coal and (to a lesser extent) domestic oil resources are developed. A strong reliance on nuclear power for electricity production can free domestic coal resources for synthesis of liquid fuels; ultimately, nuclear breeding may be a viable source for liquid fuels in this capital-rich but, basically, energy resource-poor region.

GDP growth in region III is projected to decline as many national economies mature and population stabilizes. By 2030, real annual economic growth would be as low as 1 or 2 percent per year by the scenario assumptions. At the same time, the economy would continue shifting toward services. In 2030, GDP per capita levels would exceed (by 20 to over 100 percent) those in region I in 1975. Yet the region would not entirely take on North American lifestyles. Extensive use of public transit systems would continue, air conditioning use would remain rather small, and electricity use for home appliances would not reach 1975 U.S. levels, for example. High energy costs have affected—and would continue to affect—the specific development paths for this region.

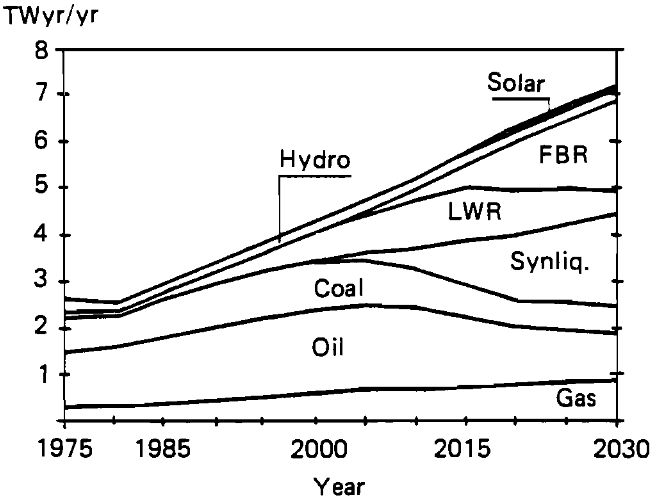
Because of its high costs, energy is currently being used more efficiently in region III than anywhere else. The potentials for energy savings through technical fixes are smaller in the region than in region I. Still, various measures can reduce energy demand growth—by dampening tendencies of increased automobile travel and by building even more energy-tight buildings.

The high oil import dependence of this region would cause it, in these projections, to shift strongly away from using liquid fuels wherever possible. Yet liquid fuel demand would necessitate 1400 to 2100 GWyr/yr of secondary liquid fuels by 2030, from just 980 GWyr/yr in 1975. If for the region domestic oil production were 300 GWyr/yr (High scenario) by 2030, and if domestic coal production were 1000 GWyr/yr, and if 400 GWyr/yr of this coal were turned into synthetic liquids, then nearly 1600 GWyr/yr of coal imports (or, equivalently, 1000 GWyr/yr of synthetic liquid fuel imports) would be required from regions I and II simply to meet secondary liquid fuel demands. These imports, coupled with oil imports of 600 GWyr/yr from region VI in 2030, paint a discouraging picture of continued import reliance for essential liquid fuels in region III. (The Low scenario would be, in these terms, more encouraging; no coal imports would be required. But oil imports from region VI would total 1100 GWyr/yr, instead of 600 GWyr/yr, by 2030 in the High scenario.)

Region III's primary energy demand would reach 4.5 to 7.1 TWyr/yr in these scenarios by 2030, compared to 2.26 TWyr/yr in 1975 (Figure 20-6). Nuclear power would represent the largest single addition to the primary

Figure 20-6. Primary energy consumption by source for region III (WE/JANZ), 1975–2030.

A. Total Annual Primary Energy, High Scenario



B. Percent Shares, High Scenario

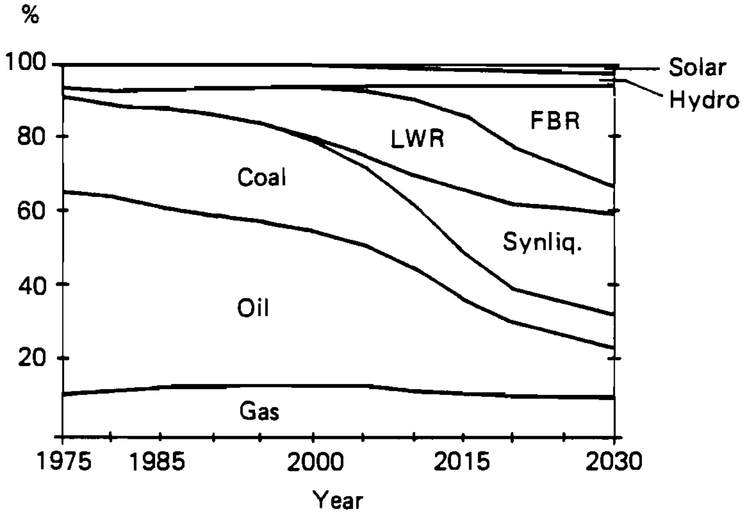
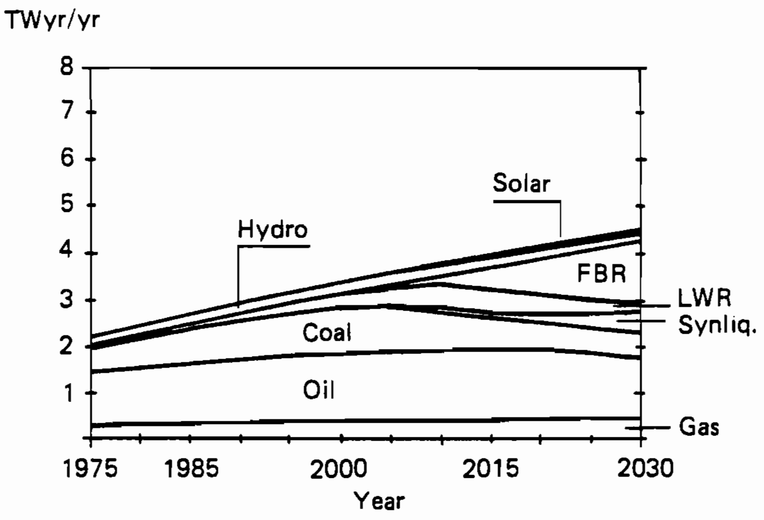
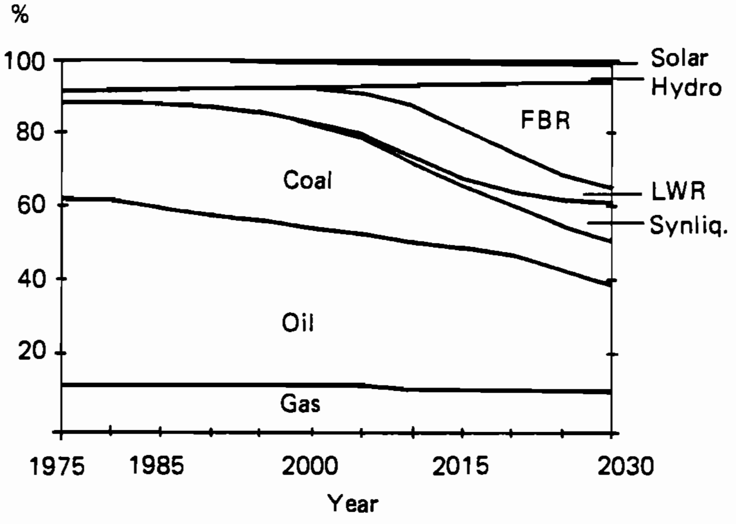


Figure 20-6 continued.

C. Total Annual Primary Energy, Low Scenario



D. Percent Shares, Low Scenario



mix, accounting for about 34 percent of primary energy by 2030 in the High scenario. Domestic oil and, especially, natural gas would be expanded at the highest feasible rate in the scenarios; still, their contribution would grow to just 1.8 TWyr/yr by 2030 in the High scenario (from 1.49 TWyr/yr in 1975), while their share together of total primary would drop from 66 to 25 percent for the scenarios. The massive exploitation of coal in this region—domestic and imported—still leaves an approximately constant (25 percent) share for coal.

Region IV, Latin America (LA)

In region IV, the dominant energy source of the past, present, and future is oil. Adding the recent increased oil resource estimates for Mexico to the vast heavy crude oil potential in Venezuela and Colombia produces total oil resource figures that seem capable of supporting even the high growth prospects of this region.

Region IV, like other developing regions, is projected to have a more rapid GDP growth than that of the developed regions. The projected range is 3.5 to 4.4 percent per year (average) to 2030; these are high by global standards, but still are reduced rates from the recent past. In the High scenario, per capita GDP in 2030 would exceed that in region III today. But the challenges to such development would be formidable; region IV would hold some 800 million people in 2030—two and a half times its 1975 population. Providing sufficient services—and jobs—for so many people would require all the energy and other wealth that the region can generate.

Assuming that some fraction of heavy crude oil can be produced at relatively low cost, then all of the oil production necessary for domestic needs in the scenarios to 2030 could be provided from resources at $16 per barrel or less. Total LA oil production would grow from 4.6 mbd in 1975 to 16 to 25.5 mbd by 2030 in the scenarios. These are 2.3 to 3.2 percent per year annual increases in output; from 1975 to 1978 the growth was 2.6 percent per year. But can 3 percent per year growth be sustained for fifty-five years?

The assessment here is that region IV can increase its oil output to meet domestic needs, but would choose not to export oil. Too rapid rises in income can be destabilizing; there are signs already that the oil-rich countries of the region would build up their petroleum industries only at a carefully measured pace. Also, oil production solely for internal purposes would be enormous, aside from any production for export. The oil production rates for the region in 2030 in the scenarios equal 30 to 45 percent of the total global production in 1975.

Major nonoil energy sources in the supply mix of the future in region IV are expected to be hydroelectricity and some other renewable sources—notably commercially distributed wood (e.g., charcoal for industry and households) and ethyl alcohol from plantation crops (extensive plans are being discussed currently in Brazil).

The primary energy source mix in the High scenario for LA (Figure 20-7)

Figure 20-7. Primary energy consumption by source for region IV (LA), 1975-2030.

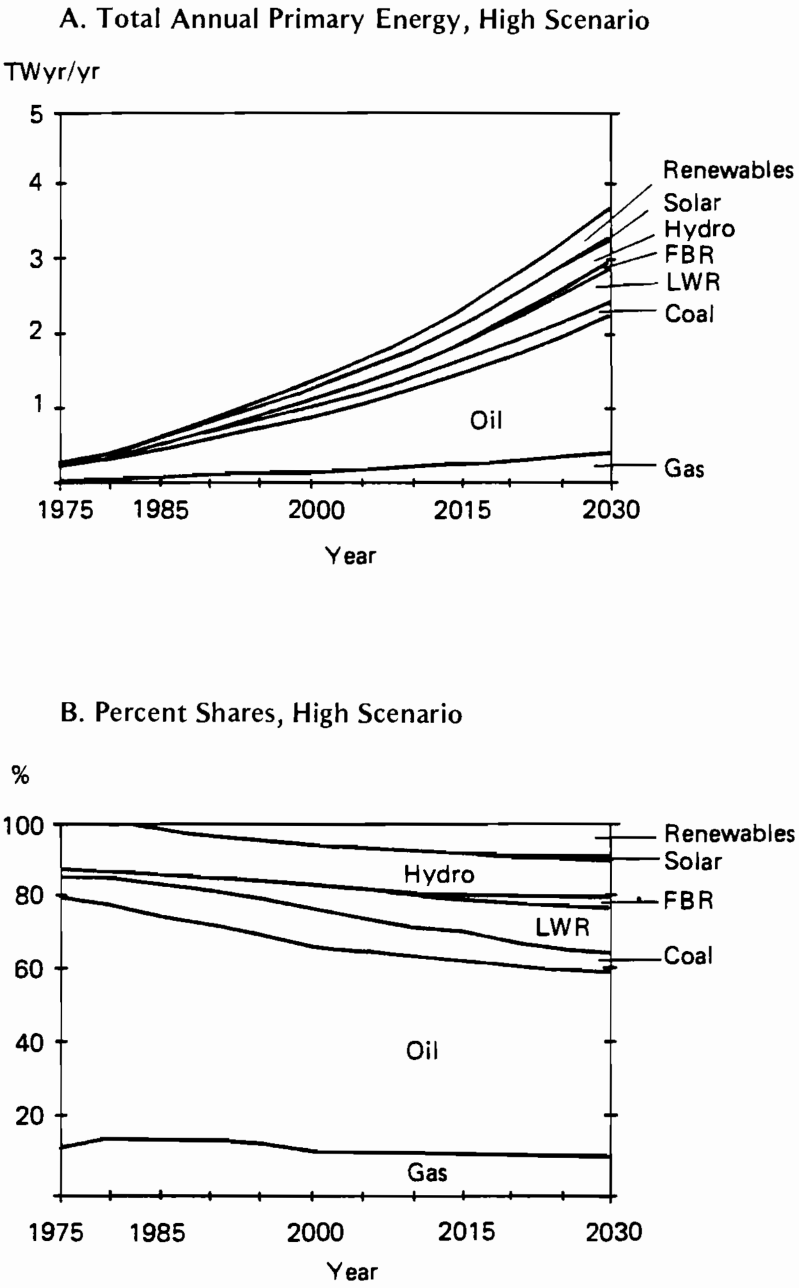
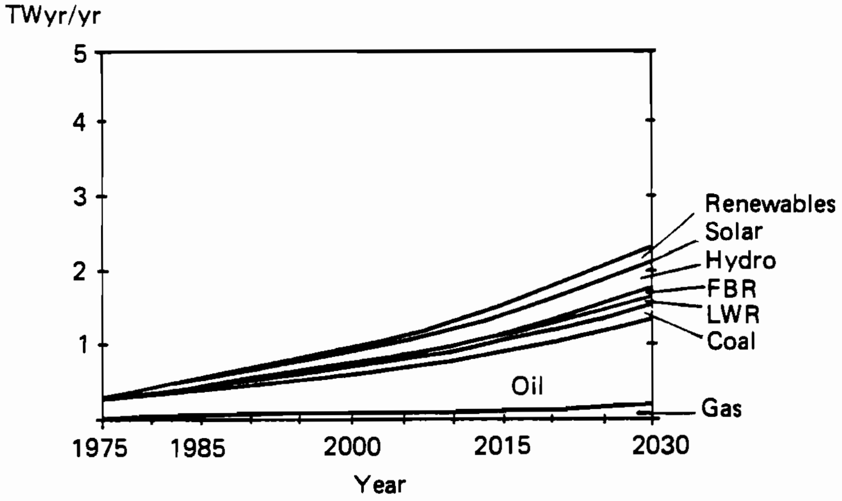
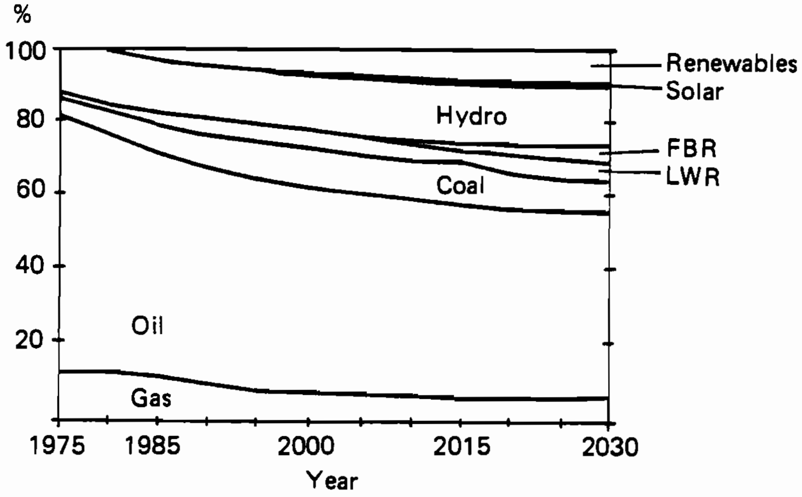


Figure 20-7 continued.

C. Total Annual Primary Energy, Low Scenario



D. Percent Shares, Low Scenario



shows that oil, while growing in magnitude, would be about constant as a share of total primary energy—while renewables and nuclear would grow to account for some 18 to 23 percent of total primary energy by 2030 (from essentially 0 percent in 1975). Natural gas use could be somewhat market limited in this region, but the resources base would allow gas to play a larger role than that in the scenario projections.

Region V, Africa (Except Northern Africa and South Africa), South and Southeast Asia (Af/SEA)

Region V may face the bleakest energy future of any region. Endowed with neither energy resource riches nor capital wealth (skills, technological know-how), while having large and rapidly growing populations, the favorable energy options for the long term seem few. Still, development objectives for the region are legitimate; while the situation is challenging and somewhat discouraging, it is not hopeless.

The region is the poorest, in per capita GDP, of the seven world regions. It would still be the poorest by 2030 in the scenarios, in spite of "vigorous" assumptions made about the region's economic and energy prospects. Real GDP growth rates would average 3.3 to 4.3 percent per year from 1975 to 2030—higher than the rates in the developed regions. The development path for this growth would continue the presently observed shifts toward the industry, service, and energy sectors and a decline of the agriculture share (from 36 percent of GDP in 1975 to around 16 percent by 2030 in the High scenario).

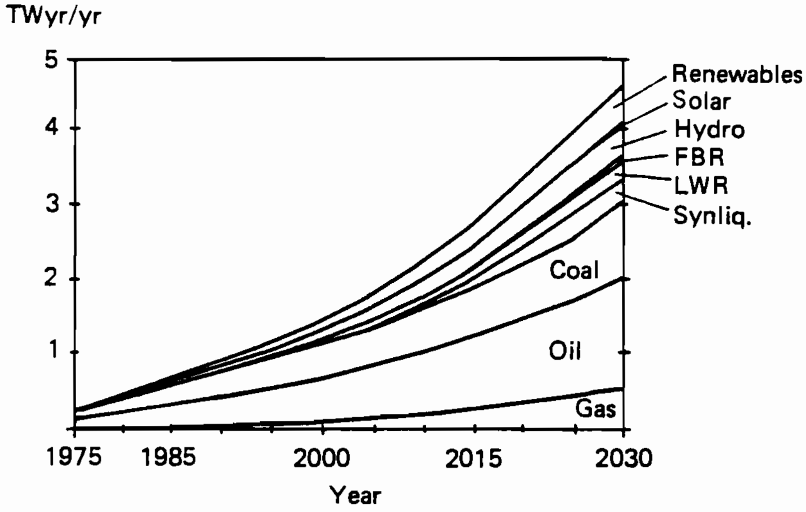
Energy savings, as noted earlier, generally require sophistication, and thus should not be expected to any appreciable extent in region V.

Today the region is a net oil exporter, because Nigeria, Gabon, and Indonesia are exporters and because aggregate liquid fuel demands are quite low. The scenarios project region V to become a net oil importer within the next decade, and by 2010 imports would be greater than domestic crude oil production. Coal liquefaction is then expected to provide a small but growing domestic source of liquid fuels.

Although liquid fuels offer a convenience and flexibility of use that makes them highly desirable for broad development objectives, they would become more expensive. Region V would therefore be wise to tap other sources where possible. Over the long term, renewables would play a growing role in the scenarios here, with biogas and charcoal assumed (in the High scenario) on an aggressive policy to meet up to 16 percent of household and industrial final energy needs. All renewables combined (including hydroelectric power) could account for some 20 percent of total primary energy by 2030 in the High scenario or even 30 percent in the Low scenario (Figure 20-8). Electricity needs (growing at 4.7 to 5.9 percent per year in the scenarios) would be met by coal, nuclear, and hydroelectric power.

Figure 20-8. Primary energy consumption by source for region V (Af/SEA), 1975-2030.

A. Total Annual Primary Energy, High Scenario



B. Percent Shares, High Scenario

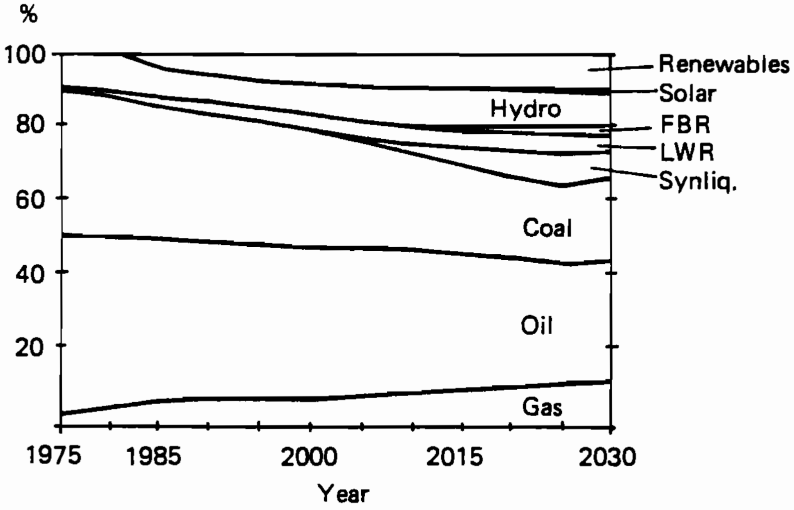
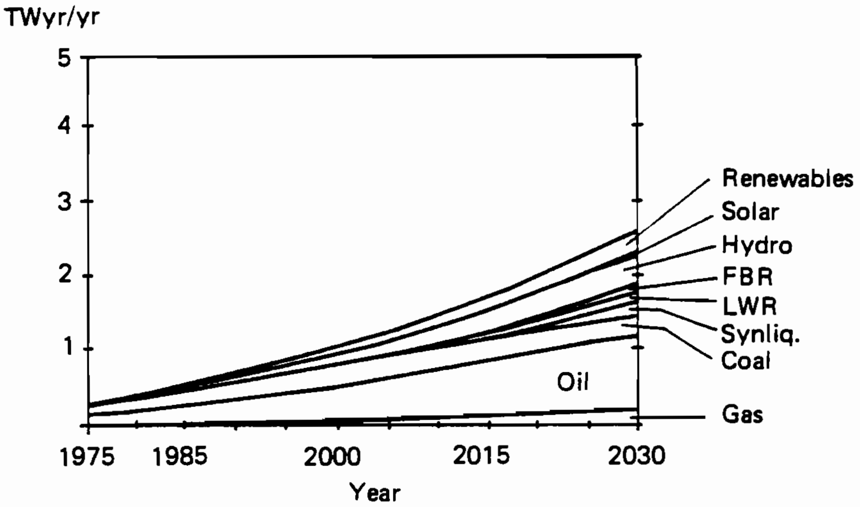
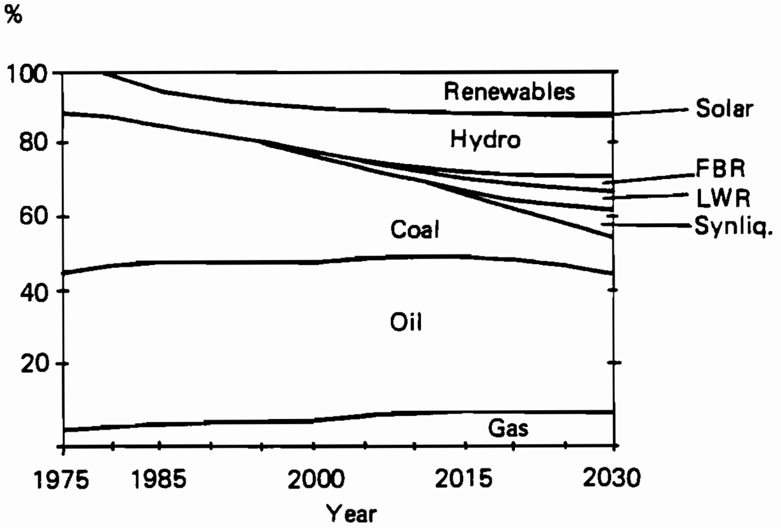


Figure 20-8 continued.

C. Total Annual Primary Energy, Low Scenario



D. Percent Shares, Low Scenario



Region VI, Middle East and Northern Africa (ME/NAf)

Not much is added here to the already extensive discussion of this resource-rich region (see especially Chapters 16 and 17). The region as a whole would want to constrain its long-term oil output—and would be wise to do so, since oil resources would be seriously depleted by 2030, with a sustained production rate of just 33.6 mbd (as assumed here).

GDP growth rates can be expected, of course, to be high for quite some time. Development would come with the growth, and region VI would, by 2030 in the scenarios, be at GDP per capita levels comparable to those in regions I and III today. Development also signals growing shares of manufacturing and services in GDP and a relative decline in the energy production sector share.

Oil and gas together provide about 90 percent of primary energy in region VI over the fifty-five-year scenario period in the High scenario (Figure 20-9). An assumed quantity of cheap natural gas, used for domestic purposes, leads to gas taking at least 50 percent of the primary energy market by 2030 in the scenarios. Gas would even be used rather extensively for electricity production.

Region VII, China and Centrally Planned Asian Economies (C/CPA)

The primary observation about the energy future of region VII is that so very little is known. Thus, the summary here is confined to a few key assumptions and resulting generalizations about the energy prospects of the region.

- GDP growth seems likely to be high, but so does population growth. With the projection of average GDP growth rates of 2.6 to 3.8 percent per year and of an average population growth rate of 1.2 percent per year, per capita GDP levels would reach by 2030 levels comparable to those of region IV today.
- It is assumed that region VII would be neither a net exporter nor an importer of energy. But domestic oil resources are not likely to be able to keep pace with rising demands; coal liquefaction would be required post-2000.
- Coal production, required for liquid fuel synthesis and electricity generation, would reach nearly 3.5 billion tons per year (3.2 TWyr/yr) by 2030 in the High scenario, from 0.48 billion tons per year (0.45 TWyr/yr) in 1975; over 2 billion tons per year of this would be needed simply for synthetic liquid fuel production. This coal production would exceed that of region I in 2030.
- The main primary energy source for the future in these projections would be coal (Figure 20-10). Natural gas and nuclear would grow noticeably,

Figure 20-9. Primary energy consumption by source for region VI (ME/NAf), 1975–2030.

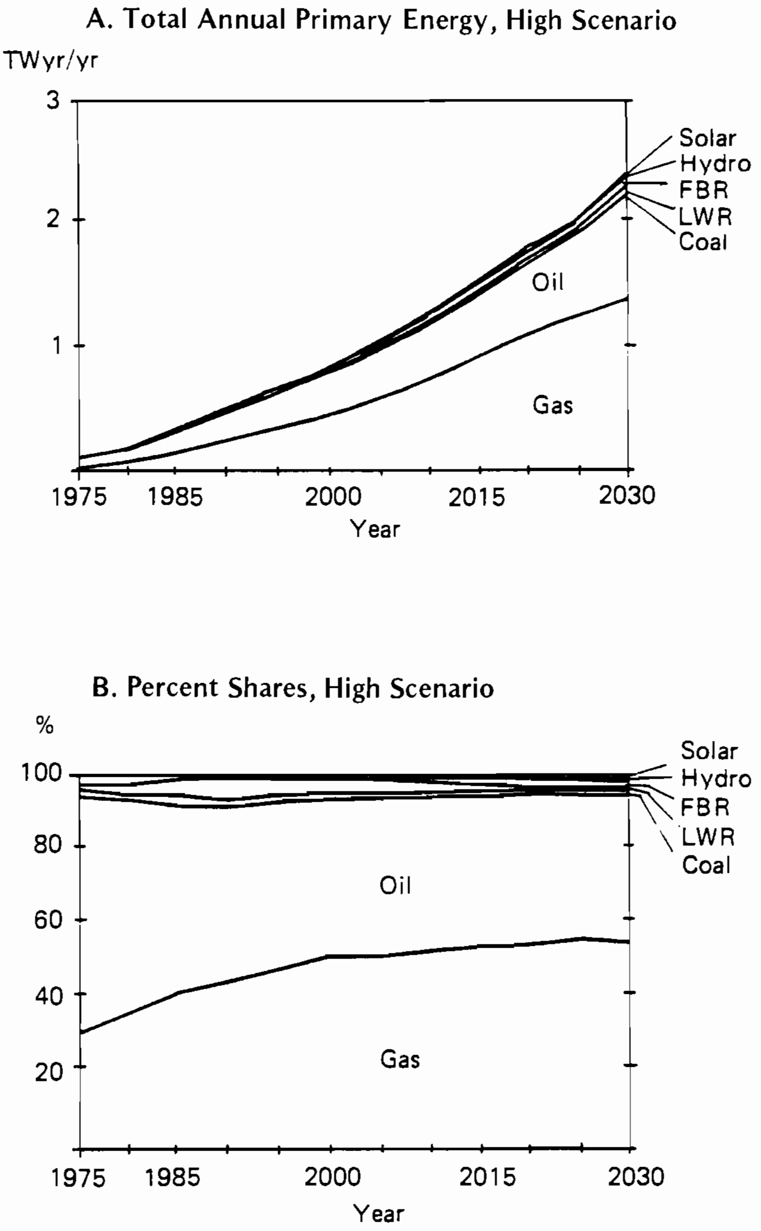
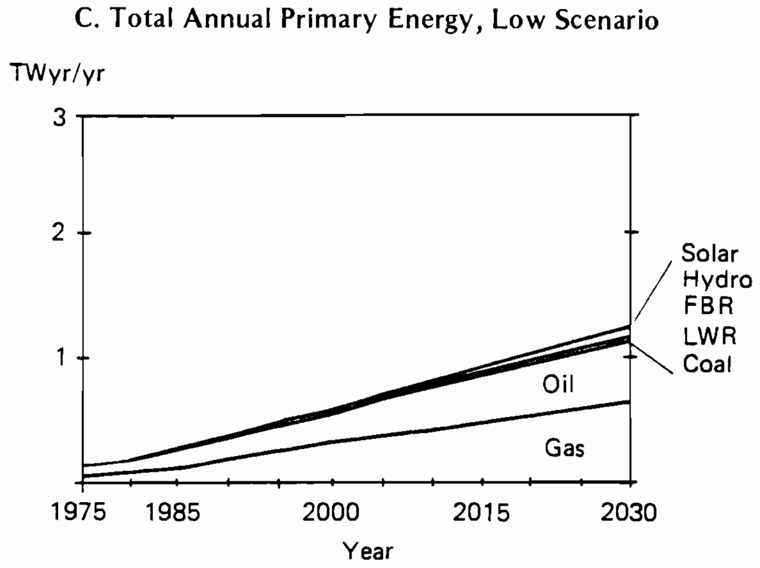
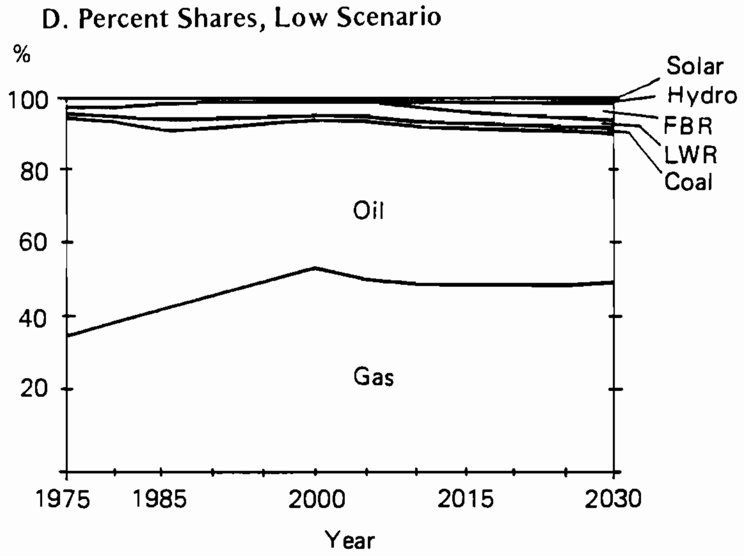


Figure 20-9 continued.



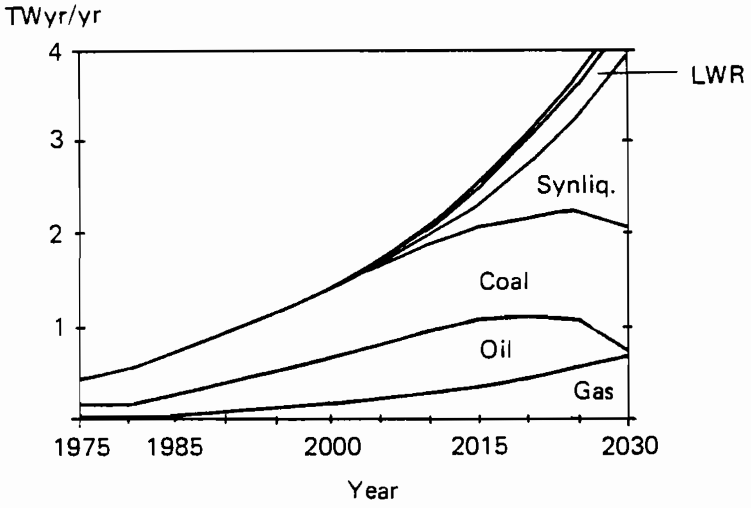
C. Total Annual Primary Energy, Low Scenario



D. Percent Shares, Low Scenario

Figure 20-10. Primary energy consumption by source for region VII (C/CPA), 1975-2030.

A. Total Annual Primary Energy, High Scenario



B. Percent Shares, High Scenario

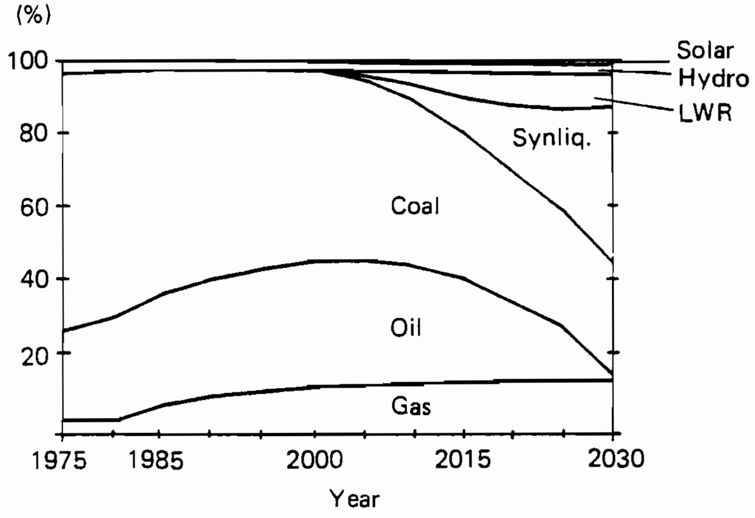
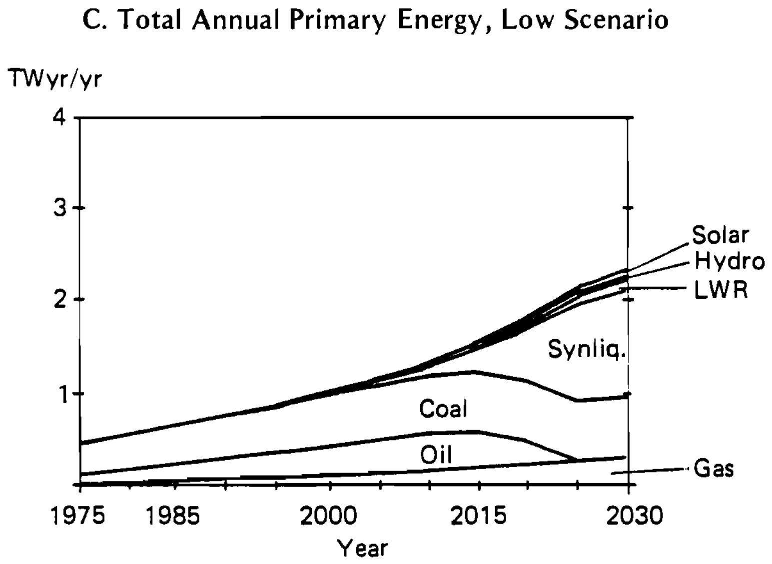
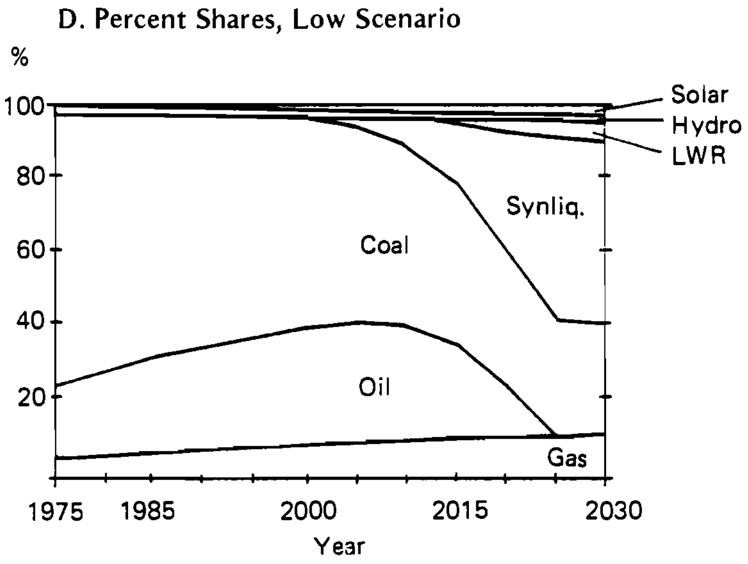


Figure 20-10 continued.





but still represent together less than 20 percent of primary energy by 2030 in the scenarios.

THE LARGEST IMPONDERABLES

No one knows the future. This cannot be said too often or too strongly—particularly after eight chapters of detailed thinking about the world and its energy systems in the year 2030. Yet after (and during) these analyses, some facets of the energy puzzle seem to be better known than others. There are perhaps (subject, of course, to different interpretations) a finite number of truly important uncertainties—a few large imponderables.

Will there be—can there be—a breaking of the link between economic growth and transportation activity? Can the world grow, can the developing regions develop, and can the developed regions spend new disposable income without large increases in transportation (and hence in liquid fuel demands)?

Will the Middle East cap its oil production at a level allowing a smooth transition to alternatives, or will the tensions caused by their oil ceiling create global instabilities? What can the world expect in oil output from the Middle East?

Will the assumed energy savings and shifts away from liquid fuel use occur, or will such attempts be thwarted by local or short-term considerations?

Can the developed world build the requisite oil-alternative industries to replace oil imports in the coming decades? Can sufficient coal be mined or shale oils or heavy oils be produced?

Will all of the energy problems restrain economic growth in the world to the extent of causing a long-term global recession?

Will the developed regions succeed in reducing their dependence on liquid fuels—by savings and by developing alternatives—so that the world's finite oil supplies can be left for the developing poor?

No one knows. But, by knowing some of the implications of various paths to the future, perhaps enough responsible decisions can be taken so that the conceivable and horrible armageddon futures will be avoided.

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V PERSPECTIVES

The quantitative explorations for balancing energy demand and supply as presented in Part IV have yielded insights and new views about some old problems. They have helped us to look anew at certain elements of the energy problem—to view them, for example, in thermodynamical and technological terms and to see how they relate to the area of urban planning and other societal considerations. Our search has by no means been exhaustive, but relates to a number of topics studied in depth at IIASA.

21 ENERGY, NEGENTROPY, AND ENDOWMENTS

ENERGY AND ENERGY SERVICES

In Chapter 1 we differentiated between energy at various stages of conversion and use in the energy system (see Figure 1-1). Here, as a prelude to appreciating some aspects of energy and its transformation and as a step for grasping the concept of negentropy, it may be useful to consider primary energy as an input: it is the resource from which energy flows arise. Secondary energy is the medium through which energy is delivered to the consumer (e.g., district heating grids and high voltage grids). In going from primary to secondary energy, some fraction of the primary energy is always lost or rejected as waste heat. As energy is converted into a final form—the energy stored in a motor, a computer, or a lightbulb—losses occur again, and more energy is rejected as waste heat.

Ultimately, as the chain of stages proceeds from primary to secondary to final energy, all energy supplied ends up as waste heat—that is, both the heat generated in the end product application and the conversion losses. This dissipated waste heat has lost its "usefulness" to us: it has become, in scientific terms, *entropic.* We shall return to the subject of entropy later in this chapter.

What is useful depends to some extent on the situation of the user. For example, at night it might be an electric lamp for illumination; in periods of cold it might be warm air for comfort heating in a home; or it might be kinetic energy as in an automobile. Each of these is a useful energy "service." Yet when we turn on a light to read a book, for example, most of the illumination is in a sense wasted, for other things than the book are illuminated. Similarly, warm air in a house heats not only the people but other objects in the room as well whose heating may be unnecessary. Much of the kinetic energy in an automobile is wasted as friction in the engine, as brake friction, or as other actions that are not intrinsic to the process of transportation. What one should examine, then, is not final energy, not even useful energy, but energy services—that is, legible books, human thermal comfort, transportation. These services are not a mode of energy; they do not obey a law of conservation; but they do engage energy.

SERVICES AND REQUIRED INPUTS

It is helpful to imagine a potter. He wants to earn a living by producing pottery. For that he has equipment (a potter's wheel, a motor for driving the wheel, and spatulas); raw materials (clay); an energy source for running his motor; and his own labor and skill. Here we shall consider the potter's equipment as his capital stock, and the clay as his resource. Note, too, that to engage the services of his capital stock, the potter must employ resources, energy, his labor, and his skill. Thus his capital stock may be considered a stored form of such inputs. In time, the potter's output of pottery per day improves: he produces less scrap, he uses less labor, and his skill improves. The amount of sustained influx of kinetic energy per output of pottery decreases; energy is substituted in part by skill. Encouraged, our potter buys a more sophisticated potter's wheel, but keeps his original motor. He also buys more sophisticated spatulas and other tools. His output improves further and, in turn, the amount of sustained influx of kinetic energy per output of pottery decreases even more. The services of his capital stock and his skill are substituting for the energy services and possibly for his labor as well.

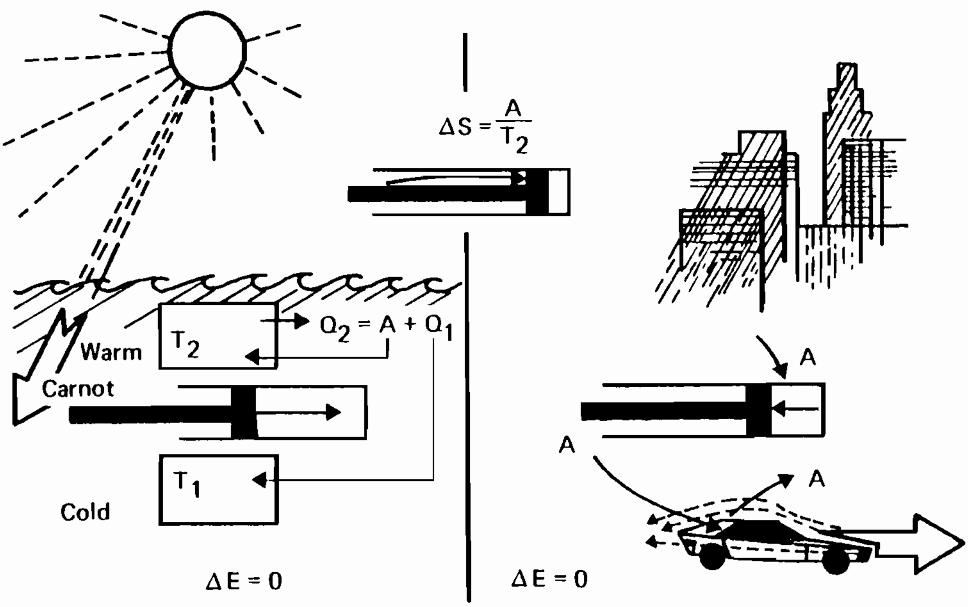
We use the example of a required transportation service to illustrate further the relationship between services and required inputs. A given amount of goods must be transported from A to B. Two methods can be applied. In the first instance an automobile is rented. The automobile travels the highway from A to B, thereby consuming a certain amount of gasoline (final energy). The gasoline is converted in the engine into useful energy for running the automobile; energy services are engaged. Also, labor and skill are engaged when a driver is hired. Engaging the services of the capital stock (i.e., the automobile) again implies the use of the stored inputs of resources, energy, labor, and skill.

But the same delivery of goods could also be made through an evacuated tube connecting A to B. In principle, such a tube could be designed to be exactly geodetic and to permit the totally frictionless gliding of a casket within the tube. Indeed, the slightest initial push would make the casket glide from A to B and stop there, to be unloaded. Here, too, resources, energy, labor, and skill would have to be invested to design, install, and operate the vacuum system, but the mix would be different. Although the capital stock services needed for setting up the vacuum system are much greater than those needed to build an automobile and a highway, and perhaps even the energy needed for constructing the vacuum system may be greater, once in operation, the vacuum system requires no further energy services. Thus, the provision of energy services involves inputs not only of energy but also of resources, labor, and skill, supplied in different degrees and at various intervals in the provision of the service. The substitutability of these inputs is a salient point: in fact, it is a key to understanding some of the basic issues involved in the energy problem. In the next section we shall examine in more detail the nature of energy services, relating to it the notion of order states. For this purpose, we shall use a *Gedankenexperiment* proposed by Marchetti (1976).

ENERGY SERVICES AND ORDER STATES: A *GEDANKENEXPERIMENT*

Energy services are generally provided in the form of work in the physical sense of the word. Although work is measured in the same units as energy, it is not the same thing. The following thermodynamic *Gedankenexperiment* illustrates this difference (see Figure 21-1). Consider a place in the ocean.

Figure 21-1. Negentropy city.



(A: WORK, E: ENERGY, Q: HEAT, S: ENTROPY, T: TEMPERATURE)

Solar influx establishes a temperature gradient in the upper layers of the oceans, say at the first 100 to 200 meters. The two boxes on the left-hand side of this figure approximate this configuration: the upper box has the temperature T_2; the lower the temperature T_1 (with $T_2 > T_1$). In the best spirit of ocean thermal electric conversion (OTEC), a Carnot machine is installed that uses this temperature differential by taking away the amount of heat, Q_2, from the upper box. The machine uses this heat to produce the mechanical work, A. The remainder, Q_1, is given to the lower box. And, of course,

$$Q_2 = A + Q_1 \tag{21.1}$$

and

$$\frac{A}{Q_2} = \frac{T_2 - T_1}{T_2} \tag{21.2}$$

But contrary to the expected uses of OTEC, the mechanical work, A, is now used to compress an ideal gas in a piston that is in good thermal contact with the upper box. Upon compression, the gas dissipates the work A into heat, and this heat is returned to the upper box—or in other words, the share A of Q_2 is returned to the upper box. The piston with the compressed gas is then transported to a town on the continent.

The energy content of the place in the ocean—the *two* boxes—has not changed. Indeed, the piston with the compressed gas does not transport energy, since its temperature is the ambient temperature T_2, and its internal energy remains unaffected by the pressure of the gas. However, the entropy content of the place in the ocean has changed: it has increased by $+ A/T_2$, because A has been returned to the upper box at the temperature T_2. This is equivalent to saying that the state of order in the ocean, with cold water below and warm water above, has been altered by the transfer of heat, Q_1, from the upper box to the lower box: the segregation of "hot" from "cold" is less perfect. The entropy increase is just a mathematical, quantified statement of this fact.

Consider what happens when the piston with the compressed gas is transported to a town on the continent. Upon decompression of the gas two things happen: the gas cools off and, simultaneously, provides mechanical energy. The amount of such mechanical energy is, of course, equal to A. Because of the piston's thermal contact with the ambient atmosphere, the cooling of the gas is compensated by taking on the equivalent amount of heat from the atmosphere. The mechanical work, A, is then used as useful energy—say, for running an automobile. This useful energy ultimately becomes waste heat, thus giving back to the ambient atmosphere the same amount of heat that was taken from the atmosphere.

This is exactly the analog of what has happened to the energy share of A in the upper box in Figure 21-1: it has circulated on the spot, between the upper box and the piston, and in the atmosphere around the automobile. In none of these places has the total energy content changed, nor has any waste heat been delivered to an energy sink. Both in the ocean and in the town the energy balance is locally closed.

The entropy content of the place in the ocean has increased by $\Delta S = +A/T_2$. Its negative equivalent, $\Delta N = -A/T_2$, has been taken away by the piston with the compressed gas. In other words, the compressed gas represents a technical "order state" that quantitatively equals the amount of disorder remaining in the place in the ocean. (For now, we shall use the term "order state" in just this technical sense; later in this chapter we shall explain it.) This order state is then transferred to the running automobile, in which it is ultimately consumed by friction. That is, the entropy amount $+A/T_2$ is produced, thus compensating for the amount $-A/T_2$; the order state from the place in the ocean is therefore consumed.

Note that without friction, the automobile would continue to run as long as it stays on a flat place, and its energy could at any time be transferred back so as to recompress the gas and transfer it back to the ocean. In other words, this energy could be used to reverse the whole process.

This reversibility is a key notion of thermodynamics. Indeed, the total entropy of a system is changed only by irreversible processes such as the dissipation of the automobile's energy through friction. Irreversible processes consume order states. We therefore observe that energy consumption means the consumption of order states by means of energy services through useful energy.

We continue with our line of reasoning. The provision of the amount of mechanical work, A, to make an automobile run once is a one-time thing. After friction has consumed the technical order state of running the automobile, more compressed gas would be needed to make it run further. We would have to go back for another piston. In the *Gedankenexperiment* above, the shining of the sun reconstitutes the original natural order state of the ocean, making it possible to obtain the compressed gas continuously. The *Gedankenexperiment* is meant to be a heuristic one only: the salient point is that there is an ongoing influx of order states from the sun. It is not the solar energy as such that matters. Indeed, all solar energy is radiated back quantitatively to outer space in the infrared. The sun-outer space configuration provides an order state that permits the influx of solar power to the earth, thus creating a permanent source of order states. In other words, the order states provided for are the energy services of the sun. This leads us to a second observation that, upon reflection, is well-known, but whose implications are not always recognized: All order states of the earth—be they natural or technical—result from the openness of the earth's system. We are not locked in.

Clearly, it is the abstract property of an order state that is important rather than its materialization in one form or another. From this follows a third major observation: Since resources are not consumed but are, in fact, simply degraded by use to materials with less order, it is only order states that can determine the usefulness of these resources. If there is a "limiting" factor at all, it is how these resources are deployed rather than resource quantity. As long as man cleverly uses and preserves existing order states and there is an influx of order states of some kind, a civilization—or a world—could operate, in principle, without any steady input of new resources. In our opinion, theories of limits to growth because of limited resources are, in principle, senseless.

NEGENTROPY, INFORMATION, AND ORDER STATES

How, then, can man cleverly make use of the earth's existing order states and preserve them? To answer this question, we first equate thermodynamics with communication and then go one step further and equate negentropy and information with order states. We begin by referring again to our *Gedankenexperiment,* analyzing it thermodynamically in terms of free energy, F:

$$F = U - TS \tag{21.3}$$

where U is the internal energy of the gas in the piston, T is its absolute temperature (an intensive parameter), and S is the entropy of the system (an extensive parameter). The internal energy does not change upon compression of the gas, but the entropy decreases, and the free energy increases accordingly. Although the compressed gas does not carry energy away from the ocean, it does transport free energy; it is this free energy that drives the automobile.

However, in the discussion that follows, we have chosen to emphasize the entropy rather than the free energy because, for consistency with our *Gedankenexperiment,* it is the degree of order that can be found and preserved that is subject to man's control. If nature provides man with a high temperature, he will get more free energy; but regardless of temperature, we maximize F by minimizing S.

Here it is useful to introduce the term *negentropy.* By this we do not mean negative entropy, which according to the third law of thermodynamics is not possible: rather, negentropy is the negative value of entropy increments ΔS:

$$\Delta N = -\Delta S \tag{21.4}$$

Indeed, friction losses and other irreversible processes increase entropy while they consume (and thus decrease) negentropy.

To grasp the usefulness of the negentropy concept, we examine Shannon's formal information theory (Shannon and Weaver 1949). He defines entropy not in thermodynamic terms but in communication ones. He refers to the negative increment of such entropy in communication as information. This is only natural, because the entropy in communication expresses uncertainty about the outcome of a certain question: once this information is obtained, uncertainty decreases. Equation (21.4) relates to thermodynamical entropy, but is otherwise exactly analogous to communication entropy.

Indeed, the analogy between negentropy and Shannon's information is so close as to suggest that they are identical. But are they really the same thing? This question has stimulated much thought. For an overview of this subject, the reader is referred to the work of Tribus and McIrvine (1971), among others. Shannon developed his information theory in 1948. Much earlier, Schrödinger (1926) pursued such questions within the context of the adequate interpretation of the quantum theory. According to Schrödinger, the so-called ψ function of quantum mechanics is an information catalogue; as new information is received and measured, the information changes, thus leading to the phenomenon of instantaneous and abrupt reduction of wave packages. Significantly, Szilard (1928) reported on the reduction of the entropy of a thermodynamical system upon interference of intelligent beings. More recently, Brillouin (1956) dealt with the seeming violation of the second law of thermodynamics by the Maxwell demon: he demonstrated that there was no such violation when the information needed by the demon was also taken into account.

The simplest and strongest link between negentropy and information is provided by the use of information entropy to resolve Gibb's paradox. The interpretation given here is derived from lectures by J. von Neumann (1949). Consider a single particle in a box. Now partition the box. The volume containing the particle is one-half of the original volume, and according to classical thermodynamics, the energy of the particle has increased by $kT\ ln\ 2$. Yet no work has been done on the system! Von Neumann, following Shannon, pointed out that, indeed, useful work could nevertheless be extracted, provided one knows in advance which side of the box contains the particle; a random choice of sides, on the average, would not provide work. Clearly this knowledge, which is only one bit of information, is in fact the source of the related negentropy that is gained. We conclude that thermodynamical entropy and communication entropy are therefore the same.

Thus far, our reasoning has reflected an established scientific consensus. We now go further, equating Shannon's information not only with negentropy but with our so-called order states. It may be helpful to consider order states as a generalized kind of information. Strictly speaking, Shannon's notion of information refers to communication channels only.

Our purpose here is solely heuristic: rigorous and quantitative treatment of the notion of order states is not yet possible. Only special cases, such as the *Gedankenexperiment,* seem to lend themselves to that. In the *Gedankenexperiment,* we were able to identify the entropy increase of the place in the ocean and to equate it with the technical order state of running an automobile. For the earlier example of the potter, there are patterns in the pottery produced, but it is not yet possible to identify the negentropy content of such patterns. Patterns point to an even deeper level of analysis. Human values come into the picture, too. What is it that makes a piece of pottery so beautiful that people are willing to pay a high price for it? What makes a person suffer when he sees a spoiled landscape around a mine? What is negentropy and what is entropy in this context?

Equating macroscopic order states—patterns, and particularly patterns that have human value—with information and thermodynamics may seem to be carrying the analogy too far. But for our heuristic purposes it may be useful.

MACROSCOPIC ORDER STATES AND THE ENVIRONMENT

We have now crossed the threshold of scientific reasoning and conjecturing. We have moved from order states that rigorously define thermodynamics to order states that have analogous properties but are not yet well defined.

We need to say more about order states. The environment—the biosphere, the geosphere, the atmosphere, and the hydrosphere—is ordered: it has a pattern. Fossil resources, for example, are a part of this pattern. Indeed, it took the biosphere billions of years to concentrate the carbon dioxide of the atmosphere and, together with water and sunlight, to create the order states that are stored as hydrocarbons. Likewise, the technoeconomic infrastructure that makes our civilization function represents a high concentration of order states: it too is a pattern. Within this pattern, there are capital stocks—be they in industry, agriculture, or elsewhere—through which the yearly product is produced. As illustrated by the example of our potter, capital stock is an investment (accumulated order states) that has the capacity to generate more order states. In this way, we view these additional order states as the interest on our investment; indeed, the monetary interest obtained from capital investments can be subsumed under such a general notion.

The generation of such an interest (the additional order states) does not violate the laws of conservation. We again equate negentropy with order states, with all the caveats already mentioned. Let us consider a closed system. According to the second law of thermodynamics, the entropy of this closed system does not decrease. However, if negentropy is produced through the generation of interest, then somewhere in this closed system entropy must be generated in order to (at least) compensate for the negentropy produced.

Using the above line of reasoning, we examine the use of fossil fuels, which could lead one to suppose that the earth is a closed system. The state of vastly diffused atmospheric carbon dioxide or of a spoiled nature around coal mines seems to reflect an increase in disorder (i.e. entropy). The analogy would seem to support the pessimistic view of the Club of Rome about man's future on the earth. Indeed, one could view environmental damages and wastes as increased entropy that at least compensates for the negentropy produced by man for his survival. Is pollution a necessary consequence of increasing the number of order states? The answer fortunately is no, regardless of whether one views the earth's system as closed or open. The reasons for this statement are explained below.

In a closed system, the quantitative relationship between the negentropy gained in creating order states, and thus the entropy to be accepted in compensating, involves very small numbers. Our earlier example of the frictionless vacuum tube transport system can be applied here. In principle, the order state of having a good at A or at B is just one bit of information. The energy to be supplied in moving the goods from A to B can indeed be negligible. What we have done in creating this system is to invest negentropy so as to improve the efficiency with which we create further negentropy. Properly invested negentropy makes it possible to approach the thermodynamic limits of efficiency: in a closed system, just one additional bit of entropy has to be accepted to create one bit of negentropy. But in the absence of appropriate investments, the efficiency of information output to entropy input is usually very low; for many processes one can calculate efficiencies of 10^{-10} or less. Thus, exploring the potential for negentropy efficiencies most often means exploring the potential of energy efficiencies. The goal of energy conservation has a deep, theoretical basis and justification. But for reasons that will become apparent later in this chapter, our discussion here still centers around the consumption of natural order states for generating technoeconomic order states needed by man for his survival, not realizing that there is a different mode of using resources.

Our second reason for not accepting pollution as a necessary result of increased order states is that the earth is, in fact, an open system. As we have seen in our *Gedankenexperiment*, there is a steady influx of energy services (order states) from the sun. It is therefore not necessary to equate the one bit of negentropy needed for man's technoeconomic infrastructure with the one bit of additional entropy to be accepted by the earth. But a prerequisite to this is an appropriate investment, say, of a photovoltaic cell array. Once the array is in place, electricity can be generated to deliver the negentropy carried by the electricity. The environmental impacts of operating such an array can be kept to a minimum. For instance, the waste heat at the place of the photovoltaic cells can be compensated by appropriate albedo changes in the surface around the cells, and surface roughenings can be avoided by adapting the array to the original surface. In Chapter 5, we state that the material investments for large-scale solar power will probably be very significant. Such material investments will also require the use of resources, but these resources would be used in an investive mode that would make the negentropy bit of the sun flow directly into the technoeconomic infrastructure. By contrast, the above-mentioned consumption of natural order states as, for instance, by the use of fossil resources can be seen as a consumptive mode of resource use. Certainly, these resources were originally created by influxes of negentropy from the sun, but as Marchetti (1978) has explained, for now these resources represent one-time storages of negentropy that are being consumed.

We have pointed to the distinction between consumptive and investive uses of resources in Chapter 4, as well. Indeed, the continuous use of light water reactors and of other nonbreeder reactors with once-through fuel cycles would lead to the depletion of natural uranium. This, among other things, would mean large-scale mining operations on a similar scale as for coal—a scheme we have labeled mining "yellow coal." On the other hand, the use of breeder reactors implies drastically smaller water, energy, land, material, and manpower (WELMM) implications; once installed, the breeder requires almost no new resources. As explained in Chapter 4, the factor of 3×10^6—the ratio of specific energy content between fissile material and coal—eliminates de facto the consumptive use of resources. However, what is needed is the investment of fissile material sitting in the breeder reactors, the material functioning de facto as a catalyst for the use of fertile material. In this way, the use of fissile resources may be properly regarded as investive. In the breeder reactor, both the fissile material and the power produced may be considered "breeding gains" of the negentropy invested. This, then, is in full accord with our notion of interest generated from a capital investment.

ENDOWMENTS AND THE EARTH'S CARRYING CAPACITY

Up to now we have considered the natural environment, focusing on consumptive and investive uses of resources. Earlier we noted that the provision of energy services involves a mix of inputs of resources, energy, labor, and skill. Indeed, when looking at the investive uses of resources, be it the photovoltaic array or the breeder reactor, there is a concurrent investment of energy, labor, and skill; they, too, relate to order states. This line of reasoning now leads us to the notion of endowment: An endowment is a negentropy investment of resources, energy, labor, and skill for generating a negentropy interest. It is only this interest that should be consumed in a technoeconomic infrastructure.

But endowments are subject to deterioration and must be depreciated by the influx of new negentropy. In many instances, this can be dealt with in classical thermodynamical terms. The wearing out of surfaces and the corrosion of metallic pieces are examples of irreversible processes that consume order states: the negentropy decreases; the entropy increases. This must be compensated by an influx of new order states, usually referred to as maintenance or replacement.

We use these notions of endowments and investive uses of resources to consider the carrying capacity of the earth. In fact, it was the pessimistic views held by others about man's future on the earth that led us initially to examine these notions. As civilization progressed from hunting to farming, several important changes occurred. For hunting societies, the earth's carrying capacity was very limited (about one person per km^2 or less), and the use of resources (i.e., food gathering) was consumptive. But as man turned to an agricultural society, an endowment was made—the seed grain. By maintaining this investment, it was possible for man to live from the interest—the harvest. And with such an endowment, the earth's carrying capacity increased by two orders of magnitude. However, when hunger was so great that it forced people to consume the seed grain, this usually meant the end of not only the endowment but also the population.

Similarly, Doxiadis (Doxiadis and Papaioannou 1974) estimates that the infrastructure of the first industrial revolution increased the earth's carrying capacity again by a factor of about ten. Yet the establishment of this infrastructure (i.e., the endowment) called for large capital investments, which required sacrifices. What can we learn from history? Intuitively, over the short term it often appears easier to have a consumptive mode of resource use. But in view of the rapidly increasing world population, we consider it possible to increase the earth's carrying capacity further only by means of endowments. In this way, it is inconceivable that there are limits on carrying capacity, even if the world's population were to reach the highly impractical level of 1000 billion, as proposed by Marchetti (1978) in a mind-stretching exercise.

Some additional comments should be made here about high capital costs of technologies. Solar power in particular, but breeders and fusion as well, have associated high capital cost investments, viewed usually in terms of today's economics. Such costs are often obstacles to the deployment of these technologies. The application of the notion of endowments should, however, make these technologies more acceptable. A decrease in their costs by means of further research and development is a rational response to this problem of cost. In fact, this would alter the mix of the elements making up the endowment, with skill—the most noble source of negentropy—substituting to a greater degree for capital.

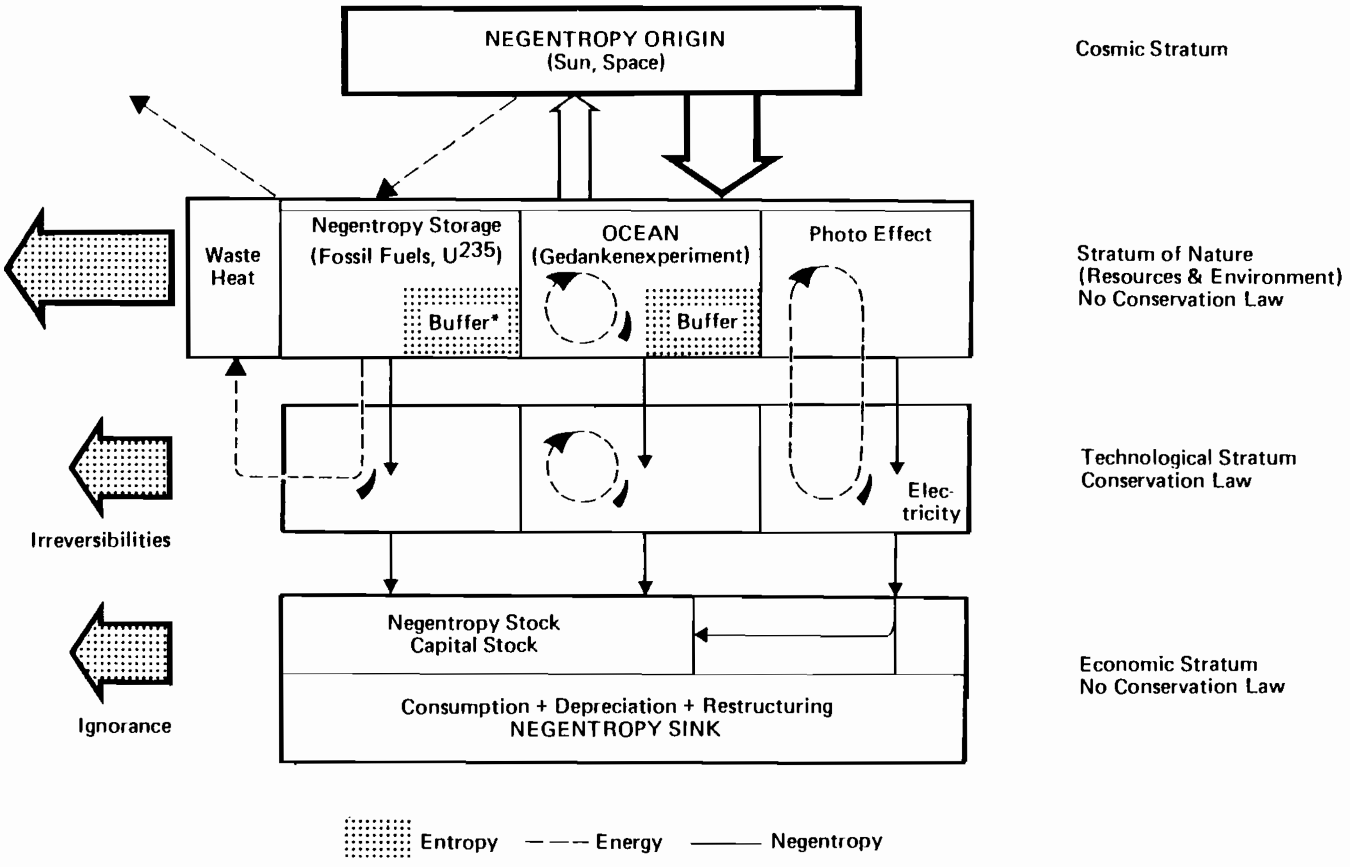
There is not yet a rigorous approach to evaluating the negentropy mix of an industrial product, such as a piece of pottery or an electrical generator. Today's economics, however, does this on an operational basis through prices. Practically speaking, it is relative prices that are the common denominator for resources, energy, labor, and skill by today's standards. But for the assessment of future energy strategies and for overall long-term development, it is the notions of investive uses of resources and endowments that are essential.

A CONCLUDING DIAGRAM

These largely qualitative and heuristic considerations can be summed up by considering the diagram in Figure 21-2. Four strata are considered there. The first is the cosmic stratum. The configuration sun-outer space permits the continuous use of the energy services of the sun. The negentropy influx from the sun is stored in hydrocarbons; it is supernova negentropy that is available in uranium. In the second stratum, the stratum of nature (resources and environment), mining these resources leads to a buffer of entropy. For instance, in our *Gedankenexperiment* there is such a buffer—the natural order state of the place in the ocean remains perturbed when negentropy is taken to the city. For the photovoltaic cell array, there is a one-time perturbation while establishing the endowment. All this is contained in the stratum of nature.

The third stratum is the technological stratum. By means of energy fluxes that are subject to a conservation law, negentropy is processed into the fourth stratum, the economic stratum. Losses of negentropy through the use of irreversible non-Carnot processes do happen in the technological stratum. In the economic stratum, negentropy is either stored in capital stocks or is consumed by man for his survival and by the depreciation of these stocks.

Figure 21-2. Negentropy in nature, technology, and economy.



* Referring to consumptive uses only (see text).

It is easy to identify the purpose of endowments: they are meant to minimize the generation of entropy in the nature stratum by moving the negentropy from the cosmic stratum as smoothly as possible into the economic stratum. This is possible because the earth is an open system. And accordingly, the future of man is open too and could be bright if man continues to engage his skill.

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22 NEW OLD TECHNOLOGIES

INTRODUCTION

The IIASA High and Low energy scenarios elaborated in Part IV of this book have given insights into the dimensions and quality of the energy supply over the next fifty years. We feel strongly that these insights should be translated into fresh perspectives on how we might better exploit and extend old and existing technologies—thus the title of this chapter. In doing so, we do not aim to be complete or to delve into elaborate detail. Rather, we hope to stimulate the thinking of technologists—particularly those concerned with research, development, and testing.

Technology plays a major role in increasing the resource-to-reserve ratio, be it for coal in place or for deuterium in the sea. Consequently, projections of technological development should be analyzed when one is designing energy scenarios. However, the introduction of new technologies into the energy market—not to mention their development—is a time-consuming process, as was shown in Chapter 8 on market penetration. One should therefore hesitate to place undeserved expectations in sharp bends as many small-bore prophets suggest.

For this reason, this chapter deals not so much with technological innovations such as fusion or central solar as it does with potential developments that are less glamorous but that may nonetheless significantly extend the capabilities of technologies now in common use. For example, a new rig that would permit drilling deep oil wells at twice the speed and half the cost of today's machines—a tiny development in comparison to making fusion operative—would, for a given exploration investment, perhaps double the magnitude of new additions to oil and gas reserves. And, this new technique could well penetrate the market in only twenty years, bringing it to full fruition during the golden years of the demand for hydrocarbons.

We begin by looking at four particular areas—energy storage, natural gas transportation, drilling, and enhanced oil recovery. Within each area, and with the results of Part IV as background, we explore briefly existing technologies and, in particular, aspects that show some promise for near-term development. The purpose is to focus anew on potential developments that, when appreciated within the context of the global energy system, are considered to ultimately have quite a lot to contribute. In the second half of the chapter we take our explorations one or two steps further. That is, we examine, concentrating more on the longer term future, those technological developments that can both contribute to immediately expanding the capabilities of existing technologies and, at the same time, facilitate a continuous gradual transition to a sustainable, asymptotic energy system.

A robust analysis of the problems we touch upon would require a well-elaborated evaluation: first, of the state of the art of different technologies; second, of the probability of their technical and commercial success; and third, of the receptivity of these technologies to stimuli in the form of money and status. While this might be done by sounding the invisible colleges with Delphi surveys and by estimating market penetration rates by analogy, we do not offer here anything quite so systematic. Consequently, our aim is to attract attention to the very strong links and constraints that bind the technologies to the system.

POSSIBLE NEW DEVELOPMENTS IN OLD TECHNOLOGIES

On Energy Storage

The characteristics one requires of an energy storage technology depend on the application one has in mind. In particular, technologies that are well suited to stationary applications may be singularly inappropriate for use in the transportation sector. For this reason the discussion below has been divided into two rather broad categories—stationary storage and mobile storage.

Stationary Storage. Energy storage has the function of buffering the demand curve against the production and transportation curve. Since a demand curve usually has daily, weekly, and seasonal cycles, storage can be roughly classified according to the length of these three periods as short, medium, or long term. In the particular case of renewable energy sources, where production characteristics can be as complex and variable as are demand fluctuations, the buffering function of energy storage may provide an integrating effect among various sources.

Essentially, storage is a substitute for production capacity, and the level of storage is normally established on a trade-off basis. As production capacity is usually expensive, all systems tend to have sizeable storages.

Electricity is not storable as such, and peak demand therefore must be met with capacity. Because of the structure of demand, there are fairly low system utilization factors, in the range of 50 percent; thus the system investment of about \$2000 per kW(e) rises to \$4000 per mean kW(e). With an installed global electric generation capacity of about 1 TW, the fact that electricity is not storable increases system investments by some \$1 trillion (10^{12}). All efforts of electrical "storage" should more properly be interpreted in terms of providing low investment capacity to be operated during peak demand periods.

An entirely different approach to alleviating the problem of idle capacity involves trying to influence the shape of the demand itself. This has been attempted mostly through the manipulation of tariffs, and the major developments in cheap communication and computing equipment pave the way to a more sophisticated intervention. Many appliances (e.g., water heaters and refrigerators) have, as a result of their inherent storage capacity, a built-in capability for automatically, alternatively starting and stopping. In the case of washing machines, operation can be somehow displaced in time. Direct control from the utility using signals sent along the line to switch off these appliances during peak hours is technically possible and not very expensive, and its introduction is expanding (Siemens 1978). However, we see that it is possible only to alleviate the problem, because weekly and seasonal cycles could certainly not be influenced in this way.

When thermal generation is the basic electricity source, peaking machinery usually comprises gas turbines or obsolete steam plants. Fuel costs tend to be high. For hydraulic generation, the machinery is relatively inexpensive, and when a storage basin is available, electric generation capacity is usually installed substantially in excess of hydraulic capacity and then used for peaking, typically 1000 hours per year. The machinery can be used reversely, with generators operating as motors and turbines as pumps. Thus, electricity produced elsewhere when demand is low can be used to pump water and to increase peak capacity. This system is widely used wherever water storage exists, despite the fact that it results in large amounts of electricity circulating idly in the net. In some limiting cases, the basin has little capacity of its own and is used only to store pumped water. Because hydroelectric machinery is inexpensive, pumped storage is easily one of the most important means for turning around the investment problem (i.e. the requirement for peaking capacity).

Storing compressed air in caverns using off-peak electricity has also been tried (e.g., Whitehouse, Council, and Martinez 1968; Harboe 1971), but it has never taken off as a technology. However, there are other "fluids" to compress that are more suitable for an electric system, and magnetic fields are receiving increasing attention. The spur is given by the development of superconducting windings, making it possible to "hold" very intense magnetic fields with very few losses. A magnetic field has much in common with a compressed gas—for example, with the same energy and volume, a magnetic field would exert the same pressure on the walls (in this case the windings) as would a compressed gas. The advantage of magnetic storage, then, is that the interface with the electric net can be made with static electric equipment, transformers, rectifiers, and so on, providing for the swift transfer of the energy in and out. The storable energy density is determined by the mechanical forces acting on the containment, as in the case of a gas compressed in a cavern. Because of this fundamental mechanical limitation, magnetic storage does not appear likely to play a strategic role in the organization of the electric system, although it may well play an important tactical role (Haimson 1978).

Because of the similarity between electricity and mechanical energy, in the sense that the interface, the generator, is efficient and inexpensive (about \$20 per kW(e)), flywheels may play a role very similar to that of magnetic storage; but this is possible only if their use can become economic. Another possible approach is to use electricity to produce chemical products that, in turn, can be used to make electricity. This principle is best illustrated by the battery. Batteries, however, have not really made a dent in the electrical system, essentially because their prices cannot be made competitive, even on the level of the daily cycle.

Nevertheless, we shall pursue the concept of storing the chemicals outside the battery. In this way one can view efforts to produce hydrogen and oxygen or hydrogen and chlorine in an electrolytic cell and to recombine them in a fuel cell for making electricity. This system is under active development in the United States, and the first target is to make it competitive, in terms of capital and efficiency, with pumped storage.

The hydrogen and chlorine scheme may well be the first to reach this objective, since the electrolytic overpotentials are very low and the same cell can be used for both electrolysis and recombination, leading to efficiencies in excess of 80 percent. Such cells, in the megawatt range, could be located at the level of electric substations, thus releasing transportation and most of the distribution net from peak load requirements. These chemical accumulators seem to have large potential for cost reductions and consequently may have a significant role to play in the future (Gileadi et al. 1977; Beaufrere et al. 1977).

If the primary energy source is not a fossil fuel, then the primary electric-generating capacity could be dimensioned to the highest peak, and all off-peak electricity could be used to manufacture energetic chemicals. The technology developed for electricity "storage" may well provide the basis for this further expansion.

A bolder, but far more efficient, method would be to use the hydrogen to substitute for some electrical applications in instances where the technology is simple and the results are similar. The guidelines for such applications are contained in the results of TARGET, a \$100 million research effort sponsored mainly by the American Gas Association and directed toward expanding the use of natural gas in the home. In order to gain flexibility, this gas was re-formed to hydrogen.

With the same characteristics of efficiency, cleanliness, absence of flue gases, and instantaneous switching on and off, hydrogen can substitute for electricity in heating, cooking, hot water production (through the use of catalytic plates), and even lighting (through the use of proper phosphors activated by the oxidation of hydrogen). It might be interesting to envisage both "electronic" and "protonic" uses of the principal element hydrogen. "Electronic" refers to electricity as a sensible form of secondary energy, whereas "protonic" refers to the complementing form of hydrogen as a chemical. For the "electronic" system, which includes such activities as running motors and television sets, no direct storage is possible; while this system is qualitatively important, it may not, in the end, be very significant quantitatively. The "protonic" system, on the other hand, includes most of the heavy tasks, and it is storable. In this way, the electronic generation system could run at full capacity all the time. The interface between "electronic" and "protonic" is the electrolytic cell, which is discussed in more detail later in this chapter.

This scheme is obviously a long-term one. Cities have undergone a painful transformation from towngas (largely hydrogen) to natural gas and may not be particularly amenable to a quick return. Also, the use of hydrogen in place of electricity requires, on the consumption side, new appliances. But the interesting fact to be kept in mind is that it can be done technically and promises a definitive reduction in capital investments at the system level, basically through a strong increase in the utilization factor as well as through economies of scale.

The situation is better, but far from satisfactory, when we try to store energy in the form of sensible heat. Heat is usually stored by changing the temperature, and sometimes the phase, of a storage material. The weak point in the procedure is that heat capacities are relatively small. For example, a cubic meter of water heated to 100°C accumulates about 100 kWh. Just for comparison, a cubic meter of oil contains about 10,000 kWh (of free energy).[a] The problem is physically insoluble, as the situation simply reflects the difference between vibrational and chemical bond energies. For seasonal storage, then, the only solution appears to be the use of very large masses. These masses must be part of the earth, since moving and reassembling them would lead to excessive costs. The problem is to make parts of the earth thermally accessible.

One proposal for solving seasonal storage problems consists in using an aquifer as a storage tank. The aquifer must be fairly stable or made so by clay injections at the rim. Water is then pumped in and out at proper depths and temperatures, just as though it were a giant water heater. Both cold and heat can be stored, and in the limit, we can view the store as a flywheel between summer and winter. Thermal conditioning of houses and buildings would then become inexpensive in terms of energy. Another proposal is to

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[a] Free energy is defined mathematically in equation (21.3).

use the earth. Soil is a very poor thermal conductor, the alternation of seasons being barely felt a few meters below the ground. However, this is not a particularly serious handicap, since seasonal heat is put in and extracted at very slow rates. Computer modeling indicates that it would be feasible to construct a system in which heat is injected and extracted using narrow pipes inserted in the soil like long hairpins at distances of 2 to 3 meters from each other and extending 10 or 20 meters downward. These proposals should be pursued intensively as they promise a low technology, low capital, and low energy solution to the problem of procuring low quality heat (or, alternatively, in our terms, low negentropy heat) for space conditioning. In essence, the suggested mechanisms are not very different from those exploited by primitive men living in caves, where the temperature is mediated over the year by the surrounding earth and rocks.

A procedure similar to those above and using air as a heat vector might be to store high temperature heat in, for example, dry sand or gravel basins. This problem of storing large amounts of high temperature heat is particularly critical for the large-scale production of solar electricity (Bergougnou and Roy 1978).

Another category of storage technologies is that involving solid fuels, but currently this area does not appear promising enough to warrant applied research. Solids are stored in heaps. Rain leaches these heaps, producing pollutions; similarly, wind blowing over them raises dust. Manipulation of these solids is dirty, "noisy," and expensive. Small storages, so important for the success of liquid fuels, are very unwieldy.

Liquid fuels are, especially for small quantities, by far the best form of stored energy, since they are both light and easy to manipulate. Practically the entire transportation system currently operates on liquid fuels. Their storage, however, is expensive when the cycle is long (e.g. seasonal), as in the case of heating oil. The storage tank for a single-family house may cost, in place, $500 per ton of oil stored and can be filled only once or twice a year. With oil costing in the range of $150 per ton (1979 dollars), the capital and maintenance charges because of the storage facility at the family level are above $100 per ton of oil consumed. For reference, the Alaska pipeline, often taken as an example of extraordinary investments in the energy system, has a capital investment of about $100 per ton of oil per year.

Storing oil on a large scale, as is needed for seasonal leveling and strategic reserves, is significantly cheaper, though hardly inexpensive. We give about $100 per ton of oil as a figure of orientation. If the storage is required only once a year, as for seasonal leveling, then the investment cost of the storage system is similar to that of the Alaska pipeline and substantially adds to the price of the oil stored.

Gas, on the contrary, is difficult to store in small tanks and, in spite of much technological ingenuity, has not really found its way into the transportation sector, for example. Pressure bottles are too heavy, and liquefied natural gas (LNG) is too complicated at present for widespread public use. But the comparison of gas and oil changes drastically if one considers large storage. Porous geologic structures can be easily used for gas storage. Typically, exhausted gas fields that happen to be relatively near consumption centers are routinely used as "lungs" to buffer daily, weekly, and even yearly oscillations in demand. Similar structures, such as a porous layer sandwiched between impervious layers, are very common in sedimentary basins. The porous layer is usually filled with water, and gas can then displace the water from the pores, creating a "bubble" around the gas injection wells. By choosing the depth, one can choose the pressure of the operation. All the ancillary techniques and geological know-how, both of which are similar to those for gas fields, have been under development for the last thirty years, and storage in porous structures appears as a good candidate for the large seasonal storage of gas, which is expected to be required, given the current expansion of gas consumption in the domestic and commercial sectors (DeBernardi 1978).

Note that a gas system, unlike an oil system, does not require local storage for individual buildings and that the investment saved can be more efficiently placed upstream, in the production and transportation of gas. For such reasons, it is important that technological evaluations and subsequent policy decisions be based on comparisons of systems and not just on comparisons of fragments of systems.

As previously stated, the primary economic function of storage is to reduce production and transportation capacity requirements by acting as a buffer for oscillations in final consumption. If generation is linked to sources with variable output—as, for example, for solar and wind power—then the buffering action may be interpreted in terms of integrating the different sources. The point of breaking even between extra storage and extra generating capacity is a complex function that depends on the demand curves, the characteristics of generation, and the storage costs. Because storage technology usually has received less attention than have generation and transportation, more research on these storage issues may yield substantial reductions in costs with immediate benefits at the system level.

The secondary function of storage is to provide resiliency against vagaries in either the supply or delivery system. It is in this sense that one should interpret the sixty- or ninety-day supply of crude oil that many countries have in reserve. Natural gas offers a cheaper alternative to these strategic reserves, and an automated gas grid is fairly resilient to strikes and boycotts.

Another function of storage is the saving of energy, particularly by seasonal storage of low grade heat. In the limit, all heat and cold for space conditioning could be provided in this way. The problem is certainly not one of technical feasibility, but one of capital investment. The amount of energy to be saved can be estimated today to be on the order of 30 percent of the total energy budget, and among the different possible uses for fuel, it is in this area that (second law) thermodynamic efficiency is at its lowest.

Storage in the Transportation Sector. The previous arguments refer basically to energy storage on a large scale or for fixed consumers. The problem of energy storage for vehicles is a class of its own and is critical to defining energy strategies for transportation.

Currently, almost all free-range vehicles run on hydrocarbons. The reason is simple: for a given volume or weight, hydrocarbons are a very efficient store of energy. Their chemical flexibility makes it easy to adapt them to different final end uses (e.g., gasoline, diesel, jet, or naval engines); they can be produced relatively simply and efficiently from crude oil—a primary resource that for the moment is relatively inexpensive (before royalties and taxes) and abundant. Their dominance of the energy market seems hard to dent, at least in the transportation sector.

On the other hand, hydrocarbons have the drawback that they are a heavy source of pollution. This is true at all stages of their manipulation, but particularly when they are finally burned, threatening among other things, the global climate system (see Chapter 10) and creating risks to human health (see Chapter 11). Consequently, research has been devoted to searching for acceptable substitutes. A typical example is the electric car to which inventors have dedicated their efforts for a century and that would be perfectly feasible if the storage system, the batteries, were satisfactory. Electric batteries can most simply be viewed as a bag of chemicals reacting to produce electricity. And then, by passing electricity through the battery, the reacted chemicals can subsequently be restored to their initial state. The weak point in this system and the insoluble problem deriving from it is that no amount or mix of chemicals can beat hydrocarbons burning to carbon dioxide and water in an open cycle with oxygen from air. The rationale for continuing research in this direction is that by restricting the purpose of the vehicle (e.g., by running it only inside the city as a taxi or a delivery van), the full potential of the hydrocarbons is not needed, and consequently a less energy-efficient type of storage will do.

Another approach to circumventing the pollution problem is to leave the internal combustion engine as it is, but to use an intrinsically nonpolluting fuel—specifically, hydrogen. Here too, the technical problem focuses on hydrogen storage. Carrying hydrogen as a cryoliquid is possible, and in fact a liquid hydrogen "gas station" has been constructed and very reliably operated (Peshka and Carpetis 1979). But such an approach is not really well adapted to general public use. The solution to the storage problem upon which most research now concentrates involves the cryptometallic properties of hydrogen. In the Mendelejeff table, hydrogen belongs to the series of the alkalis, with lithium, potassium, and sodium located in the same column, and is in fact capable of making alloys with many metals, improperly called metal hydrides. These alloys often have high hydrogen pressures and can be rapidly formed or destroyed by changing the level of this pressure. Such storage, even in its present form as developed by, for example, Mercedes Corporation in the FRG, is still inferior to the gasoline tank, but is sufficiently superior to the battery as to be almost acceptable.

However, once hydrogen is available, there exist possible short-term solutions that fit well with the current complex energy distribution and consumption infrastructure. The most promising of these is the use of methanol. Methanol can be synthesized using a carbon source in a reduced form, such as coal, or even in an oxidized form, such as carbon dioxide. The use of exogenously generated hydrogen, with either nuclear, solar, hydroelectric, or geothermal energy as the primary source, permits one of two things—an open cycle that consumes carbon resources or, given the development of a reasonable method for recovering carbon dioxide from the atmosphere or from stack gases, a closed carbon cycle. With methanol, automobiles can run almost without modifications. For example, a single catalyst developed by Mobil Oil Company in the United States (Meisel et al. 1976) can transform methanol into light oil, which in turn is most probably adjustable to jet fuel. In this configuration, hydrogen can be seen as the perfect chemical intermediate with which to mobilize fossil fuels and intermittent sources of energy into the oil system.

Since hydrocarbons cannot be the world's primary energy source forever, and nuclear, fusion, or solar energy hold the most promise for making the transition away from hydrocarbons, one can discuss at length the best long-term systemic strategy to link the primary source to the vehicle. And because hydrogen will presumably be the inevitable intermediate between the primary source and the synthetic fuel—whatever it is—it would obviously be a great simplification to use hydrogen directly. As we have mentioned, most of the problems are in the storage area, hydrocarbons being practically unbeatable in terms of energy per unit volume. In terms of weight, liquid hydrogen beats them by a factor of 2.5. Although liquid hydrogen may at the moment be poorly suited to general public use, airplane designers, who are very sensitive to weight considerations, have kept an eye on the possible use of hydrogen in commercial aircraft. That day seems to be approaching, and firm proposals to retrofit a fleet of twelve L-1011 long-range cargo planes have been made by the Lockheed Corporation in the United States (Brewer 1979). The basic technology for handling and storing liquid hydrogen is one of the spinoffs of the space program.

An important second-order effect of these proposals would be to give certain people experience in handling liquid hydrogen, under a variety of circumstances and on a daily basis, and possibly confidence and know-how could spread progressively to larger strata of vehicle users and finally to the general public. One should not forget that only 150 years ago in the United Kingdom automobiles had to be preceded by a man on foot waving a red flag because they were carrying an extravagant and dangerous fuel—gasoline. At that time coal was the reference fuel.

In its most succinct form, then, the lesson that emerges from this brief explanation of possible transportation fuels is that through the shortest route, liquid hydrogen can play a vital role in helping the transportation system adapt to the use of nonfossil fuels, provided that the hydrogen storage problem can be solved.

On the Transportation of Natural Gas

Throughout our analysis of the energy system and the way it is optimized, we have seen the central importance of the transportability of fuels or of secondary energy carriers such as electricity. In fact, the success of oil globally is essentially because of its high transportability, by pipeline and especially by tanker. The Middle East would still be a barren desert if oil had to be trucked like wood.

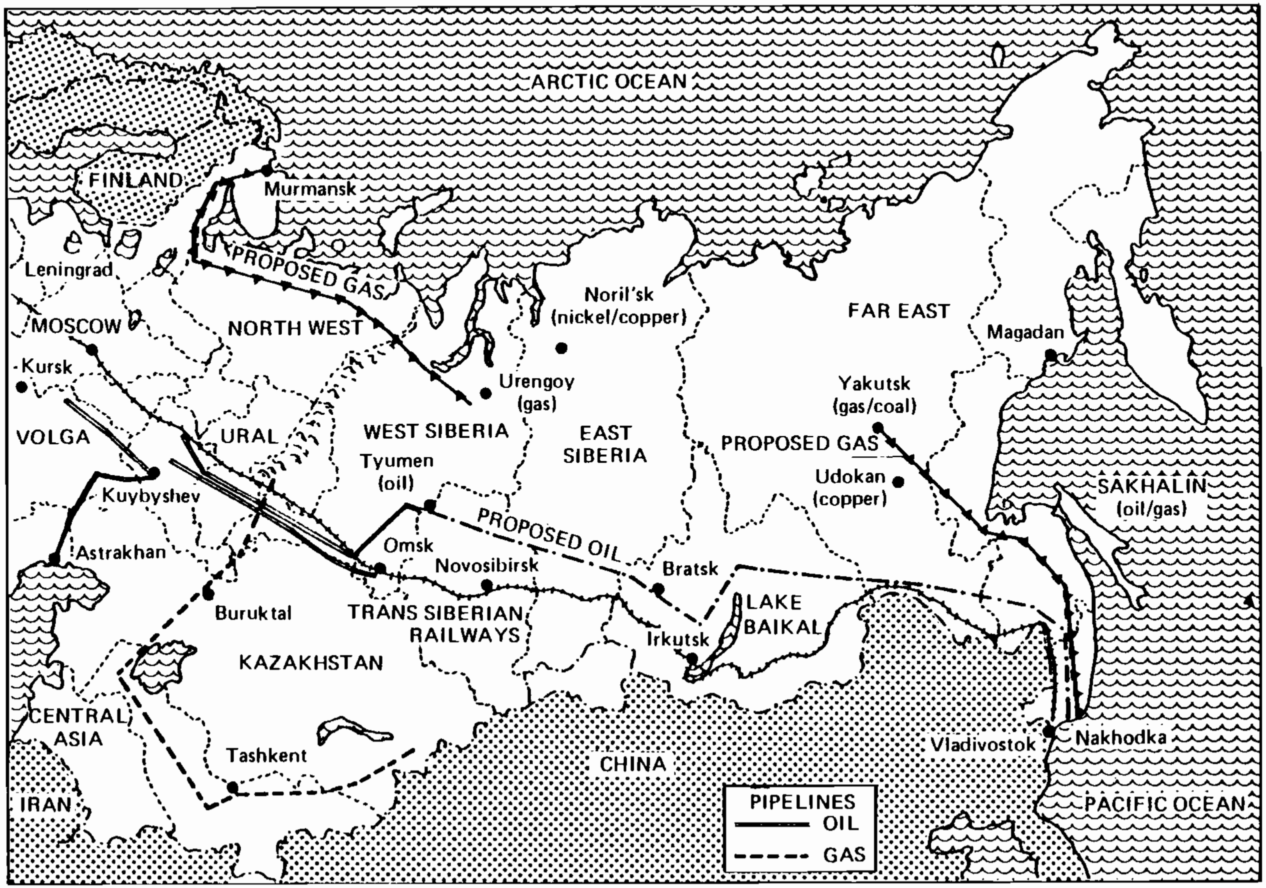
The transportability problem is now intensively felt in the area of natural gas exploitation. Natural gas is in increasing demand, but as in the case of oil, gas deposits and consumer areas are hardly coincident. It is only poor transportability that makes oil producers flare perhaps 0.5 TWyr/yr of associated gas.

The Pipeline. Historically, natural gas has always been transported by pipeline. As a rule of thumb, the economics of a pipeline can be condensed in the following statement: the cost of transportation is roughly proportional to L/d, where L is the length of the pipeline and d is its diameter; the amount transported is roughly proportional to d^3. Thus, there is a great incentive to have large diameters, provided gas deposits and consumer areas justify the capacity of the pipeline.

To give a practical example, a 1.5 m diameter pipeline, the largest size that can currently be constructed using present technology, can carry 20 GWyr/yr of natural gas, with acceptable costs, up to 2000 to 3000 km. A 3 m diameter pipeline would carry 130 GWyr/yr (nominal capacity) at the same unit costs over 4000 to 6000 km—assuming, of course, that current technology could be homogeneously extended to that size. Taking into account only associated gas, which now is mostly flared, the Middle East could have two 3 m diameter pipelines to Europe providing 200 GWyr/yr of natural gas. Steel pipelines of 2.5 m diameter have been constructed experimentally in the Soviet Union, and the metallurgical problem of making such large pipes capable of resisting pressures of up to 100 atm have been practically solved. The real problems that remain have to do with the field erection of such pipelines: specifically, the tube sections are too heavy, too rigid, and too difficult to weld and to put in place. In other words, present technology seems not to be directly extendable to such sizes, and consequently, by historical analogy, we should look for a breakthrough via a new conception. The existing stretches that could use such very large bore pipelines are Middle East to Europe, Eastern and Western Siberia to Europe (Figure 22-1), Nigeria-Sahara to Europe, the Northern Slope to the United States, Northern Canada to the United States, and Mexico to the eastern area of the United States.

One important goal of research would be to design a pipeline that could be assembled in situ, from easily transportable components, using automatic machinery. Another possibility is to use pipelines of current sizes but to increase the pressure of the gas, which can be done by reinforcing the pipes (e.g., by winding them with a steel cable or a steel band, a technique developed a century ago for constructing large bore guns). However, going to higher pressure does not substantially improve the economics of transportation, nor does it extend the range of the pipeline as a transport medium. Current pressures of 50 to 100 atm are optimal economically. Still, the

Figure 22-1. Plans for large-scale transcontinental pipeline nets requiring large bore pipeline technology. Source: Based on information from Comité Professionnel du Pétrole (1978).



amount of gas transported by a pipeline of a given diameter grows roughly proportionally to the pressure. Higher pressures would reduce the number of pipelines in those cases such as the very rich fields of Siberia, where the level of output would normally require many pipelines. Apart from the fact that such developments in pipeline technology would make available to the consumer areas perhaps a couple of terawatts of natural gas, we note here that the approximately 500 GWyr/yr of natural gas actually flared worldwide (valued at, say, \$150 per ton of oil equivalent) represents a loss of around \$50 billion (10^9) per year. In this light, spending \$1 billion per year on research and development is a conservative proposal.

The Tanker. Because liquids can be transported by tankers, the next solution is to liquefy natural gas. If successful economically, the natural gas system could take on global dimensions in the same way oil has done (Figure 22-2). A tanker system would have more operating flexibility than a pipeline and, overall, more resilience. Historically, local problems have never really upset the delivery of oil, mostly for this reason.

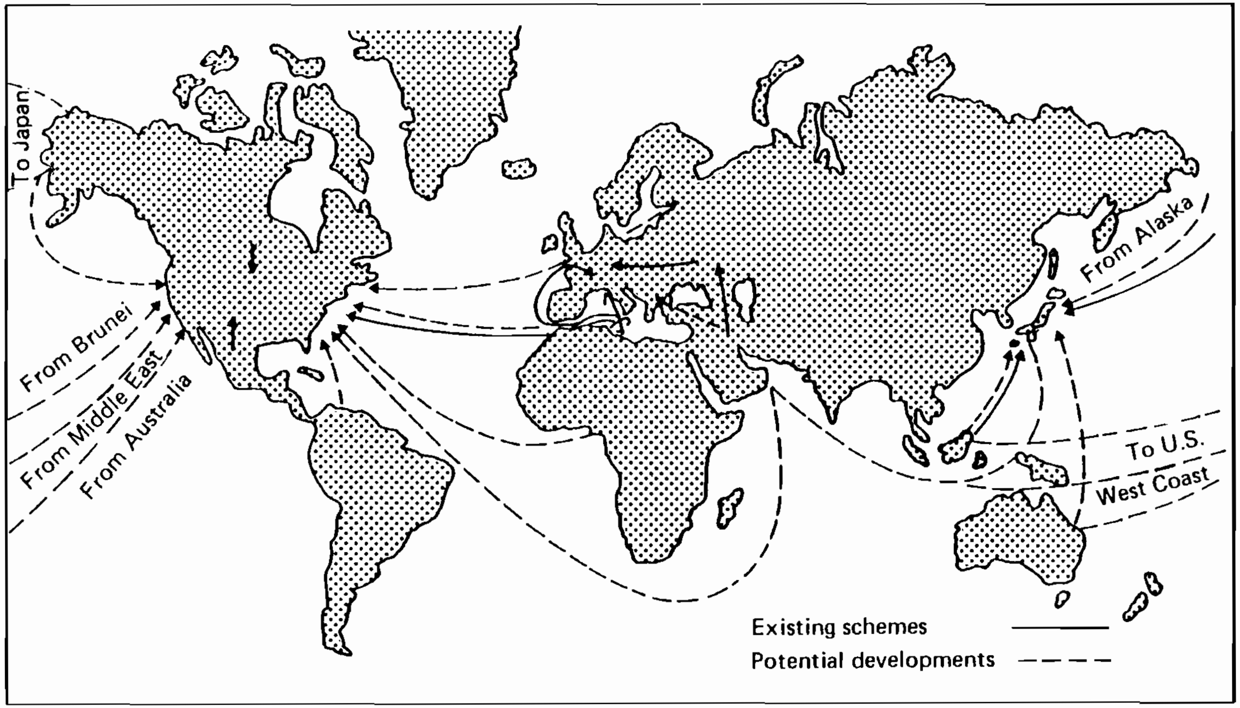
However, cryoengineering on such a scale is orders of magnitude above what has been done before. Liquefying natural gas means cooling it to -160°C and requires cryotankers for its transportation. Both technologies are neither easy nor inexpensive, but they have been developed at a very fast rate by private industry under the spur of fast-growing demand.

The liquefaction problem is not especially challenging in principle, as it is easier to liquefy natural gas than air—an industry that is almost a century old. Challenging is, first, the scale that is required and, second, the fact that more often than not these complex and delicate plants have to be erected in low technology countries. Technically, perhaps the most critical item in a liquefied natural gas (LNG) plant is the heat exchanger. (The plant consists basically of a compressor, expanders, and heat exchangers, the first and the third items playing the most important role in the efficiency and economics.) Research and development could thus be concentrated on new and promising concepts of heat exchange. Concerning the logistic problem, there is a growing preference for mounting plants on oceanic barges and assembling them in the friendly environment of a shipyard.

A gas liquefactor requires about 15 percent of the energy of the gas for the liquefaction process and may add about \$50 per ton of oil equivalent to its cost. A cryotanker costs today an order of magnitude more than a corresponding oil tanker and may add another \$50 per ton of oil equivalent to the cost of the gas. This explains why LNG may end up being sold at more than \$150 per ton of oil equivalent. In this case, LNG then has to be used for special purposes appropriate to its premium value (e.g., for peaking, for burning in power stations when meteorological conditions require low sulfur emissions, or for domestic uses).

This initially marginal market leads to small (typically 125,000 m^3), expensive tankers, for as is well known, the size of the ships is strongly correlated to the size of the market. However, the cost of a supertanker grows roughly with the 0.4 power of its displacement, and perceptive ship engineer-

Figure 22-2. Plans for large-scale international trade in LNG requiring large LNG tankers. Source: Based on information from Comité Professionnel du Pétrole (1978).



ing companies have designs for LNG tankers of up to 500,000 m^3 on their drawing boards. Apart from the question of what size will be in demand, the market for LNG, when small, drives the learning curves toward lower costs, thus paving the way for the potential boom of LNG transportation in the 1980s.

Methanol. In our discussion of storage we have briefly discussed the potential of methanol in future energy transportation structures. Here, we look at methanol as part of the discussion of ways to transport natural gas. Natural gas can be transformed into methanol by methane steam reforming into carbon monoxide and H_2, followed by catalytic synthesis of methanol. Methanol can be transported in supertankers, just like oil, but at double the cost, as its calorific value per unit volume is half that of oil. But in absolute terms the costs of transportation by supertankers are very low. Comparing this technology with that of LNG one reaches comparable figures at the end point, with the reforming and synthesis process generating energy losses on the order of 40 percent of the input.

This "methanol route" is not very attractive if the methanol is used only as a fuel substituting for gas (e.g., in power stations) because the younger LNG technology may well reduce its costs faster over the medium term. The approach could, on the other hand, become attractive once methanol is consumed as such for premium uses (e.g., as an antiknock additive in lead-free gasoline).

A first, courageous experiment in this direction has just been started in the Soviet Union. Siberian gas is being transported as such to an industrialized area and then transformed into methanol in two plants, each having a capacity of 2500 tons per day. The methanol is then sent by a 3000 km pipeline to Odessa for shipping abroad. This capacity is quite large per se, world production being in the range of 25,000 tons per day. It is nonetheless negligible when methanol is considered as a fuel.

Finally, methanol (CH_3OH), and methane (CH_4) are very similar molecules, the only difference being a hydrogen substituted by a hydroxide. Thermodynamically it is possible to go from methane to methanol—for example, by using a catalyst and a source of oxygen (e.g., air). Some academic research effort in this direction may well be worth a large investment of public money.

On Drilling

As stated in Chapter 2 on fossil energy resources, the location and structure of hydrocarbon deposits may be very different in one-hundred years because of today's limited knowledge of these deposits. As statistical analysis has shown, one must drill to be able to know accurately what is in the ground. Drilling is very expensive, and only a very small volume of the earth's crust has therefore been explored. To give a tangible example, a 10,000 m deep "wildcat" may cost $5 million—a burning figure if one considers that nine out of ten wildcats have proven to be dry wells.

Drilling technology plays a pivotal role in hydrocarbon procurement, and improvements or breakthroughs would be rapidly reflected in the extension of reserves and resources. However, one should not get the impression that geological insights and measurements are unimportant. Because of the very high cost of the drilling operation, any improvement of the base case of stochastic drilling can pay for large amounts of educated guesses. The actual gain from geological methods seems to be nearer to a factor of two than to a factor of ten (Varnado 1979).

Over the last forty years, the market has been dominated by rotary drills. The basic mechanisms of drilling consist of breaking the rock by applying concentrated loads through spiked rollers or crowns and then liberating the working face from the chips by a flow of mud or compressed air. The rotary drilling head is usually moved by a rotating pipe operated from the surface. This pipe has a diameter of the order of that of the borehole, typically 20 cm, and the level of brinkmanship in a drilling operation can be easily perceived if one visualizes a 20 cm steel pipe, twisted at one end and turning a drilling head, perhaps 5 km distant, downward. One of the typical limitations in this sort of configuration is that the power transmitted cannot be very high—perhaps 50 kW in the best conditions, with the drilling head running at 50 to 100 rpm. Part of the problem is because of the intrinsic limitations of the pipe to transmit a torque, but there is also the problem of the friction losses of the pipe turning in a hole often filled with viscous mud. Typically, only 10 to 20 percent of the input power finally reaches the drilling head.

Experiments have been tried with the alternative configuration in which the motor is near the drilling head. The motor is then operated electrically or through mud flow. This technique of downhole motors has received much development effort, especially in the Soviet Union, and is currently used in special cases where good control of the direction of boring is required (e.g., in curved wells). Performance, however, has not been impressive (understandably). The motor has to be very thin (20 to 25 cm in diameter) and must operate reliably in a very hostile environment, with mud and grit circulating, with temperatures of 100°C and more, and with pressures of hundreds or even thousands of atmospheres. Today's drilling heads usually turn at low rpm, in the range of 100, which severely constrains a motor that should develop at least 50 kW. A gear might solve the problem, but it is too complicated a construction, given such an environment. The alternative would be to have "fast" heads, but for historical reasons only slow ones are available on the market. However, as wells become deeper and consequently transmission through the rotating pipe becomes more and more difficult and inefficient, downhole motors certainly have a future as drill drives since they are much less depth dependent.

A problem common to all types of rotating drills is that they wear quickly, especially on hard rocks. For orientation purposes, a typical run in tough structures can be 20 or 100 m of drilling. The wear is on the conical rollers and on the bearings, both of which are difficult to protect from intrusions of grit. When a bit is worn out, the whole pipe holding the bit has to be pulled up; each pipe section has to be unscrewed progressively, the bit has to be changed, and the operation has to be repeated in reverse. With a 5 km string this requires endurance and motivation. Consequently, compromises are usually made that aim to save on the life of the bit (e.g., by low loading at the expense of drilling rates).

With this as background, and limiting ourselves to discussing how to improve established technology, the main problems to be solved are, first, how to increase the life of the bit and, second, how to increase the power at the bit. A third aspect could be added—how to increase the efficiency of the bit. This is a tall order for technologists who operate mainly through expensive empirical testing.

Much of the research has actually gone beyond variations on the basic bit and has led to the invention of all types of drilling heads—for example, drilling heads that spit supersonic jets of liquids, shoot projectiles, explode and implode bombs, spark the rock, cavitate it, lase it, spray it with aggressive chemicals, and so forth. The result of this random exploration will certainly enrich technological museums, but for now it does not seem to have developed a reliable solution.

Not only the bit's efficiency and endurance but also its versatility are of interest. If it is sufficiently tough, the bit may drill long enough to encounter geological strata of quite different characteristics. In reviewing the literature on what kind of bit is appropriate for what kind of rock, one sees that deeper scientific insight is needed, but that a versatile bit, capable of efficiently penetrating all sorts of formations, may be possible after all.

We have concentrated our brief exposition on drilling heads because at the moment they appear to be the weakest link in the complex technology of drilling. However, another fundamental question is how to remove the cuttings. If the formation is sufficiently compact and dry, this can be done with compressed air; otherwise, water and mostly muds are used. These muds are certainly a nuisance, but they are unsubstitutable for stopping fluids (e.g., water) from penetrating the well. If a different way to control the walls of the borehole during drilling were discovered, this alone could be a fundamental breakthrough in technology.

Worms drill their holes mostly by compacting the soil around them, and while it is true that topsoil is loose, even deep strata have usually some porosity. For orientation, a not atypical figure might be 10 percent. This observation is the basis of the "subterrene" penetration developed by the Los Alamos National Laboratory in the United States. There, a very hot cone is used to drill holes by melting the rock first and then squeezing it into the surrounding porosity. Ideally, a similar effect could be obtained with mechanical or other devices: currently, the cuttings not only have to be brought to the surface and separated from the working fluids through a complicated procedure, but their disposal also constitutes a source of pollution.

Our market penetration analysis (see Chapter 8) indicates that hydrocarbon demand within the 2030 time horizon will tend to concentrate on natural gas, which for geological reasons associated with higher temperature during formation periods, tends to be concentrated in the lower strata. Therefore, the demand for drilling technologies can be characterized as twofold—cheap and deep. The extraordinary rewards to be gained will probably attract an increasing amount of industrial research into this area. The money being spent today amounts to perhaps a few tens of millions of dollars, which is a respectable sum. However, probably for commercial reasons, most of this investment seems to be spent on empirical research with short-term objectives. In view of the broad interest in this technology and of the large geopolitical consequences of a breakthrough, it might be wise to finance, with public money, more research and the dissemination of its results than has been supported up to now.

On Enhanced Oil Recovery

Oil as a mineral appears in different configurations—as a low viscosity material in a permeable structure, as is often the case in the Middle East; or as a piceous stuff in structures of medium permeability, as in the Orinoco basin; or as a glassy material mixed with sand, as in Atabasca. Depending on geologic conditions and history, essentially any possible combination of fluid and porosity can actually be found in nature.

Usually attention is restricted to the straightforward procedure of drilling only oil of the first category. Even under the best of conditions, however, the amount of oil squeezed or seeping into the boreholes is only a relatively modest fraction of the oil in place, typically between 20 and 30 percent. Understandably, harvesting the huge "leftovers" of the oil industry has always been the dream of inventors and managers. Visualizing an oil field as a huge sponge, we see the problem as one of convincing the oil to come out from the tiny pores in which it is held and to flow into larger channels where it can be collected in the normal way. Unhappily, all the methods invented have been relatively expensive—so much so that in general it has been cheaper to discover and drill new oil fields than to squeeze the old ones dry. We are referring here to what is usually defined as tertiary recovery and not to current techniques for keeping the dynamics of the field in the brisk state (e.g., by repressurizing the gas cap and by injecting water at the bottom of the field and in other configurations).

A great stimulation for tertiary recovery processes was provided by the "oil crisis" that occurred first in 1973. Although the statement that "it is cheaper to discover than to recover" is probably still valid, in general the current structural and institutional constraints on the energy system have given new impetus to research on recovery. However, the application of that research has yet to make an impact, and recovery levels remain in the 30 percent area.

Because the problem of tertiary recovery is so complex and dynamic, we can draw here only a rapid sketch, though later we focus briefly on a process that is the most recent and perhaps the most promising. The main problem, as we have said, is to make lazy oil flow, and the principal obstacles are high viscosity, closed or tiny pores, and poor driving forces. Viscosity is probably the most important parameter, if for no other reason than because it is present in all cases. To reduce it, two mechanisms are usually put to work—increasing the temperature and dissolving something in the oil.

Increasing the temperature is not too difficult, although it requires large amounts of heat, since all the geological mass containing the oil must be warmed up. This is usually done by injecting steam in a continuous or alternating way (huff and puff), and as the fields are often deep, the steam must have high pressure. The process is rewarding but not uncomplicated; 30 percent of the oil extracted must be burned again to produce steam.

In order to use the oil in the deposit wisely, proposals have been made to employ nuclear steam for this purpose—that is, to install a nuclear power station over a presumably very large oil field so as to provide the steam to heat the deposit. Proposals of this sort have been studied by Atomic Energy of Canada, Ltd. (AECL) for the Atabasca tar sands and by the Kraftwerk Union (KWU) for Venezuelan heavy crude oils.

Another possibility is to inject air (or oxygen plus steam) into the field and set it on fire (fire flooding). A hot-burning front chases oil ahead of it, and the oil "wave" can be collected in nearby wells. However, controlling fires at great depth and in a blind configuration is a tricky task, and it is possible that ultimately everything could become plugged by hard tars moving ahead of the flame front. Still, research and development is proceeding in many places. One of the difficult problems to overcome is that oxygen, in spite of its abundance, is expensive and may cost, per volume, approximately the same as natural gas.

Decreasing viscosity chemically appears a more natural process. The use of gasoline as a (recoverable) solvent has been successfully tested, although again the economics are not brilliant. Short-chain hydrocarbons, such as propane and butane, can provide the same effect more efficiently. Both are highly soluble in heavy oil and can reduce viscosity by one or two orders of magnitude. Furthermore, both are recovered simply by changing the pressure. Nitrogen as a sweeping gas operates in this way. In moving through the oil field, nitrogen collects light hydrocarbon vapors; when the concentration is sufficiently high, everything, including nitrogen, dissolves into the oil.

A fourth possibility, which we consider to be the most interesting in the long run, involves using carbon dioxide as a fluidizer. This gas is highly soluble in heavy crude oils and in fact increases their volume by up to 50 percent while decreasing their viscosity by one or two orders of magnitude. Because of its chemical properties in the presence of water, carbon dioxide usually increases the permeability of the oil-bearing structures as well.

Large carbon dioxide fields exist in Colorado, and an industry is now developing there to drill these fields and to pipe the gas to Texas. The demand, however, can be enormous if the use of carbon dioxide increases; recovering it from flue gases may then become an economic proposition.

Atmospheric disposal of the carbon dioxide generated by burning fossil fuels is likely to generate a class of problems of its own (see Chapter 10). In a geoengineering spirit one can think of integrating power generation and carbon dioxide production by first separating air; then using the oxygen in zero emission power plants that burn, for example, coal; and finally piping carbon dioxide (and even nitrogen) to the oil fields for recovering oil and, if necessary, for the final storage of carbon dioxide. The scheme may appear grandiose, with a "fuel cycle" concept being applied in a multipurpose way to fossil fuels. Manipulation of gases, however, usually requires unexpectedly high compression work, and this robs them of some of the advantages they have in tertiary recovery with respect to liquids.

The field is wide open for research and invention. The last proposal, patented in 1977, suggests hydrogenating residual oil in situ by heating the bed to 400 to 500°C in the presence of high pressure hydrogen. This concept is quite suggestive in principle; it even considers some refinery operations, although the energy expended in heating would certainly be very large. If such a concept could be embodied in a process operating at field temperatures of, say, 100 or 200°C, with a catalyst in the form of a volatile hydrogen donor solvent, in analogy to what is done in coal refining, then the scheme could become interesting indeed.

Assuming the oil left in the old fields and recoverable only by tertiary methods to be in the range of 40 billion tons, its selling value is in the trillion dollar range. This may explain the intense interest in the problem of tertiary recovery, even in the face of competition from new discoveries.

MESHING THE OLD ENERGY SOURCES WITH THE NEW ONES

Having explored briefly some of the potential for near-term technological developments in the four areas of energy storage, natural gas transportation, drilling, and enhanced oil recovery, we can now take our line of inquiry one step further and ask which of the possible near-term developments might particularly facilitate the eventual transition from fossil fuels to a sustainable, asymptotic energy system. Again, our examination cannot be vigorously complete. Rather, our intent is to draw attention to some important interconnections within the energy system–important in the sense that the system as a whole may be particularly sensitive or responsive to technological advances associated with these interconnections.

The Problem of the Active Interphase

Because the energy system is complex and slow moving, the success of new energy technologies depends strongly on both the infrastructure created by previous fuel systems and the ingenuity used in exploiting them. Competition can, in intermediate phases, become a fruitful symbiosis.

Nuclear energy is the first example of a (potentially) large, nonchemical energy source to enter the market in substantial amounts. Nuclear energy appears from the nuclear reactor in the form of heat, and the structure it parasitized was the electrical system where heat is used in large amounts to make steam. Similarly, the likely competitors in the electricity market are a variant of nuclear energy, fusion, and a variant of fusion, solar energy, both of which are most easily converted to heat or electricity.

Still, if nuclear, solar, and fusion end up competing for the electricity market, our dependence on fossil fuels and all the problems associated with that dependence will be only slightly alleviated, with the day of judgment displaced by only ten or twenty years. The only way to make a dent in the system is to enter into the chemical energy area, and tactically, the most rewarding way to make the transition may be one that also, initially, will contribute to solving a major problem of fossil fuel use. The central problem in fossil fuel use is that demand is moving progressively toward fuels rich in hydrogen—typically methane—while reserves are mostly constituted by fuels poor in hydrogen—typically coal and heavy crude oil. In other words, hydrogen is in short supply in the chemical fuel system.

Hydrogen can be produced using coal and heavy crude oil. However, it is a final product that, with respect to oil and coal, accumulates inefficiencies in the energy transformation and also requires significant capital cost investments. Thus, if the new energy sources are to be competitive, hydrogen is the proper interphase. Water is the best source of hydrogen, and the importance we attribute to the development of this interphase justifies the relatively extended treatment that is given here to the problem of water-splitting using electricity or heat.

As stated previously, oxygen and carbon dioxide are also in short supply in the fuel system. Therefore, we shall briefly touch upon some of the many possible technological approaches that exploit systematic combinations of these constituents and thereby widen the "penetration window" for such technologies and, consequently, increase their chances of success.

Historical Background and Future Trends For Electrolysis

Water electrolysis has a long scientific and industrial tradition. Originally, it established itself in elucidating the structure of matter at the time of Preston and Lavoisier. The first patent on water electrolysis was granted to the Russian, Dmitri Latchinoff, in 1888; at the end of the century, the Italian, Pompeo Gurati, discovered the monopolar cell, thus becoming the first person to achieve industrial success. Initially designed with lead electrodes and sulfuric acid (H_2SO_4) electrolyte (similar to the way an automobile battery operates in the overcharging mode), the cell was soon modified using iron electrodes and sodium hydroxide (NaOH) electrolyte. This basic technology has evolved slowly, with no major breakthroughs up to now. The demands of the space industry have stimulated the development of cells based on solid state electrolytes—that is, cells in which the liquid electrolytes are replaced by a plastic membrane of acidic type; sulfurous radicals (SO_3^-) are held together by the membrane polymeric structure, with water moving inside a molecular porosity.

The first filter press water electrolyzer (in which unit electrolytic cells are packed together and connected electrically in series) appeared in the patents of the Swiss, Oscar Schmidt, in 1899, and was manufactured by the Oerlikon Corporation in Switzerland. The evolution of water electrolysis plants was greatly assisted by the development in Switzerland of their hydroelectric power system. Their system made electricity available at low marginal cost, and the Swiss were interested in using it for the electrochemical industry. This hydrogen found its way into the fertilizer industry and into use in metal reduction. The filter process electrolyzers developed by Zdansky in the 1950s for the Swiss company Lonza and now commercialized by Lurgi in the FRG are considered probably the best on the market today.

As all water electrolysis plants have been designed for chemical purposes, their scale appears small compared to what it would necessarily be if used for the energy system. Table 22-1 shows the currently most significant water electrolysis plants worldwide. All plants are associated with hydroelectric projects, and the largest plant, by Norsk-Hydro in Norway, has a capacity of about 200 MW. The largest electrolyzer unit now available commercially from Lurgi has a rating of about 3 MW, while the largest conceptual design is from General Electric (for a project sponsored by Brookhaven National Laboratory in the United States), which contemplates a 75 MW unit. If electrolysis has to interface with large reactors within the energy system, units rated in the gigawatt range would be required.

This growth in power for the units requires a comparable increase in power density, if for no other reason than to make them transportable. Fortunately, current trends are in the right direction: the Lurgi electrolyzer has a power density of about 0.15 kW/l, while the General Electric electrolyzer's density is about 2 kW/l. For the latter, a 1 GW unit would have a volume of about 500 m^3 and a weight of 500 to 1000 tons, which is still too large. Target power densities are about 10 kW/l, which would make these machines factory assembled and easily transported. Such a target is not unrealistic, given the solid polymer electrolyte technique, the high pressure, and the possibility of gains in current densities.

As the following economic analysis will show, the cost of the cell constitutes a small fraction of the cost of the electrolytic plant, about 10 to 15 percent. Consequently, an increase in efficiency and reliability of these cells should be the aim of research and development, since such increases would

Table 22-1. Large electrolytic plants of the world.

Company	*Cell Name*	*Location*	*Approximate Capacity (MW)*	*Year*
Norsk Hydro	Hydro Pech-Kranz	Rjukan, Norway	210	1965
De Nora	De Nora	Nanagal, India	180	1960
Demag	Demag	Aswan, Egypt	130	1960
Lurgi	Zdanski-Lonza	Cuzco, Peru	20	1958

Source: Based on data from General Electric (1975).

influence proportionally the cost of the whole plant, including reactors and electric generators. Since the auxiliaries in electrolysis—namely, plant erection and capital charges for construction—account for 90 percent of the capital cost, there is significant potential for trimming the auxiliaries and producing factory-assembled (turnkey) packages.

Efficiency of cells has been progressively improved from a historical 50 to 77 percent (high heating value [HHV]) of present commercial models (by Lurgi). Laboratory cells (by General Electric) permit efficiencies (HHV) up to 100 percent, depending on the optimization. Note, however, that this is enthalpic efficiency; second law efficiency would be almost 85 percent.

A new method of water electrolysis, proposed at Oak Ridge Laboratories in the United States about two years ago and now being successfully used at laboratory scale at Dornier System in the Federal Republic of Germany, consists in electrolyzing water at high temperatures, say 800 to 1000°C (Hot Elly) (Doenitz et al. 1979); most of the irreversibilities in electrolysis are the result of poor kinetics, and high temperature practically eleminates them. But there is also a thermodynamic argument—namely, that the water molecule is weakened by temperature and less electrical energy is needed to break it. Essentially, part of the required work can be done using cheaper heat. Expected savings in electricity consumption are on the order of 20 percent when compared with advanced low temperature cells. However, making intricate structures operate reliably at such high temperatures for ten or twenty years would require a huge amount of development work.

Because of the resultant faster reaction rates, electrolyzers also tend to improve their performance when pressure is increased, up to a point. Retrograde diffusion of oxygen (O_2) through the electrolyte acts against this tendency, and consequently, there is an optimal operating pressure. However, because compressing hydrogen (H_2) is expensive, the design of most modern cells is based on optimizing H_2 pressures subject to the constraints imposed by the pipeline system (i.e., 50 to 100 atm).

Technoeconomic Considerations for Electrolyzers

An analysis of present commercial pricing systems for electrolyzers would not be worthwhile, since today's machinery is of too small a scale for the purposes we have in mind and since large-scale application will probably not become feasible for some ten to fifteen years. This is the same amount of time needed for nuclear reactors to saturate the electricity system in some countries (e.g., France and the FRG) and also for some large hydroelectric schemes to mature. Consequently, our objective here is to give orientating information and to describe the trends.

In Table 22-2 we present economic data for an electrolysis plant developed by General Electric and sponsored by Brookhaven National Laboratory and Public Service Electricity and Gas Co. in New Jersey. All components are taken at present prices, with the exception of the cell, which has a price estimated for about 1985. The analysis reaffirms our previous statement that

Table 22-2. GE bipolar—solid polymer electrolyte.[a]

Component	*Specific Cost ($/kWH$_2$)*	*Source of Estimate*
Electrolytic cell	7.41	GE/DECP
Power conditioner	35.46	GE 28$/kW Input
Switch gear	3.43	GE 2.90$/kW Input
Feed pump	0.52	Buffalo Forge Co.
Circulating pumps (3 required)	0.65	Buffalo Forge Co.
Feed water purification system	2.75	Rohm and Haas
Deionizer system	5.59	Rohm and Haas
O_2/H_2O separator tank	0.52	Carborundum Corporation
H_2/H_2O separator tank	0.52	Carborundum Corporation
Bleed cooler	0.52	GE
Oxygen cooler	0.23	American Standard
Main heat exchanger	0.93	American Standard
Hydrogen cooler	0.22	American Standard
Deoxo system	0.86	Engelhard
Dryers (3 required)	1.82	Kemp Manufacturing Co.
Back pressure regulators	0.09	GE/DECP
Mixing valve	0.09	GE/DECP
Main HW coolant pump w/auxiliaries	0.15	Purcell Pump Co.
H_2 cooler pump w/auxiliaries	0.05	Purcell Pump Co.
O_2 cooler pump w/auxiliaries	0.02	Purcell Pump Co.
Controls	0.17	GE/DECP
Fittings, piping, valves, instruments	0.71	GE/DECP
Installation (12% of above)	7.52	GE/DECP
Totals	70.23	

[a] Total system cost breakdown for base case, with no allowance made for buildings and land.

Source: Based on data from General Electric (1975).

efficiency is the real parameter to choose. Even taking at face value the approximately $10 per kW for the electrolytic cell proper, the cost of all the machinery sitting behind it is in the range of $1000 per kW. Consequently, a 1 percent increase in efficiency pays for a doubling of the cell's cost. Progress is being made in that direction and in the direction of improving the life and reliability of the components.

As can be seen from Table 22-2, power conditioning takes a sizeable share of the total cost; to this must also be added the cost of the generator, which for 1000 MW can be valued at around $15 to $20 per kW(e) (1974 dollars). Recognizing this, particular consideration should be given to possibilities for producing electricity as direct current (DC) at a voltage appropriate for electrolysis, typically 10^3 V, and with currents in the range of 10^5 to 10^6 amp. Such machines have been constructed for special applications, and it is expected that their cost would be in the range of $15 to $20 per kW(e).

Clearly, the main obstacle to increasing the efficiency of generating hydrogen using nuclear heat is the need to transform heat into mechanical work. What are the prospects for this critical link in the chain of intermediate transformations? As is shown in Figure 22-3, a historical analysis of the evolution of this efficiency shows a stable trend, with good promise for the future provided there is sufficient time. In fact, the time constant of this evolution (1 to 50 percent) is about 300 years.

Given this, let us turn our attention to a different pathway that was conceived about ten years ago in an effort to avoid this bottleneck—specifically, thermochemical water splitting or, more concisely, thermolysis. As can be seen in Figure 22-3, chemical processes appear to have faster learning curves or shorter time constraints than do processes for transforming heat into mechanical work, and consequently targets would be reached in manageable instead of historical time.

Thermolysis

The basic idea of thermolysis consists in decomposing water, using chemical reactions driven by heat. The simplest scheme would be the one-step process of water cracking, but since the temperatures available from nuclear reactors are well below the 2500°C to 3000°C needed to do this, the operation has to be performed in two or more steps. Since the thermodynamic constraints do not change by changing the pathway, the basic thermodynamics of water splitting, whether thermochemical or electrolytic, can be represented as in Figure 22-4. As our starting material is water at room temperature, to decompose it we must provide 57.2 kcal/mole of free energy. To give a quantitative feeling of the limits, the maximum efficiencies for various types of reactors are given in Table 22-3. All of the reactors listed have been constructed, although only the light water reactor (LWR) is commercially available.

Since fuels are usually graded by their enthalpy of combustion, there is good potential for a reactor heat-chemical fuel interface in the form of hydrogen. The crucial question is how fast this potential can be realized. The rate appears fairly good for chemical processes. For some of the most promising processes, efficiencies have been calculated between 40 and 45 percent where the efficiency is defined as energy (enthalpy) in the product divided by energy (enthalpy) in the input. Since these processes usually depend on high temperature reactors (HTRs) for heat, taking as a reference the theoretical enthalpic efficiency yields relative efficiencies of the order of 50 percent. This would be a good starting point in absolute terms and also a fortunate one, as the logistic learning curve has its maximum slope there. Note that the efficiency of transforming thermal into mechanical energy is in the same range, but that the time constant is much larger.

There are many closed cycle thermochemical processes that, in principle, are able to perform the function of decomposing water. Computer searches have listed them in the range of tens of thousands, although only twenty or thirty of these processes have been investigated thoroughly (see Veziroglu and Seifritz 1979). Figures 22-5 and 22-6 illustrate two thermochemical processes that have the same basic reaction but different closures. The pro-

Figure 22-3. Historical trends in efficiency. $\Delta t_{1-50\%}$ is the time necessary to evolve from an efficiency of 1 percent to one of 50 percent. ϵ is second law efficiency.

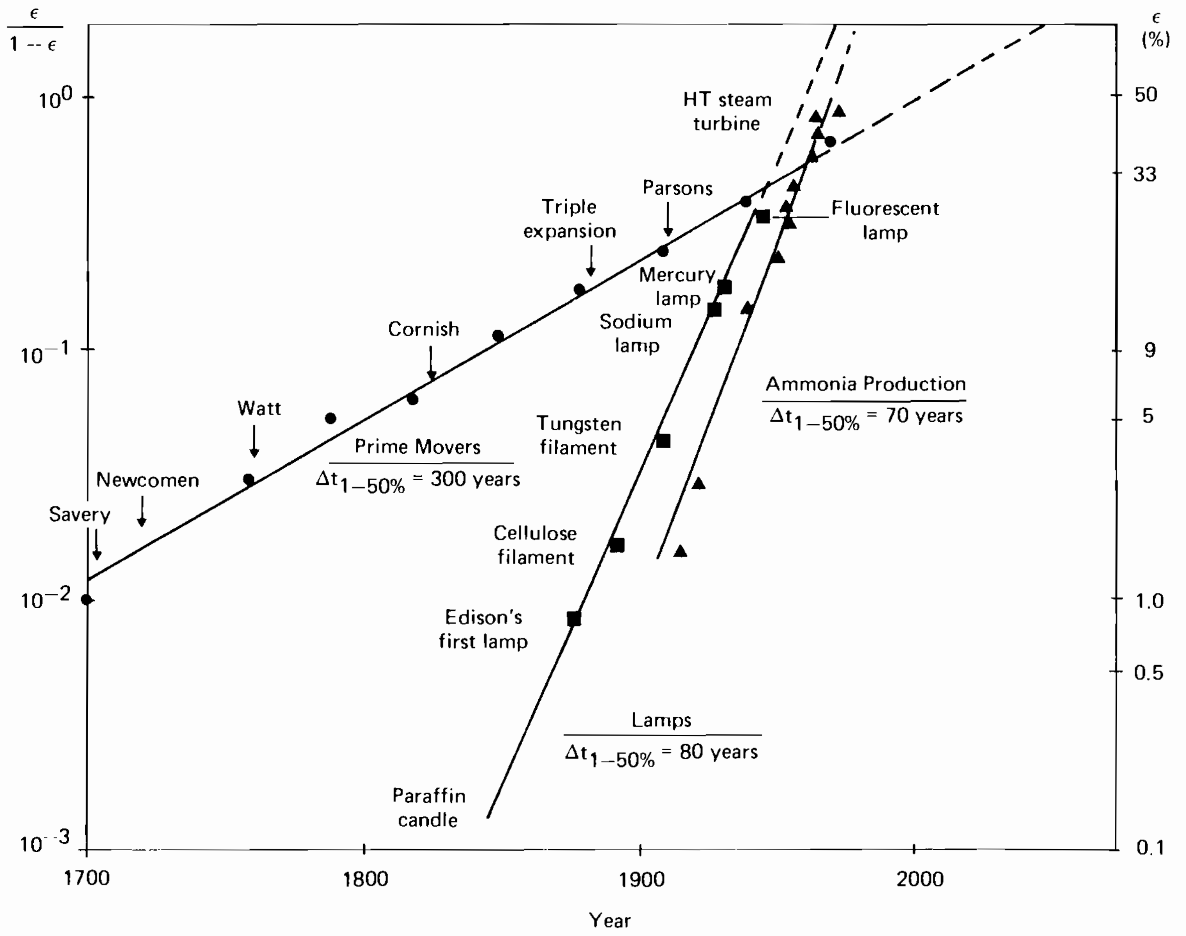


Table 22-3. Theoretical efficiencies for the reactor heat/hydrogen interface.

Reactor Type	*Characteristic Temperature (°C)*	*Reference Temperature (°C)*	*Second Law Efficiency (%)*	*Enthalpic Efficiency (%)*
LWR	300	25	46	54
LMFBR	600	25	64	75
HTR	800	25	70	83

Figure 22-4. The thermodynamics of water splitting. Curve E represents the energy consumption of the fuel cell (in kWh per produced kg of H_2); circles represent operating electrolytic plants; black dots represent possible operation points of solid polymer electrolyte (SPE) cells. Notes: The intermediate temperature cells are not under development at present; their possible characteristics are indicated by the continuation of curve E (dashed part); ΔH is the change of enthalpy, and ΔF the change of free energy. ΔF must be provided as electricity (or in another form of free energy). For electrolysis, ΔH-ΔF must be provided as heat (ΔH). Usually, because of inefficiencies in the cell, heat is provided through electric losses. This may not be the case for the Hot Elly process because of expected high electric efficiency. Source: Based on information from U.S. Atomic Energy Commission (1972).

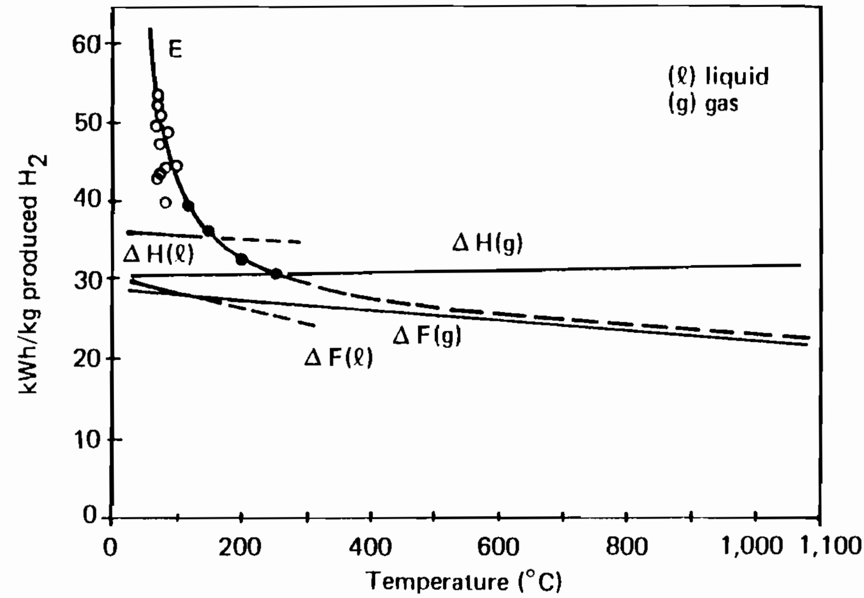


Figure 22-5. Hybrid and thermolytic water splitting. Sources: Based on data from Farbman and Brecher (1975); Marchetti (1973); Russell et al. (1976); and Besenbruch et al. (1978).

CLOSURES:

— Basic Reaction $H_2SO_4 \xrightarrow{<850^\circ C} H_2O + SO_2 + \frac{1}{2} O_2$

— Electrolysis $SO_2 + 2H_2O \xrightarrow{+0.5 Volts} H_2SO_4 + H_2$

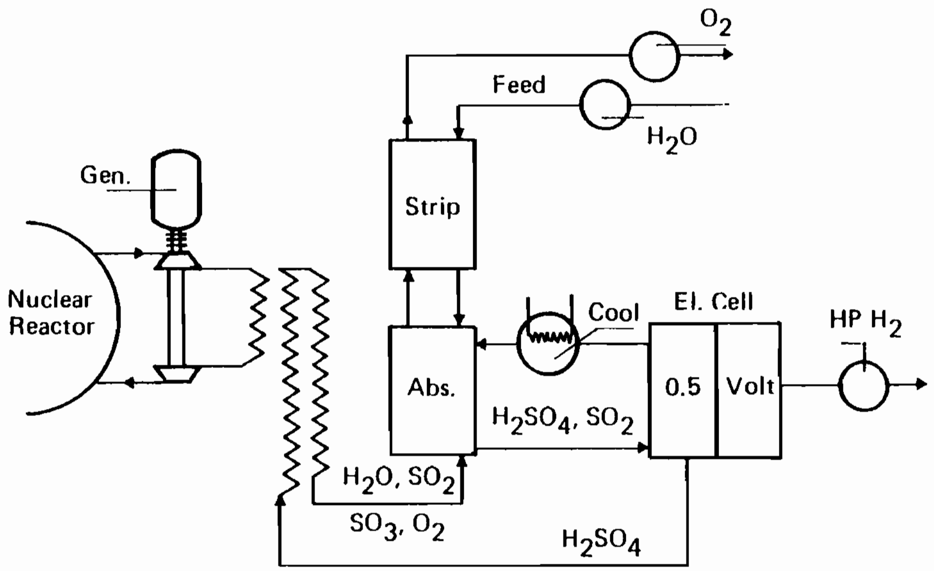
(Westinghouse)

— Iodine $SO_2 + 2H_2O + I_2 \xrightarrow{1000^\circ C} H_2SO_4 + 2HI$

$2HI \xrightarrow{300^\circ C} H_2 + I_2$

(General Atomic)

Figure 22-6. Scheme of the Westinghouse hybrid water-splitting process. Sources: Based on data from Farbman and Brecher (1975); Marchetti (1973).



cesses indicated are among the most intensely studied in terms of potential industrial application. One of these processes is actually a hybrid: one part of the operation of decomposing a water molecule is done chemically and the other part by means of electrolysis. Electric consumption would be roughly one-third that for pure electrolysis.

All systems that serve to connect a nuclear reactor with the chemical fuel system are obviously sensitive to the cost of the nuclear heat. Nuclear energy has so far developed mainly in the ecological niche of electricity production, and had the electrical system not achieved its present size and structure, the introduction of nuclear energy would not have been possible for several reasons. First, the electrical system provides the capacity to "digest" large power units, and second, the system requires heat, putting nuclear energy at the same level as that of other fuels for which heat can be considered a derivative product, though one easily obtained through combustion.

The use of nuclear reactors to produce synthetic fuels is a retrograde operation: heat is transformed into a synthetic chemical that would compete with natural fuels. Viewed in this manner, a tight constraint would be put on the cost of nuclear heat, since only a substantially lower cost could absorb both the transformation costs and the transformation losses.

Now, when fossil fuels had a price of $0.5 per MBtu, nuclear heat was priced at $0.45 per MBtu. But when the price of crude oil increased to $2 per MBtu, through a miraculous alchemy, nuclear heat costs rose to $1.8 per MBtu. Also, coal increased in price, following the path of oil closely. What this may mean is that once a large market opens up for absorbing nuclear heat, all available elasticity will be put to good use to reduce costs.

An engineering study of an advanced nuclear-electrolytic production facility was done by the Institute of Gas Technology for the National Aeronautics and Space Administration (NASA) in the United States (Escher 1975). The study considered a fully operative hydrogen plant powered with either LWRs or HTRs. Since no electricity is generated, the entire system is streamlined to produce hydrogen baseload. The capacity factor of the plant was assumed to be 80 percent. Table 22-4 lists the relevant information, compiled from the data in this report. Some comments may help to better interpret these data.

For the base case (LWR), only technology available commercially in 1975 was taken into consideration. Prices for the reactor and for the electrolytic units were taken from published literature and bids; the characteristics of the reactor are roughly those of LWRs coming on stream in 1975. Cooling is by wet tower. The electrolytic plant uses rectifiers to interface with the electrolytic cells, and the cells adopted are the Lurgi-Lonza type: 280 units of nominal 2.5 MW capacity are used. The advanced concept used a HTR with basic design characteristics and costing as provided by General Atomic in the United States. The very efficient cycle (50 percent) is based on a set of three gas turbines operating a direct topping cycle and on an ammonia turbine for a supercritical Rankine bottoming cycle. Cooling is again by wet tower. A set of homopolar generators coupled to the turbines provide the DC current for the cells, thus eliminating the need for expensive electrical

Table 22-4. Fully dedicated nuclear-electrolytic H_2 plant, 1975 and 1985 technology.

Technical Characteristics

Reactor type	*Thermal input electricity output*	*Primary temperature cycle*		*Electrolysis*	*Final efficiency H_2 (HHV)/Heat (%)*
LWR (1975)	3 GW(th) 1 GW(e)	320°- 280°C	Steam 269°C	Rectifiers Lurgi Cells	24.7
HTR (1985)	3 GW(th) 1.5 GW (e)	980°- 570°C	Direct gas turbine (3 X 360 MW) Ammonia turbine (1 X 420 MW)	Homopolar Generator SPE Cells	42.9

Economic Characteristics

			Operating Costs		*H_2 costs (NO O_2 credit) (80% plant capacity)*
Reactor type	*Total plant cost (M$)*	*Electrolytic system(M$)*	*Capital (at 15%)(M$)*	*Fuel and operation (M$)*	*($/MBtu)*
LWR (1975)	935	327	140	35	~ 10
HTR (1985)	806	70	121	35	~ 5

Source: Based on data from Escher (1975).

conditioning equipment. The cells are of the solid polymer electrolyte type being developed by General Electric. Costs and characteristics are those estimated by General Electric for 1985. Capital charges are of the utility type, leading to a gross charge of 15 percent per year. Plant capacity was assumed to be 80 percent. For comparison, mature chemical plants can reach 90 percent capacity, and this would lead to a straightforward reduction in the H_2 cost of about $0.5 per MBtu. O_2 credit at $10 per ton could add a similar benefit. This may be critical for the first plants, but unless new large-scale uses of O_2 are found, the market would be rapidly saturated. (One example of such uses is a zero emission power plant where fuels are burned with oxygen; and carbon dioxide, water, and other combustion products are removed as liquids, thereby eliminating emission releases.)

On Solar and Hydroelectric Power as Primary Sources

Most of the previous treatment of water splitting refers to nuclear energy as a primary energy source, mainly because most water-splitting studies have been done in that context. However, for electricity generation, the primary source of energy is, up to a point, immaterial.

Solar energy systems, especially if conceived on a grand scale, will need a transportable and storable energy vector. Here too, hydrogen is the most suitable candidate. If solar energy is captured with photovoltaic cells, then electrolysis is the best interface. If the plant is thermal, then thermochemical splitting may come into play. Photoelectrolytic cells are also possible and have been constructed at the laboratory stage (Hantala et al. 1979). A similar situation exists for some large-scale hydroelectric schemes, as for example those contemplated for Greenland or for Brazil. These projects would probably be too large for the energy generated to be absorbed by one of the current electric-intensive industries (e.g., aluminum); although sites are usually too far away from very large consumption areas, electrolysis can then connect them with a vast chemical market. A precedent is that of ammonia synthesis, which provided a similar solution during the period between the two world wars, when the large hydroelectric base of European electric systems made available large off-peak electricity blocks.

Electrolysis for Electricity Storage

Solid electrolytes developed for the space program promise cheap and efficient electrolyzers, and as mentioned earlier in the chapter, this has led to contemplating the use of electrolysis and fuel cells as a storage medium for electricity. The method promises to improve the economics of pumped storage, and various schemes have been proposed—for example, electrolyzing water and storing hydrogen in metal hydrides or electrolyzing HCl or HBr and storing Cl_2 and Br_2 as solution and condensates. The second solution in particular appears attractive since the same cell can be used with good efficiency for electrolysis and electricity generation (Gileadi et al. 1977; Beaufrere et al. 1977). These "batteries" could be incorporated into electric substations, accumulating energy during off-peak hours and releasing it during peak hours. This configuration has several advantages—specifically, releasing the transport lines from peak loads and providing local generation in case of failure of the main system, thus adding a great resiliency to the net.

Coal Gasification: The Molten Iron Process

As mentioned earlier, methanol is an easily and cheaply transportable energy storage medium. A first large-scale conversion of natural gas into methanol has already been described in this chapter, and another approach to its synthesis is that using coal as the primary input, as introduced in Chapter 3.

"Coal," in fact, is a name for a group of solid carboniferous substances that range from "carbon-polluted rocks" and "carbon-polluted water" (the lowest quality lignites) to anthracite, consisting of more than 90 percent carbon. Consequently, the initial equation describing the gasification of coal may be written in a symbolic form:

$$[\underbrace{(C + 1/2\ H_2) + \text{minerals} + H_2O}_{\text{raw coal}}] + O_2 \rightarrow$$

$$[\underbrace{CO + H_2 + H_2S + C_mH_n + CO_2 + \ldots}_{\text{raw gas}}]$$

$$+ \text{ashes} + \text{nonreacted C} + \text{heat}$$

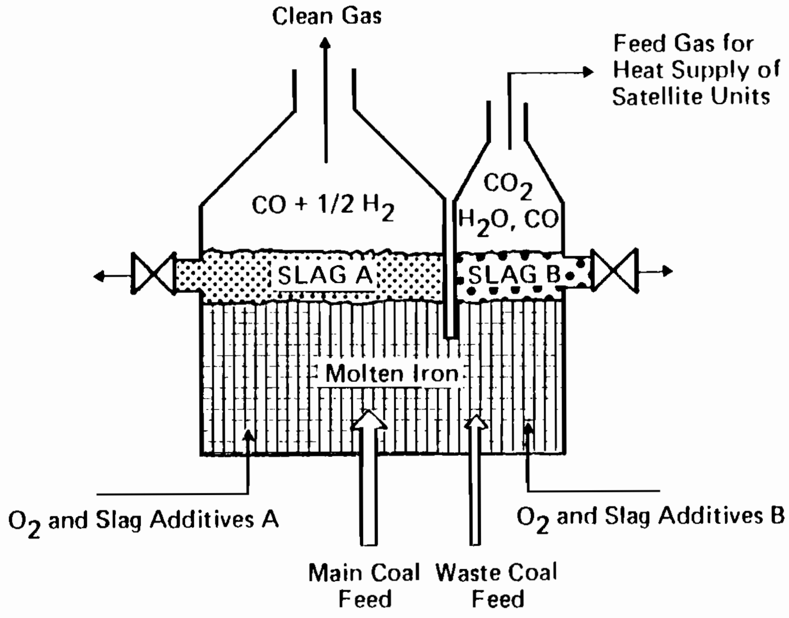
In contrast to "simple" complete combustion of coals, where the reaction products are just separated physically into stack gases and ashes and discharged into the environment, the gas composition must be carefully controlled if producing synthetic fuels is the objective. The chemical synthesis step requires a clean raw material, especially for making methanol.

Coal gasification technologies in use or under development today generate raw gas requiring costly additional treatment in order to make it suitable for methanol synthesis involving catalysts that are extremely sensitive to poisoning. A few commercial gasification techniques have evolved that are capable of producing pipeline gas or synthesis gas by making full use of the specific properties of a narrow range of coals. Given such a situation, we took as a reference the molten iron process (MIP)—a gasification technology that, although it has not yet been proved commercially, appears to be insensitive to the quality of the coal input.

Figure 22-7 illustrates the basic material flow of the process. The molten iron process, mainly investigated by Klöckner Humboldt in Cologne, FRG, applies for a different purpose the Linz-Donawitz (LD) process for transforming pig iron into steel. Figure 22-8 presents a schematic drawing of a LD converter. Pure oxygen is fed in at the top as a supersonic jet impinging on the surface of the bath. Dissolved carbon is oxidized and leaves the bath in the form of pure carbon monoxide. Sulfur and other substances that were transferred in the blast furnace from coal and iron ore into liquid pig iron are fixed chemically by the slag forming on top of the bath. Molten raw iron is discontinuously transformed into steel. However, the converter (Figure 22-8) can also be operated in principle as a coal gasifier. In this case, fresh coal has to be added continuously to make up for the oxidized carbon leaving the converter as carbon monoxide.

The molten iron process was selected here for several reasons. First, physical and chemical reactions at the temperature of 1500°C in a liquid metal are very fast, and the difficulties of "surface" chemistry in the solid gas systems common to other gasification processes are avoided, as are baking problems and the formation of complex hydrocarbon substances. Second, liquid slag chemistry is a comparatively simple and highly developed technique for absorbing ashes and impurities in coal and for separating them continually from the reactive medium, the liquid iron. Finally, in present steel plants, most of the components of the molten iron process operate with physical dimensions that are appropriate for large-scale energy applications—that is, they are potentially capable of converting coal at the gigawatt level. The first two points suggest that no constraint on the specific properties of

Figure 22-7. The Linz-Donawitz (LD) process modified for coal gasification for synthetic liquid fuels production: TANDEM scheme. A and B distinguish between two different slag additives. Source: Based on Mietzner and Schwerdtfeger (1980).



coal would be imposed as long as the energy balance of the reactions and the composition of the slag can be controlled.

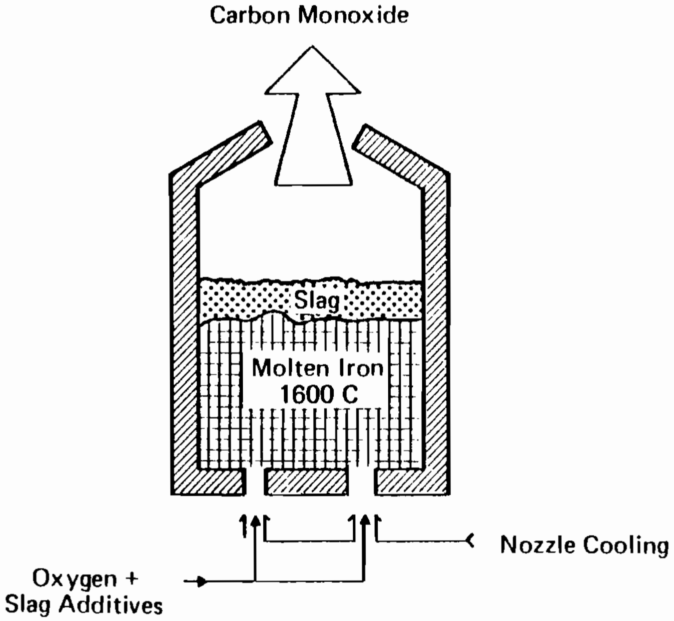
In order to allow for the flexible handling of varying coal inputs as well as for a simple process control, the Tandem process of Figure 22-7 comprises two separate gas- and slag-handling systems but one common liquid iron loop. Within certain limits this concept allows low quality coal inputs without modifying the output gas quality or the technical layout.

First tests of the molten iron process indicated that only limited purification is necessary for the gas delivered by the Tandem process before it can enter the catalytic conversion into methanol. Using data from steel converters, we estimated investment costs below $100 per kW for unit sizes in the gigawatt range. This would place coal gasification for methanol synthesis at a similar level as surface mine investment costs.

OBSERVATIONS

In Part VI, we will develop further some of the observations of this chapter, suggesting how some of the technological developments touched upon here

Figure 22-8. The iron/steel converter with bottom oxygen feed (OBM process, Maxhütte). Source: Based on Mietzner and Schwerdtfeger (1980).



might contribute to future energy strategies. Here, however, it is still useful to focus briefly on one possible set of future relationships among some of the technologies discussed.

We begin by observing that the difficulty of directly storing electricity has led to generating capacity that is often idle. We can imagine introducing electrolyzers and fuel cells at generating stations. The argument proposed here would then apply to idle capacity of nuclear or solar origin since, for both, the fuels and the fuel-related costs would be small, thereby making the full load throughout the operation of nuclear or solar generating capacity practical. Such a development would provide for both experience with, and improvements in, hydrogen technology, and it would initially not be constrained by hydrogen demand, as there already exists a hydrogen market for ammonia synthesis and oil refining. If hydrogen were used for storing off-peak electricity, then the system would be closed. If, further, we were to introduce the synthesis of methanol (or whatever synthetic liquid hydrocarbon turns out to be the most appropriate), then the market would be practically unlimited. The methanol produced would help satisfy the pressing demand for liquid fuels, and the experience gained would help prepare us for a time when electricity and hydrogen would be the principal, if not the only, energy carriers in the system.

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23 ENERGY DENSITIES, LAND USE, AND SETTLEMENT PATTERNS

INTRODUCTION

The way humans settle on the land and use it is a key to understanding energy supply and demand. The settlement pattern introduces large inhomogeneities in energy demand densities, which in turn influence the potential both for exploiting natural energy sources and for transporting and distributing energy. This influence may be felt on a large scale (e.g., the existence of large areas inhabited so sparsely that they can be significant only as sources of centralized energy for large-scale transmission to remote demand centers) and on a smaller scale (e.g., the existence of concentrated human settlements—so-called "conurbations"—that require large, concentrated energy sources). Indeed, an understanding of the relationship among settlement patterns, land use, and energy demand densities permits the projection of global energy demands independent of regional analyses.

Obviously, a region's settlement pattern determines how it consumes energy. The settlement pattern in turn results from orography, climate, the availability of natural means of transportation—in particular of waterways—the spatial occurrence of raw materials, soil, biosystems, or from a multiplicity of demographic, social, political, and historical factors.

Humans have tended to cluster their settlement patterns. The degree of clustering is apparently limited only by the technology available to supply materials and services to the cluster and to permit some degree of individual mobility within the cluster. One of the services to be supplied is energy. It is generally easier to transport energy to places where all other conditions for settlement are favorable than to transport other commodities and change the natural conditions at those places where energy is abundant.

Only a few conurbations have developed on the basis of industrial exploitation of nearby energy resources—for example, the Rhine-Ruhr area of the FRG, the British Midlands in Europe, and the Ohio River (Pittsburgh) complex in the United States, all based on coal; and the Texas-Gulf Coast complex in the United States, based on oil. However, in general, large metropolitan areas such as Tokyo, New York, London, Moscow, and Paris, as well as some fast-growing ones in the developing countries such as Sao Paulo and Calcutta, are not located on or very close to major coal, oil, or gas deposits.

The impact of land use on energy consumption and generation is also direct. Again, energy density is a key factor. For example, "soft" energy technologies—that is, small-scale technical devices for harvesting energy from the local environment—can largely be deployed only on inhabited land areas. But only a fraction of the human population, and indeed a steadily decreasing fraction, inhabits land at a low enough density so that the density of natural supply exceeds the density of demand; the rest of the population must import energy. And even where natural supply densities appear adequate, there are competing demands for land use—for example, agriculture, forestry, recreation, and wilderness preservation for ecological values.

The environmental impacts of energy conversion and use must also be considered in relation to land use, settlement patterns, and energy densities. Many of the environmental impacts of energy conversion units (e.g., refineries, power plants, motors, and stoves) occur on inhabited land. These impacts are felt predominantly as impacts on human health and safety. Consequently, energy consumption densities provide more meaningful information if calculated on the basis of inhabited or at least inhabitable land, rather than on the total land area of a country or a region.

Energy densities thus enter into the assessment of energy problems at four points. Two refer to the supply side—the assessment of the potential of soft energy technologies and the assessment of the environmental effects of all energy conversion technologies, be it at the supplier or the consumer end. Third are the impacts resulting from the strong, nonlinear dependence of the costs of energy transport systems on the amount of power transmitted and hence on the consumption densities of the areas to be serviced. Finally, energy demand densities appear to be characteristic of settlement patterns, so that a projection of these patterns can be translated directly into an energy demand projection.

HUMAN SETTLEMENT PATTERNS AND ENERGY DENSITIES

Table 23-1, based on data from an analysis of potential long-term settlement trends (Doxiadis and Papaioannou 1974), illustrates the global land use situation. Some 50 percent of the total global land area (of 148×10^6 km^2) is

Table 23-1. Estimated global land use.

Land Use	*Area (10^6 km^2)*
Inhabitable	
Human settlements	0.4
Arable land	13.0
Pastures (partial use)	21.3
Forests (partial use)	35.3
Usable (but impracticable)	3.9
Total	73.9
Uninhabitable	
Wastelands, deserts, high mountain regions	62.1
Polar regions, uninhabited islands	12.5
Total	74.6
Total land	148.5
Ocean surface	361.6
Total of earth's surface	510.1

Source: Based on data from Doxiadis and Papaioannou (1974).

considered uninhabitable. These areas comprise the polar regions, sand and ice deserts, high mountain regions, and a sizeable fraction of semiarid grass lands and low productivity forests in extreme climate. Following this definition—which would suggest among other things that the tropical rain forests can be fully exploited—Table 23-2 gives an (optimistic) estimate of the inhabitable areas of the seven IIASA world regions discussed in this study.[a]

Table 23-2. Potentially inhabitable land of IIASA world regions.

Region	*Total Area (10^6 km^2)*	*Fraction Uninhabitable (%)*	*Inhabitable Area (10^6 km^2)*
I (NA)	21.5	42	12.5
II (SU/EE)	23.5	34	15.5
III (WE/JANZ)	15.5	39	9.5
IV (LA)	20.6	28	14.8
V (Af/SEA) VI (ME/NAf)	43.4	43	24.7
VII (C/CPA)	11.5	68	3.7
World	136.0	41	80.3

Source: Based on data from United Nations (1976).

[a] See Figure 1-3 for a definition of these regions and Appendix 1A for the list of the countries in each of the regions.

Table 23-3. Population and potential energy consumption densities of the Low and High scenarios, based on inhabitable land area.

Region	*Population Density*[a] *(cap/km²)* 1975	2030	*Energy Density (W/m²)* *Base year* 1975	*Low scenario* 2030	*High scenario* 2030
I (NA)	19	25	0.21	0.35	0.48
II (SU/EE)	23	31	0.12	0.32	0.47
III (WE/JANZ)	59	81	0.24	0.48	0.75
IV (LA)	22	54	0.02	0.16	0.25
V (Af/SEA) VI (ME/NAf)	63	158	0.02	0.16	0.28
VII (C/CPA)	246	463	0.12	0.62	1.20
World	49	99	0.10	0.28	0.44

[a] Based on data from United Nations (1975) and Keyfitz (1977).

Based on these estimates, Table 23-3 lists the expected changes in the average population and energy consumption densities over the period 1975-2030 for each of these regions. Dramatically high population densities may be observed for China and the Asian countries with centrally planned economies (region VII) if one considers that the projected value of 463 cap/km² for this region in 2030 is close to 50 percent of the current population density of the large metropolitan areas of the world.

Certain countries in other regions would have similar dramatic situations by 2030, which cannot be observed directly from the data in Table 23-3 because of the averaging process of grouping densely and less densely populated countries into regions. For example, high population densities would occur principally in the Southeast Asian countries of region V and in the countries of northwest Europe of region III.

A more even distribution may be observed from the energy consumption densities listed in Table 23-3. The expected maximum and minimum levels for the IIASA High scenario in 2030 differ by a factor of five whereas this difference is as large as a factor of twenty for the population densities. The global average energy consumption of 0.1 W/m²[b] of potentially inhabitable land, achieved in 1975, is already a high figure. It is comparable to the activity level of the biosystems. The average production of wood in the global forests (as of 1975) is 0.2 W/m² (Revelle 1975). Against this figure the projected global energy consumption densities for 2030 appear significant indeed. (For the Low scenario, the global energy density in 2030 is 0.28 W/m², and for the High scenario it is 0.44 W/m².) They range between 0.16 W/m² for the aggregate of regions V(Af/SEA) and VI (ME/NAf), and region IV (LA) in the Low scenario and 1.2 W/m² for region VII (C/CPA) in the High scenario.

[b] Throughout this book energy flow densities are given as power densities.

URBANIZATION

Population—and along with it energy consumption—are not homogeneously distributed over the inhabited land area. The process or urbanization that began in the nineteenth century in the now developed countries is a worldwide phenomenon. The regularity and the incredible speed of this change in the settlement pattern can be easily observed from Figure 23-1, which also shows U.N. population projections for the coming decades (United Nations 1975). According to these projections, around the year 2030 the new developing countries would reach a level of urbanization close to the current level of the now developed countries. Even in the developed countries, where currently more than two-thirds of the population live in urban areas, the growth of urban versus rural lifestyles still goes on. When analyzed for details, each city appears unique. Yet several characteristics exist that are common to urban systems, even in different regions.

Table 23-4 summarizes 1975 population densities and energy consumption densities of six large metropolitan areas. To be sure, the choice of boundaries has a direct effect on the density data, but these are standard definitions of metropolitan areas to which these boundaries conform (Hall 1977). They delimit a region of common cultural patterns (even allowing for the healthy diversity that makes cities vital) within which mobility is much greater than is mobility across the boundaries. As can be seen from Table 23-4, both population densities and energy consumption densities averaged over the area covered by these metropolitan areas vary within a factor of

Figure 23-1. Estimated rural-urban population, 2030. Source: Based on papers submitted to the U.N. Population Conference, Bucharest, 1974.

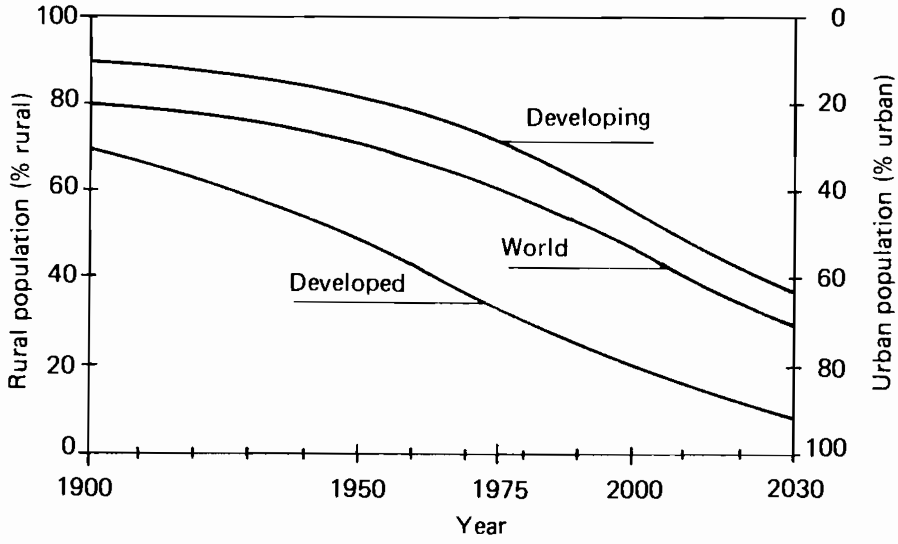


Table 23-4. Population and energy consumption densities, 1975.

Urban Area	*Inhabitants (10^6)*	*Area (10^3 km^2)*	*Population Density (cap/km^2)*	*Energy Consumption (kWyr/yr,cap)*	*Energy Density (W/m^2)*
Tokyo-Yokohama	33	34	980	3.9	3.8
New York	19.7	35	560	11.4	6.4
London	12.7	11.4	1100	5.2	5.7
Rhine-Ruhr	10.9	8.5	1280	5.0	6.4
Moscow	10.6	14	750	5.4	4.1
Paris	9.8	12	820	4.3	3.5

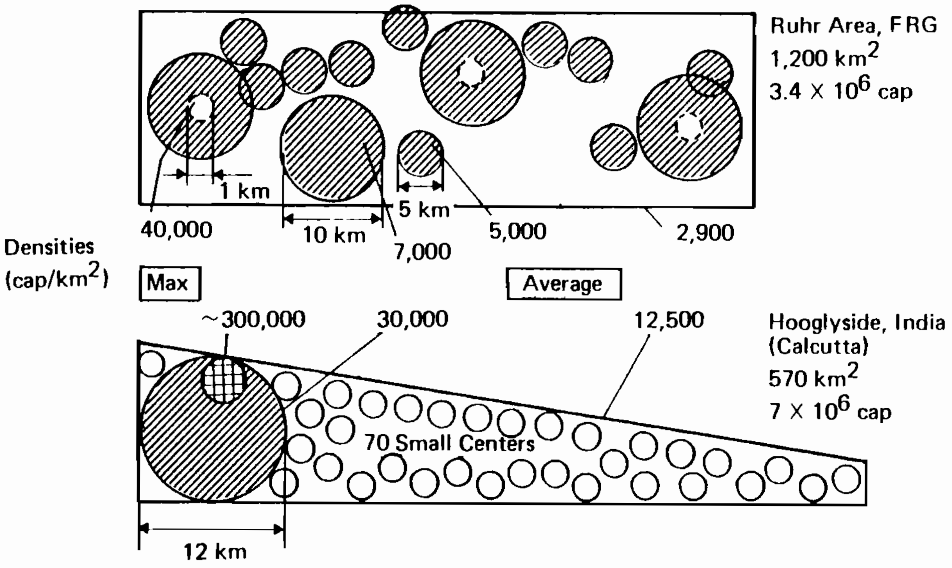
Source: Based on data from Hall (1977).

two only, typical figures being 1000 inhabitants/km^2 and an energy consumption of 5 W/m^2. Within each of the areas a detailed structure exists, with population densities reaching of the order of 50,000 inhabitants/km^2 in the central parts, which are usually of the order of a few km^2 in area. The corresponding energy densities peak around 100 W/m^2. The concentration of activities in the centers is not balanced by much below average density levels at the outskirts, however. Open areas, which are maintained within the metropolitan areas for recreational purposes, have a spatial distribution that tends to homogenize population densities, with the exception of the innermost parts of the "centers of gravity."

Figure 23-2 illustrates the spatial relationships of two conurbations—the Rhine-Ruhr area and the Hooglyside area of Calcutta—in the format of a simplified model. The core area of the Rhine-Ruhr metropolis has a polycentric structure. In contrast to monocentric conurbations, this settlement pattern is largely self-sufficient in land requirements. There are relatively small problems caused by commuting and segregation. The total population within the rectangular area of 1200 km^2 seems to have stabilized over the past twenty years. Net population growth is found at the outer parts of the conurbation, which is seven times larger than the core area represented in Figure 23-2. The "open space" within the rectangular area is still used for agriculture, although it also houses large industrial complexes as well as forests preserved mainly for recreational purposes. Transport and municipal service facilities compete for scarce "open" land. On the average, an inhabitant of the core part of the Rhine-Ruhr conurbation arranges his life on an area of 350 km^2, most of which is located at a distance of five to ten km from his home.

By contrast, because the Hooglyside area extends along the river Hoogly, th open land outside the core area is more accessible than is the case in many other conurbations with monocentric patterns in developing countries. The population densities of the Hooglyside area are much higher than those found in the urbanized areas of developed countries. The Hoogly area seems to exemplify the situation in developing conurbations much in the same way as the Rhine-Ruhr area can be considered representative of developed

Figure 23-2. Spatial relationships of the Rhine-Ruhr and Hooglyside areas. Source: Forschungsgemeinschaft für Hochspannungs- und Hochstromtechnik e.V. (1977).



conurbations. Scarcity of land appears to be the overriding factor in the developing conurbations: on the average, 80 m^2 per inhabitant is available in Hooglyside, with the incredibly low figure of 3 to 4 m^2 per inhabitant found in squatter areas on the outskirts of the central places.

Population densities in small towns and even villages, where direct access to the natural environment is still possible, are generally higher than the figures given in Table 23-4 for major urban areas. The reason appears to be that recreational and agricultural areas are not incorporated into the town or village area, as they are in metropolitan areas. Thus, various examples indicate energy consumption densities of approximately 10 W/m^2 for settlement units of a few thousand up to the range of 100,000 inhabitants. When adjusted for open space in the immediate surroundings, energy consumption densities are comparable: there is less difference between a small town of a few thousand inhabitants and the large metropolitan areas than one would expect—at least in the developed countries.

URBAN AND RURAL POPULATIONS

Studies of energy consumption densities for various settlement patterns are scarce. Practically no material exists in this respect for the developing countries. Yet some indicative values can be derived indirectly. Table 23-5

Table 23-5. Energy balance of India, 1971.[a]

	Area		
	Total	*Rural*	*Urban*
Energy consumption (GWyr/yr)			
Total	344	116	228
Commercial	181	16	165
Noncommercial	163	100	62
Population (10^6)	547	440	107
Population (%)	100	80	20
Energy use per capita (kWyr/yr,cap)	0.63	0.26[a]	2.13

[a] Excluding animal and human power, which is estimated to be 0.06 kWyr/yr per capita.

Source: Based on data from Goeltze (1977), Parikh and Parikh (1977), and Revelle (1975).

summarizes the findings of several studies for India, considering both commercial (e.g. oil, gas, coal) and noncommercial (e.g., fuelwood from wastes) energy forms. Most of the energy requirements of the rural population are met by these locally available noncommercial sources. Commercial energy is supplied predominantly to the towns where roughly 20 percent of the population of India live. On a per capita basis, the urban population of India uses ten times more energy than does the rural population. Taking for India the same ratio as is found in the developed countries between the politically defined smaller area of a conurbation and the area actually influenced by that conurbation, the average energy consumption density for the larger Hooglyside area—Greater Bombay, New Delhi, and the other large conurbations—turns out to be of the order of 10 W/m^2.

In Table 23-6, population and consumption densities of urban and rural areas are compared for the examples of India and the Federal Republic of Germany. Their average population densities are relatively close, although India will probably soon overtake the FRG in that parameter. Both countries are more densely populated than are the regions in which they are located (Table 23-3), yet they can be considered typical (not average), since the uneven distribution of population over the area of a whole region leads to the situation where more people live in high density areas than in the few places where actual and average densities coincide. According to Table 23-6, the population densities of the urban areas in India are several times above those of the FRG.

This relationship is also characteristic of major conurbations in other developing countries. However, the lower per capita energy consumption of the urban population in the developing countries seems to balance their high population densities so that, on an area basis, energy consumption densities of conurbations in developing countries are comparable to those found in the conurbations of the developed countries. It may be that a given infrastructure, with houses, transportation systems, utilities, and basic commercial distribution, requires a specific throughput of energy that is insensitive to the number of people using this infrastructure.

Table 23-6. Energy consumption densities in developing and developed countries.

	Federal Republic of Germany	*India*
Population Density (cap/km²)		
Average	245	186
Urban[a]	1500[c]	6000[d]
Rural[b]	150	135
Specific Consumption (kWyr/yr,cap)		
Average	5	0.6
Urban[a]	≈ 5	2.0
Rural[b]	≈ 5	0.3
Energy Consumption Density (W/m²)		
Average	1.2	0.10
Urban[a,e]	7.5	12.0
Rural[b]	0.75	0.04

[a] Conurbations.

[b] Including farms and small towns.

[c] Forty-five percent of total population.

[d] Represents 9 percent of total population.

[e] The figure is higher here than that of Table 23-4 because conurbations down to 25,000 inhabitants are counted here for the FRG.

Oversimplifying, one could say that the differences in urban material lifestyles are owing to the number of people that have to share a given urban infrastructure. In terms of energy, conurbations pose nearly identical problems worldwide, a well-known fact among a few experts but one that has been largely neglected in public discussions. Between the more developed and the less developed countries, the chief differences in energy density are to be found in rural areas. The rural energy densities of the developed countries are one order of magnitude smaller than the energy densities of the urban areas in these countries. On the other hand, in developing countries, rural energy densities are more than two orders of magnitude smaller. On the basis of the data in Table 23-6, one might characterize rural settlement patterns by an energy consumption density of 1 W/m² or less and urban settlement patterns by a benchmark figure of 5 to 10 W/m².

SOFT ENERGY FOR URBAN SUPPLY

In Chapter 6, the usable energy densities from renewable energy sources were demonstrated to be of the order of 0.1 W/m². This seems to rule out renewable energy sources for urban use, since it would require on the order of one hundred times as much land for energy supply as is contained in the urban area. Still, there is considerable land around many small cities, and energy harvesting could conceivably compete with other uses of this land.

But "soft energy" is more than renewable energy. As was discussed briefly in Chapter 6 and will be treated in depth in the following chapter on the hard-soft controversy, soft energy contains the element of individual access in one way or another. Here, we question how far down the system one has to go before one can expect even partial user autonomy.

To examine this point, we have set up a crude model to estimate the distance over which energy must be transmitted for various combinations of total population and population density. The results are set out in Table 23-7. Settlement types are characterized as "farm," "village," "town," or conurbation, according to total populations listed. The table is set up so that a settlement type spans two orders of magnitude of population size: thus, a "village" is a distinct settlement containing 100 to 10,000 people. The assumption is now made that the source of supply is located on a "plantation" at the edge of the inhabited area, and the average distance from consumer to source is listed in kilometers in the main column of Table 23-7. It can be seen that the distances become large for towns of 100,000 people, even when the towns are so densely populated as to approach "point sinks" of energy demand (for which settlement pattern, individually controlled [soft] energy sources must give way to collectively or corporately managed ones). Somewhere between settlements of 10,000 people (for loosely settled small towns in the United States pattern) and 50,000 people (for densely settled towns typical of the Asian Far East region), the town loses the characteristic of individual access to the energy supply system, even in principle.

In towns of 10,000 to 50,000 people, it may still be possible to generate a useful amount of domestic energy autonomously from renewable sources. This possibility disappears rapidly as the town becomes a conurbation. As we have seen, the urban pattern of land use, even of uninhabited land, leaves little remaining area for harvesting energy. Thus, from the standpoint of "soft" energy, the chief opportunity for its application lies in the rural sector—farms and villages—with some further contribution being possible in the domestic sector of small towns. The distinction between urban and rural made here seems to correspond to that used by the United Nations (1975) in projecting urban and rural populations (Figure 23-1)—that is, although their definition of urban seems to have been made largely on sociological grounds, these are congruent with our distinction by population aggregation.

Table 23-7. Distance of local energy source to point of use, as a function of settlement pattern.

Settlement Type	*Typical Settlement Population*	*Population Density, Inhabitants/km²* *Distance in kilometers*		
		50	*100*	*500*
Farm	10	0.4	0.3	0.14
Village	1000	4.0	3.0	1.4
Town	100,000	40.0	30.0	14.0
Conurbation	10 (10^6)	400.0	300.0	140.0

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24 THE HARD-SOFT CONTROVERSY

INTRODUCTION

During the past few years, the public perception of the energy problem has been increasingly influenced by a controversy revolving around the concept of a "hard" versus a "soft" path. "Hard" and "soft" have become catchwords that lend themselves to a range of interpretation, a fact that has tended to obscure some of the vital issues underlying the controversy. In this chapter, we review the "energy problem" through the lens of the controversy with the hope of clarifying what is really at stake for our world civilization if it should choose one path to the exclusion of the other.

First, it may be useful to examine the recent origin of the terms *hard* and *soft.* They were drawn from the domain of information handling in which *hard*ware connotes the computers and other physical elements, such as input and output devices, and in which *soft*ware connotes the programming languages, logical structures, algorithms, and so on that are run on the computer systems. The terms have also been adopted by some researchers in the life sciences. For instance, neurophysiologists sometimes refer to nerve cells (neurons) and networks of nerves in living systems as the hardware or hard wiring and to the conditioning, learning, and behavior exhibited by such nervous networks as the software. The fact that the basic elements of computers (e.g., relays and magnetic cores) and the basic elements of living systems (neurons) act as essentially "yes/no" devices gave powerful support to the analogy as well as to the notion of computer hardware plus software assemblages as being giant (artificial) brains.

But when the terms "hard" and "soft" were drawn into the energy field, such a straightforward analogy broke down. One might, for instance, describe a particular energy technology within the frame of such an analogy as "hard" once its function is determined by a fixed, in-built program of performance. It is possible to view an interlinked national electricity grid, running with automatic power control, as a piece of computational hardware that translates the local stochastic demands of final consumers for electrical power into a set of operations controlling the inflow of water into turbines and of oil, gas, and coal into the combustion chambers of thermal power plants. Ultimately, the inbuilt logic of the grid also controls the flux of neutrons in the core of a nuclear reactor. As long as this computational hardware performs according to its specifications, the national grid provides energy. By and large, the electric grid has a yes/no characteristic: it either works or it does not work at all. Therefore, a national electricity grid or its components could properly be described as a hard energy technology.

It is not as easy, however, to define a soft energy technology within the framework of the same analogy. Software, in contrast to hardware as noted above, is not a material device but a logical structure, separate or distinguishable from the carrier on which it is imprinted. Its difficulty and its advantage are tied to the fact that it needs some hardware to be utilized, but that the software normally is independent of a particular type of hardware. (For instance, a program may be designed to be run on different types of computers.) One is thus led to look at the features of tools rather than the features of "machines" when one searches for examples of soft energy technologies. An axe certainly would fall into the soft category or even possibly a stove. Both do not automatically supply energy once a demand is signalized. Instead, they need determined, informed, and repeated activation by individuals in order to produce the desired function. That is, a person needs to learn how to cut wood with an axe, just as he must learn to light a fire—and that learning is the software. As one scrutinizes this analogy, then, it appears that "hard" and "soft" should not be defined on a purely technological basis. Rather, these notions refer to alternate relationships between man and his tools or devices.

And in fact, as one studies the thesis of the chief proponent of the soft path, Amory Lovins, one finds that he refers to a body of energy technologies as being soft when they are flexible, resilient, sustainable, and benign (Lovins 1977). Moreover, he generally seems to identify the soft technologies as those that are decentralized—spread throughout man's environment and used and controlled by many individuals—as opposed to the centralized energy technologies such as a large electric power station that is run (controlled) by relatively few people and that is meant to serve the needs of many people over a hard-wired grid.

We must agree with Lovins in his assertion that the distinction between hard and soft energy paths rests not on how much energy is used, but on the technical and sociopolitical *structure* of the energy system, thus focusing our attention on consequent and crucial political differences (Lovins 1977). But without going into depth at this point, we must assert (in agreement with the soft proponents) that the consequences of following either the soft or the hard path will be crucially different for the future of mankind; however, the outcome of following the soft path will be radically different than that projected by the soft proponents. Rather than the "millennium," it could be disaster. When one analyzes the character of the "energy problem" on a global scale, and when one looks sufficiently far into the future, one foresees that the soft path can but aggravate an already existing problem and possibly doom billions of people in the future, the very reverse of the hopes of the soft path strategists. But before we can develop this argument further, we must dive into the current hard-soft dialogue.

WHICH ROAD, WHAT CONSEQUENCES?

Any classification of technologies serves a specific purpose. And it is the eventual goal that suggests one should discriminate a group of technologies into renewable or nonrenewable, into cheap or expensive, into polluting or nonpolluting, or into hard or soft subgroups. Obviously, the judgment of what is preferable, tolerable, or should be rejected refers to well-established rules in a resources analysis, an economic analysis, or an environmental analysis. However, other than in the first three instances, it is difficult to identify the underlying purpose and the goals behind the introduction of the opposing notions of hard and soft.

Lovins (1976) put forward a soft energy path in contrast to a hard path. Shortly thereafter we held extended discussions with soft proponents in order to clarify the underlying perception of the "real" problems giving rise to this hard-soft controversy. We reproduce—in part—a document that summarizes some conclusions emerging from our discussions in 1976 with Amory Lovins and Dennis Meadows on the subject of which concept should govern the future evolution of the energy system (see boxed material and also Sassin et al., 1977).

The challenge posed by Lovins and Meadows has forced us to rethink our own biases and to express our ideas more clearly. The real problem facing world civilization today is that it cannot continue doing things as it has done in the past. Neither the hard nor the soft path holds the answer to the fundamental problem. The fact is that the principles that were sound and effective for a world population of up to one billion—principles that were established in a period 8000 or 10,000 years ago when mankind developed agricultural settlements and gradually turned its back on hunting and gathering over wide terrains—these principles, which lead inexorably to the urbanizations we know today, are no longer valid. They no longer allow us to support even the world population of four billion in a meaningful way. The demographic trends that have been under way for more than a century and that point to a population of eight billion or more by the year 2030 merely sharpen the reality of this basic problem. Thus, all societies, developed and developing,

CRITERIA FOR AN ACCEPTABLE APPROACH TO THE ENERGY PROBLEM

In searching for the sources of opposing conclusions with respect to nuclear, large-scale solar, coal, other renewable sources in a local or regional context (such as wind, wave power, biomass utilization, and small-scale solar heat), and energy conservation measures (such as better insulation or the cogeneration of electricity and process heat), it turned out to be helpful to address the following questions:

1. Which long-term fundamental problems other than energy questions have to be faced by mankind within the coming fifty years?
2. Is the appropriate scale for analyzing these problems global, regional, or local?
3. In which subsectors should the economy be disaggregated in order to tackle the problem of self-reliance and resilience?
4. How can one define a technological solution for the energy supply with respect to the anticipated state of affairs in terms of dos and not in terms of don'ts?
5. How can one specify an energy strategy leading from today's situation into a long-term future when the goals to be achieved vary with time and in principle are subject to revision?

PRELIMINARY RESULTS OF THE JOINT DISCUSSIONS

Questions 1 through 3 above were answered in some detail. Questions 4 and 5 remain open for further joint analysis.

Both sides agreed that major global reliance on conventional oil and gas reserves must be phased out over the next fifty years. Both felt that even the provision of plentiful energy supplies would leave many other crucial problems unsolved. Beyond that, two obviously incompatible global perspectives evolved. They are briefly outlined below.

Perspective of Dennis Meadows and Amory Lovins

The carrying capacity of the globe will continue to deteriorate. The global population will not rise above eight billion people, perhaps not above six billion. Population will stabilize in some regions through reduced fertility, in other areas mortality will increase and may even produce declining populations. War, pestilence, and famine will continue in cycles more or less as they have over the millennia. One might term this scenario "business as usual" except that it includes for the first time the possibility of massive climate change. The conflicting trends of consolidation of political blocks on the one hand and increasing breakup of others will persist. The outcome of this is not clear, but it will almost certainly combine with other trends to decrease the possibilities for free trade worldwide.

Under these circumstances it is probably inappropriate to plan on more than 2.5 kWyr/yr,cap or around a doubling of total global energy production above current levels. The intermediate future could well see a decline in energy availability with concurrent social disruptions. It is unrealistic to expect that any significant political entity will be content to plan deliberately for sole dependence on other national political entities for its energy supplies. However, the difficulties of shifting off oil and gas leave an inescapable period of several decades dependence on the oil and gas exporters.

Under these circumstances, one does not count on the adoption of global energy strategies or even on programs that require massive shipments of energy across national boundaries. One must find sources that use regionally available energy, that are very efficient in satisfying end use demands, and that are highly resilient and easily decoupled.

According to Meadows and Lovins, sociopolitical constraints provide the basic starting point for reanalyzing and further modification of the technological system. For the analysis, no concept of a sociopolitical lifestyle can be solely expressed in terms of technology. But general notions of future sociopolitical prospects can lead directly to identification of preferred technologies. Technological fixes are not an end in themselves, however. This view leads to small-scale solar applications, to wind, to the use of agricultural wastes, and to deliberate efforts to attain zero energy growth in the wealthier nations as quickly as possible.

Soft technologies are less vulnerable with respect to social, political, or military interference. If the IIASA approach is followed, Lovins and Meadows suggest that the potential damage a nation could sustain from the interruption of its energy supplies from centralized facilities will exacerbate international tensions and lead to self-destruction of the technologies and the infrastructure originally designed on the basis of the assumption of international order and altruism. Small-scale technologies will, in contrast, tend to stabilize the political system, because small-scale conflicts, which are inevitable in any foreseeable future (this past year was really the first since the beginning of World War II that did not see major armed conflict somewhere on the globe), do not automatically lead to escalation.

It is also felt that the major problems are distributional rather than related to absolute scale. One should concentrate on the minimum or the modal energy availability rather than on the average.

Perspectives of IIASA's Energy Systems Program

Starting from the observation that the technological possibility indeed exists to have ample energy for all ages and thereby to provide a means to practically eliminate all raw material problems and all environmental problems, it seems a prudent and necessary approach to separate technological and sociopolitical considerations to the extent possible. The rationale is to first identify the features of present and future supply systems capable of providing the required carrying capacity for man in the billions—a systems' capability that is orders of magnitude beyond that which untouched and unmanaged nature can offer. Such an effort shall then serve as a basis for political groups and decisionmakers in analyzing and weighing the indeed enormous institutional and social problems against the benefits that accompany the extension and evolution of modern energy systems. Some groups believe that our sociopolitical constraints will be too narrow to permit for a still further utilization of our technological possibilities to significantly extend man's material resources. We hold that such a judgment can only be based on an unbiased analysis of the inevitable conditions and implications of such supply systems. The decision to abandon these systems is a highly political one, with very far-reaching consequences. Therefore, a scientific analysis must not start by implicitly assuming that this decision has already been taken. Indeed, it should reveal as clearly as possible what is at stake.

It is in line with such an approach to reckon with the purely demographic growth path of the presently four billion people that will level off, according to U.N. population projections, at twelve to thirteen billion people. Consistent with the whole approach, a further growth of the average energy consumption from the present 1.8 kWyr/yr,cap to 3 to 5 kWyr/yr,cap is fixed as a figure of orientation. Whether one considers the accepted fact that dozens of TWyr/yr can be supplied only by hard technologies as an attractive or a frightening perspective is not of prime importance here. Such an evaluation asks for an assessment with respect to the general framework chosen. Science can certainly put forward alternative cases. An evaluation and final decision about what is to be considered attractive or frightening is not to be performed, however, by scientists; this is within the domain of politics.

Some of the present energy systems are already "hard" and global in nature. The Persian Gulf is nearly a point source of energy, yielding 1.7 TWyr/yr, which are supplied across global distances. Discarding hard options and limiting our choices to local, resilient forms of energy, as suggested by Meadows and especially by Lovins, would deprive mankind of many of its cheapest energy sources, which are found in only a few areas. This even holds for solar energy. Such a development, though difficult to quantify, would tend to reduce the availability of energy and to put the burden of heavy investments on those countries that lack rich natural resources, most of which belong to the family of the less developed countries. Thus, reduction of world tensions would hardly be an immediate and likely consequence of the introduction of soft energy technologies. By contrast, IIASA's notion of resilience here applies to large energy systems rather than to single, weakly interacting small entities.

Implying the political preparedness to maintain and further evolve present global structures resilience, as understood within IIASA's Energy Systems Program, points to international cooperation and economic exchange. These rely on efforts that are both a prerequisite and an integral part of hard energy technologies. Such systems do have the ability to compensate for unexpected outages. A case in point was the closure of the Suez Canal, followed by the introduction of a new class of large oil tankers, which now take the route around the Cape of Good Hope.

Rather different geographical dimensions of the systems to be organized in a resilient way are chosen both by Meadows and Lovins and by IIASA. In the one case, these dimensions result from the implicit goal to adjust technology to an assumed deteriorating sociopolitical environment; in the other case, they are a consequence of the goal to explore the role of energy technology in avoiding a possible degradation of that environment.

This brief and certainly oversimplifying outline of the two approaches, which are characterized by diverging assumptions on development of population, economy, and political interdependence, makes it obvious why a purely technical argumentation will not be able to bridge the gap between the general standpoints of "hard" and "soft" exponents.

that today rely on variations of the hard and soft paths, respectively, are in the process of a rapid and fundamental change—a change in which energy shortages are but a symptom. Efforts to carry the existing infrastructures for either the hard or soft ways merely continue the past with all its limits. In the future world, neither the hard path of overconsumption of resources nor the soft path of mere subsistence should be allowed. It is these very limits that make life so nearly intolerable in the world today for the majority of its population. Therefore, there is a need to explore alternative ways of organizing global civilizations. We must learn how to build new infrastructures for a world that would house (properly) four billion people and that would house eight billions in the year 2030.

This is not such a unique problem of energy systems as the hard-soft controversy has thus far led us to expect. We must focus our creative attention elsewhere. To get perspective, one has only to realize that every year seventy million babies are added on a "net" basis to this world—"net" meaning that they cannot hope to grow up in an infrastructure that they will inherit from their ancestors dying away.

Some twenty years from now, this population increase will force the development of an appropriate infrastructure—for example, housing, transportation systems, food production, and processing facilities—over and above the need for energy that will have fully developed for this population increment. If the seventy million babies, added annually, were to live up to the standards of the average U.S. citizen of today, a new East Coast of the United States would have to be built every year. If the seventy million babies were to live up to European standards, by and large, the present European capitals and their supporting hinterland would have to be added somewhere on the globe. For the transitional period, we must reckon with another Mexico City, Teheran, Sao Paulo, Lagos, Calcutta, and Bombay every year. The North-South issues indicate how slowly the world even recognizes the mortgage it has thoughtlessly accepted over the past decades. Whether more decent infrastructures are provided sooner or later is not the point here. What counts is that mankind commits itself eventually to providing an appropriate materials infrastructure with the arrival of every new citizen. The fact that it seems impossible to respond to this commitment for the roughly three billion "have nots" of today (found mainly in the developing but also within the developed world) by simply multiplying present technologies is the deeper root of the North-South conflict and the real message of the Club of Rome's prediction. A further doubling of the global population adds just a quantitative difficulty to an already established new qualitative situation.

NEW DIMENSIONS OF THE ENERGY-SOCIETY PROBLEM

The painful difficulties that many places, all over the world, are having in providing an energy supply adequate for present or expected standards of living are but an illustration that the world is finite. In planning for a world that will have more people, the limitations become more apparent. In contrast to the past, we no longer consider it proper for the strong to pass their problems on to the weak or to assume an infinite and forgiving natural setting or for the present generation to mortgage the resources—and, indeed, the lives of future generations.

It is against that background that we had to analyze and categorize energy technologies. In fact, it was this gradually emerging future world background that quickly guided and controlled the studies of the Energy Systems Program, the results of which have been laid down in the preceding chapters of this book. Through these considerations, and stimulated by the hard-soft controversy, we were led to clarify the basic principles or notions that should be used to assess energy technologies for a world that will ever more intensely experience the burden of this commitment.

Our world is finite, but the human population is growing. The world is finite, but knowledge is increasing. We are learning that some things previously thought tolerable cannot be allowed to happen (world-scale war, massive pollution) and that some things previously inconceivable are now possible (space exploration, informatics, high speed, long-range communication). We are observing the evolution of new social structures, even within societies that appeared static.

We can characterize our concerns about energy and society by asking what is varied by new social techniques, new technologies, and new human conditions. The variables that we have identified can be characterized as the dimensions of the problem. That is, if we can assign some measure to them, we can understand what the world would be like. These dimensions are carrying capacity, interaction, equity, and legacy. How they relate to the energy and social systems is explained below and summarized in Table 24-1.

Carrying capacity refers to global, regional, national, or local capability to support human society. It has the extensive factor of population and the intensive factor of individual activity, so that a small, mobile, and rich population can saturate the capacity of an area as much as a larger, more stationary, and poorer population can. Limits on carrying capacity are set by resources and the ability to make investive use of resources (see Chapter 21), but also by effluents and the ability to control them. Advancing human knowledge tends to increase carrying capacity by improving production and control capabilities.

Interaction refers to the degree to which goods, people, and ideas flow from one place to another. A highly interactive world is characterized by an emphasis on trade, on shifting personal relationships, and on rapid dissemination of and response to ideas. A weakly interactive world emphasizes self-sufficiency, stable relationships, and traditional thought. Technology favors interaction, but at any given time a saturation point may be reached such that overspecialization results from trade, shifting relationships lead to personal confusion, and the kaleidoscope of ideas leads to fad and fashion.

Equity refers, of course, to distributional values. An equitable society is one in which, by and large, everybody has access equally to the same opportunities and amenities. It is also a society in which duties and responsibilities are shared equally. An inequitable society assigns both amenities and responsibilities in different shares for different people. Perfect equality is virtually unachievable, because the abilities of people to carry out responsibilities are variable and because tastes in amenity are likewise variable. Therefore, compensation for greater responsibility is usually made through more access to amenity; and so long as the measures of responsibility and amenity are considered "appropriate," this much inequality is considered equitable.

Finally, legacy refers to a time sense. A society that consumes its resources without making something out of them is wasteful and has a low sense of legacy. A society that pollutes its environment is also low in legacy: the pollution is a burden on the future, rather than an inheritance. A society of builders and planters has a high sense of legacy. Knowledge is probably the highest legacy of all; a society that learns and communicates its learning is doing the maximum for posterity. A society that simply preserves is neu-

Table 24-1. New dimensions of the energy-society problem.

			Society's Rating on Problem Dimensions for a	
Problem Dimension	*Relationship to Energy Problem*	*Global Implications*	*Low technology society*	*High technology society*
Carrying capacity (capacity to support human society)	Strong (direct)	Restrictions on energy supply limit—either population and living standards or both	Low	High
Interaction (degree to which goods, people, and ideas interact)	Weak	"One world" concept is necessary, applying strong interaction at personal level, which can saturate especially when carrying capacity is high	Low	High
Equity (distributional values)	Weak or nil	A major world problem that must be solved independently of energy decisions	Highly variable	Moderate
Legacy (time sense)	Strong (direct)	There is a need to build up investments in knowledge and in systems that do not require continuous labor and resource inputs and that do not pollute	Neutral	Variable

tral. Technology is neutral to legacy, in the sense that it can be directed toward consumption and pollution or toward construction and growth and carrying capacity.

We are not in a position to scientifically quantify standards for these four variables that would make the threshold between a stable and an unstable world fifty years hence. Nevertheless, technological strategies can be compared by assessing how they would rate relative to each other on these scales.

Traditionally, low technology societies are low in carrying capacity and interaction, and neutral in legacy. They are highly variable in equity, ranging from free bands of hunters or farmers to highly hierarchical tribes and fiefdoms.

Today's high (advanced)technology societies are high in carrying capacity and so high in interaction that saturation effects are beginning to appear. They are moderate in equity; a trend toward increased equity is correlated with higher carrying capacity, but there is no demonstrable cause-effect relation, and there are examples of egregious inequity. They are variable in legacy: construction and advancement of knowledge go hand in hand with resource consumption and pollution.

The view of the world, as we interpret the position of Lovins and Meadows laid down above, considers the moderate equity and the variable legacy of today's advanced (high technology) societies as inevitable and structural. They place the fault at attempts to improve carrying capacity by advanced technology and argue that this can only be done by jeopardizing legacy through pollution and resource consumption, by oversaturating interaction, and by moving toward inequity. In consequence, they argue that global problems can be solved only by deliberately reducing the role of advanced (high) technology and accepting the reductions of carrying capacity that go with it. In particular, they see centralized "hard" energy systems as employing prototypically "bad" technology—technology that degrades both equity and legacy. Their world of "soft" energy systems is one that has an admittedly lower carrying capacity than today's advanced societies, and one that is less interactive. It is claimed that such a world would be optimal in interaction and high in equity and legacy.

Throughout the work of the IIASA Energy Systems Program, we have tried to quantify the technoeconomic parameters of future civilizations by fixing minimum goals for the evolution of the global energy infrastructure. These minimum goals result from a quantification of the level of fulfillment of the four dimensions of carrying capacity, interaction, equity, and legacy required by the conditions of nature and the assumed levels of technological skills. In such an approach, carrying capacity and legacy dominate considerations of equity and interaction. In more simplistic terms, we have tried to quantify how civilization "as we find it" could arrange energywise with nature over an extended time horizon.

Sociopolitical requirements, expressed in the format of civilizations "as they should be," will exert additional pressures on technological evolution. Thus, our two scenarios as such (presented in Part IV) do not guarantee sociopolitical stability, but they mark the line of survival for a growing global population. We maintain that these additional requirements on technological systems cannot be accepted as long as they reduce the possibility of survival for significant fractions of mankind.

WHAT LIES AHEAD?

A comprehensive view of the energy problem of the major world regions reveals rather quickly that a narrowly defined categorization of energy technologies according to the notions of soft or hard would impose a violation of some, it not all, of the notions of carrying capacity, interaction, equity, and legacy for many subgroups of the world's population, once such a strict (and limited) choice were made. Should the bulk shipment of wood products by a nationalized industry in the Amazon basin to Bangladesh be discouraged even if it makes economic sense, just because it is a "hard" approach? Or should one discourage the use of a local windmill in India because, by developed economy standards, it is uneconomic compared to nuclear electricity? Both questions illustrate the obvious limitations of generalizing from the local experience with technological elements.

There is no alternative choice between soft and hard technologies in the sense that we can discard one for reasons of principle. We really need all technologies—from resource dependent to renewable, from simple to sophisticated, from distributed to centralized applicability, of rugged or fragile design, with selective or broad environmental impacts. The overriding criterion is the adaptation of the global energy system infrastructure to the many specific conditions in which it must operate. This operation of a basic infrastructure requires a broad understanding and willingness to guarantee conditions of life for complex technological systems—a real challenge in a world in which all cultural levels from hunting via farming to the different industrialization steps coexist.

To meet that challenge, youth must be given the chance to gradually evolve its understanding of technological progress and of diverse cultural levels. This can be done by experimenting and testing the strength and weaknesses of one's image of technology. The educational function of learning on simple systems before proceeding to more sophisticated and powerful ones is a learning experience both technically and in responsibility. The young person steering a sailboat learns not only about winds and waves but also what happens to other people if he or she does not perform well. This suggests maintaining a certain fraction of soft technologies even if they are not needed or are not competitive in all other categories that matter. Also, harvesting energy from a windmill and depending on it should contribute to maintaining and defending those social conditions and virtues needed to live with, say, nuclear technology or even with global environmental engineering that goes along with a heavy reliance on renewable energy sources.

Both the solar-based and the nuclear-based alternatives, as well as the long-term fossil resources problem, require the same responsibilities and charisma to integrate a global society. At this level, the danger of misinterpreting the hard-soft controversy, no matter how inadequately it might have ever been phrased, becomes obvious. It is not a technological issue, dissociable from the political principles of organizing a civilization in a finite world. What is at stake over the next few decades is the ability to survive at a high cultural level, and this depends on the relationship we develop toward technology. The calculatory differences in the billions of people for which we plan might well turn into real fatalities once society should choose either hard or soft technologies on the grounds that one would be socially less demanding than the other. The real issue beneath is how can we harmonize the ongoing process of developing individual capabilities with the parallel process of intergrating an ever larger number of individuals into a true community. Our hearts have to follow our intellects. Faced with the often conflicting goals of the individual and mankind, we have to learn how to become citizens of a finite world.

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VI ASSESSMENTS AND IMPLICATIONS

Our aim throughout this book was to be objective, realizing, however, that this is almost impossible when evaluated against absolute standards. The unique nature of the energy problem demands that our study findings be assessed and their implications be considered, since we are not treating a neutral scientific problem in the traditional sense of the word.

Such a synthesis of ideas is, of course, the result of the thinking of all members of the Energy Systems Program Group as all have contributed significantly. Nevertheless, because assessments and implications of our global energy study must be articulated by one person, Part VI has been written by the Program Leader, who is solely responsible for the views and opinions expressed.

25 THE PROBLEM REVISITED

INTRODUCTION

- *It could be done.*

Our aim when we began our research some five years ago was to take a fresh look at the energy problem facing the world over the next fifty years and to characterize demands, supply opportunities, and constraints as objectively as possible. Working from the premise that the world is finite, we questioned whether civilization would be able to meet the energy challenge. Based on an analysis of all the factors, we conclude that even with the technologies at hand or potentially at hand, it would be possible to provide enough energy for a world of eight billion people in the year 2030, using the world's resources as perceived today. It could be done. This is not a trivial statement, given the complexity of the problem and the degree of cultural pessimism that one often encounters in today's world.

Solving the energy problem would require two overlapping transitions of the infrastructures of the global energy system: the first transition would lead to the use of unconventional fossil fuels, whereas the second would bring us to an era in which there was no fossil primary energy and in which nuclear and solar power would be the basis of a sustainable energy system. This ultimate transition would not take place until after 2030.

In fact, the ultimate driving force of the global energy problem as well as of other supply problems is the increasing world population. Inherently this can lead to serious world instability. Throughout our study we have relied upon the population estimates of Keyfitz (1977), which led us to envisage a world population of eight billion people in the year 2030. It may be that we are being too conservative in our estimates. But even if that should be the case, we still maintain: it could be done.

IMPLICATIONS OF VARIOUS LEVELS OF ENERGY DEMAND

- *Balancing energy demand and supply means balancing the services of energy, capital, labor, and skill.*

The solution to the energy problem is contingent upon many sets of circumstances that are cultural, technical, political, economic, and environmental in nature. Formal scientific methods alone cannot solve the dilemma of balancing supply and demand. Some claim that the supply-demand balance could be settled at very low demand values, say at 16 TWyr/yr; others argue for median values of, say, 22 TWyr/yr; while still others advocate a high energy world, with values as high as, say, 40 TWyr/yr.

No matter which position one subscribes to, the efforts called for would have to be well organized and significantly larger than what society is used to today, combining inputs of energy, capital, labor, and skill (Figure 25-1). Clearly, the combination of these inputs would vary according to the level of demand (Figure 25-2). For both the moderate and the very low energy demand world, energy services could (conceivably) be replaced largely by

Figure 25-1. Inputs for the provision of civilization services.

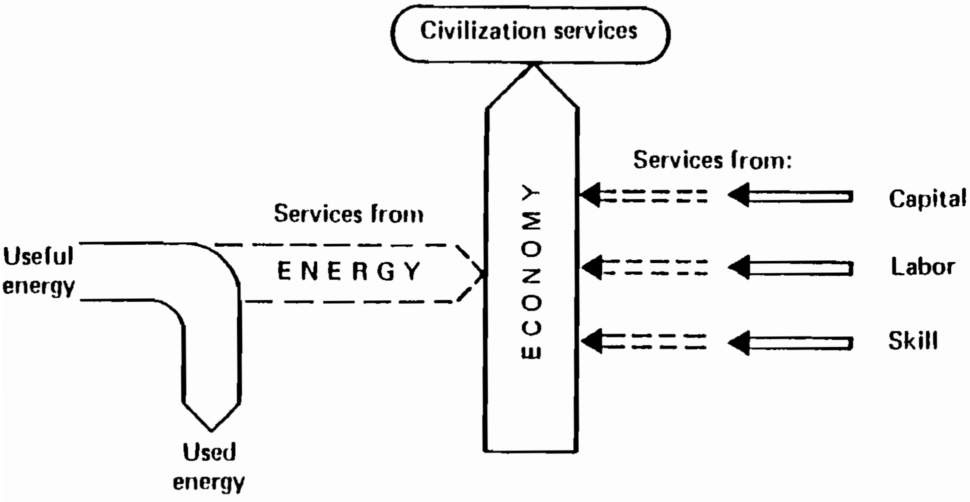
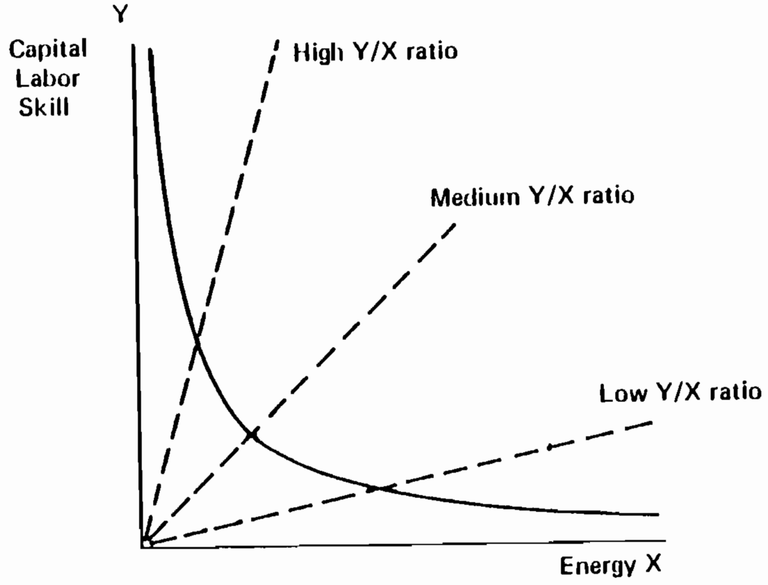


Figure 25-2. Substitutability of service inputs from capital, labor, and "skill" versus energy.



inputs of capital and labor. By contrast, in a high energy demand world, the services that civilization needs to function would come largely from inputs of energy. This is not impossible. What is impossible is to continue present trends, since in any event, we must expect significant energy conservation measures. If one foresees that radical changes have to be made, then why not begin now.

- *Only radical changes in lifestyles could lead to very low energy demand.*

We considered the implications of a very low energy demand world, using some of the data for the 16 TW case as presented in Chapter 18. Global average energy consumption per capita for this case remains at 2 kWyr/yr. We assumed gross domestic product (GDP) would continue to grow, but at a modest rate[a]—for example, at 1.70 percent per year in region I (NA) and at 2.04 percent per year in region III (WE/JANZ).[b] We were led to assume income elasticities close to zero or even negative. But as our analysis has shown, to achieve these values, fundamental changes would also have to

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[a] Throughout our study we have assumed declining growth rates. The numbers here are not meant to indicate constant and, by implication, ongoing growth rates; rather, they link the years 1975 and 2030.

[b] See Figure 1-3 for the definition of the IIASA world regions and Appendix 1A for the list of the countries in each of the regions.

take place in the structure of GDP. For instance, the service sector's contribution would have to become 65 to 70 percent; losses in converting primary energy into secondary forms (e.g., in electricity generation or coal liquefaction) would have to be minimized; and both passenger and freight transportation activities would have to be reduced. Further, there would have to be an export of energy-intensive industries from the developed to the developing regions. (Checking the consistency of the latter assumption was beyond the scope of our methodology.) Per capita demand would have to be reduced by rigorous insulation of single family houses, and there would have to be more energy-efficient apartment houses. Obviously, extreme conservation would be characteristic of this very low energy demand world, resulting in radical changes in lifestyles.

- *Our Low scenario implies strong—but probably more realistic—energy conservation measures.*

At a slightly higher demand level—say, 22 TWyr/yr of the IIASA Low scenario—we also see the need for adjustments in how people live. The conservation measures required at this moderate level, while certainly less than in the 16 TW case, are still at the limit we consider feasible if present lifestyles and freedom of choice are to be maintained. In our Low scenario projections for the seven IIASA world regions, we see that there would have to be a saturation in the per capita energy consumption in the regions of the Organisation for Economic Cooperation and Development (OECD) (I-NA and III-WE/JANZ) and only modest increases in per capita consumption in the developing regions (IV-LA, V-Af/SEA, VI-ME/NAf, and VII-C/CPA).

- *Our High scenario projects growth rates that might be considered moderately satisfactory but that would transfer the hardship to the supply side.*

Finally, we looked at what it would mean if the world were to choose a high energy demand mode, say at the 36 TWyr/yr level of the IIASA High scenario. The global average per capita consumption would then be about 4.5 kWyr/yr. For some, this would mean that many of the hardships of having to live with very low energy demand, including all the difficulties on the individual and local group level, would be relieved. Still, these hardships would not be eliminated; they would only be transferred to the supply side. For example, in our quantitative analysis in Part IV, we have elaborated on the problem of large-scale uses of unconventional fuels. Also, the problems of a functioning world market for oil, coal, and probably for gas must be mentioned in this connection. Such functioning markets could, in turn, provide a stimulus for developing countries, and it is in this context that we refer to the relatively high innovation rate that could become feasible when economic growth rates are high. Table 25-1 gives comparative data on the evolution of GDP growth rates, energy consumption per capita, and the resulting elasticities for the seven world regions over the period 1975-2030 for the two reference scenarios and the 16 TW case.

Table 25-1. GDP growth rate energy consumption per capita, elasticities, 1975-2030.

A. Primary Energy Consumption per Capita (kWyr/yr,cap), 2030

Region	*Base Year 1975*	*High Scenario*	*Low Scenario*	*16 TW Case*[a]
I (NA)	11.2	19.1	13.9	8.0
II (SU/EE)	5.1	15.3	10.4	6.2
III (WE/JANZ)	4.0	9.3	5.9	3.2
IV (LA)	1.1	4.6	2.9	2.8
V (Af/SEA)	0.2	1.3	0.7	0.7
VI (ME/NAf)	0.9	6.7	3.5	3.6
VII (C/CPA)	0.5	2.6	1.3	1.2
World	2.0	4.5	2.8	2.0

B. Comparison of Assumptions about GDP Growth Rates (percent/year)

Region	*High Scenario*	*Low Scenario*		*16 TW Case*[a]	
I (NA)	2.87	1.68	2.09	1.70	2.00
II (SU/EE)	3.91	2.99		2.37	
III (WE/JANZ)	2.93	1.88		2.04	
IV (LA)	4.37	3.48	3.24	3.94	3.84
V (Af/SEA)	4.32	3.27		3.34	
VI (ME/NAf)	5.09	3.57		4.79	
VII (C/CPA)	3.77	2.64		3.44	
World	3.44	2.37		2.50	

C. Primary Energy/GDP Coefficient, ϵ_p[b]

	High Scenario		*Low Scenario*		*16 TW Case*[c]	
Region	*1975-2000*	*2000-2030*	*1975-2000*	*2000-2030*	*1975-2000*	*2000-2030*
I (NA)	0.42	0.67	0.36	0.89[b]	-0.20	0.06
II (SU/EE)	0.65	0.67	0.62	0.62	0.75	0.01
III (WE/JANZ)	0.70	0.77	0.65	0.73	0.04	0.10
IV (LA)	1.04	0.98	1.06	0.97	0.96	0.82
V (Af/SEA)	1.15	1.11	1.18	1.19	1.38	0.90
VI (ME/NAf)	1.16	0.96	1.23	1.10	1.04	0.75
VII (C/CPA)	1.06	1.17	0.98	1.26[b]	1.12	0.54
World	0.70	0.90	0.67	0.93	0.50	0.34

[a] *Source:* U. Colombo communication to W. Häfele, 13 October 1978.

[b] This elasticity, ϵ, is defined by the following relationship:

$$\frac{E(t_2)}{E(t_1)} = \left\{\frac{GDP(t_2)}{GDP(t_1)}\right\}^{\epsilon},$$

where t_1 and t_2 are two given times, E is energy consumption measured in physical units, and *GDP* is gross domestic product measured in real noninflated monetary units. This elasticity is calculated with respect to primary energy, ϵ_p.

[c] Derived from U. Colombo's specification of GDP and primary energy consumption growth (U. Colombo communication to W. Häfele, 13 October 1978) and is not consistent with methodology of IIASA scenarios.

SOME REALITIES OF THE ENERGY PROBLEM

- *Over the next fifty years, under any set of circumstances, economic growth rates will be limited.*

When considering the implications of either a high, a low, or a very low energy demand world, naturally we were concerned principally with economic growth. A major qualitative finding of our study is that it will be difficult, if not impossible, for the world to exceed annual growth rates of 3.5 percent because of energy supply characteristics.[c]

Our estimates, compared with those of WAES (1977), WEC (1978), and the UN-sponsored Leontief study (Leontief et al., 1977) are lower (Table 25-2). This concerns us. We looked very seriously at the estimates for the Group of 77 in the U.N. study, not because they are the results of an analysis of economic feasibilities, but rather, because they reflect a declaration of political will. Indeed, this study done in 1977 evaluated world trade along the lines of the data from the U.N. Council on Trade and Development (UNCTAD); the global energy demand projected for the year 2000 is 29 TWyr/yr, which is some 53 and 93 percent more than our projections in the High and the Low scenarios, respectively. The numbers are indeed irrelevant here: what is important is the political vision of the developing countries reflected in the U.N. targets. The lower the world growth rates, the higher the probability for economic warfare in ways that are difficult to anticipate. The global instability apparent in the events of the late 1970s is probably only a forerunner of the unrest that will surface in the near future. To maintain global order with these low growth rates is therefore a point of major concern.

- *The hard-soft controversy is essentially a political issue and not a technical one.*

Here, in considering the possibilities for placing the unavoidable hardships of high or low energy demands, we also refer to the worldwide debate between the proponents of "soft" and "hard" evolutionary paths of energy systems. Living with very low energy demand favors a way of life in which transportation is at the minimum and local affairs and local self-sufficiency become highly priced virtues. This highly decentralized "soft" society would scorn the "evils" of "hard" technologies with their emphasis on complex systems and heavy technologies. For some, a traditional, conservative way of life would be the panacea to the world's problems; to others, such a mode of existence would be a nightmare and would invite disaster. Those opposing this "soft" society view the forced immobility as a means for destroying communication and interaction and ultimately causing society to disintegrate and productivity to decrease so that man would be doomed to failure in his efforts to meet supply demands.

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[c] See footnote a.

Table 25-2. Comparative GDP growth rate estimates (percent).

	IIASA Scenarios				*United Nations (Leontief study)*[a]	*WAES*[b]		*WEC*[c]
	1975–1985	*1985–2000*	*2000–2015*	*2015–2030*	*1970–2000*	*1976–1985*	*1985–2000*	*1975–2000*
High scenario	4.7	3.8	3.0	2.7	4.5[d]	6.0	5.0	4.1
Low scenario	3.6	2.7	1.9	1.7	4.2[e]	3.5	3.0	3.0

[a] *Source:* Leontief et al. (1977).

[b] World outside communist area. *Source:* WAES (1977).

[c] *Source:* WEC (1978).

[d] New Economic Order Scenario C, International Development Strategy.

[e] Old Economic Order Scenario A.

It was not the goal of the IIASA Energy Systems Program to clarify such societal visions, which are only implicit when quantifying energy demands. Our discussion of the hard-soft controversy in Chapter 24 is intended to provide insights into the problem.

In our quantitative analysis of Part IV we aimed to be pragmatic and to take a middle of the road position. Clearly, labels of high and low change their meaning over time. Today, for example, some consider our Low scenario as probable, while others view our High scenario as "too high." Irrespective of the emotional position one assumes, we see our scenarios as benchmarks that allow for inter- or extrapolations.

- *The reality of political, societal, and institutional problems will probably make the situation more grim than has been described in our two scenarios.*

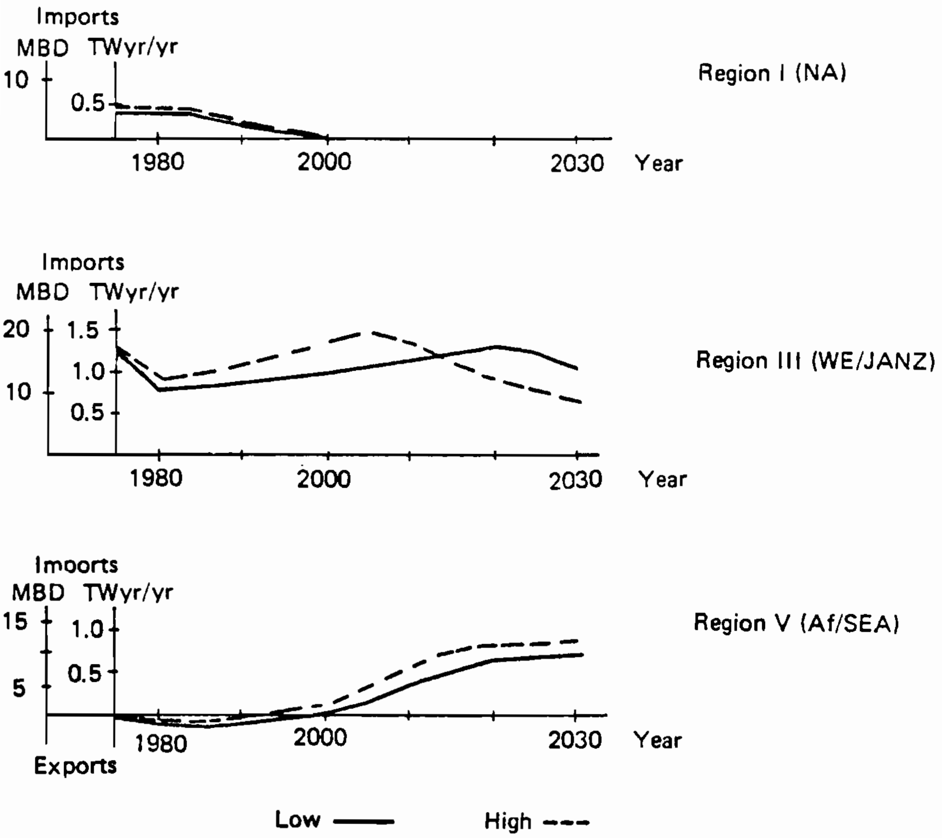
It could be done: the energy problem could be solved physically. To reach this conclusion, we have relied greatly on the quantitative analysis of our scenarios, as reported in Part IV. Still, our overall picture is based on the accounting of regional differences among the seven world regions. We must face the political reality of having many more countries in the world. The situation is complex and certainly less than optimal.

At which points would reality be more grim? For our analysis we have assumed a constant value for the U.S. dollar. What we have not done is to translate these into real monetary terms, which means incorporating the effects of inflation and the problem of the balance of payments. Decoupling the terms of trade from the side effects of these problems is not optimal, but is consistent with the determination to focus throughout this study on the factual basis of the energy problem.

As a result of our findings, we see that a further extension into the political realm might also be an analysis of the stability or, more precisely, of the resilience of the global energy supply system. The security of energy supplies is indeed a problem. Oil embargoes would impede growth. Likewise, the supply situation for natural uranium is being hindered by fear about the proliferation of nuclear weapons and by antinuclear movements. In fact, there is practically no free uranium market today.

For our scenarios we assumed that over the next few decades region VI (ME/NAf) would set a production ceiling of 33.6 million barrels of oil per day. We have also alluded to the relative inelasticity of demand. Evidently, disturbances in the oil production levels of this region are a possible source of major global instability. Let us examine this from the standpoint of three world regions (Figure 25-3). In our scenarios, sometime around the year 2010, region I (NA) will arrive at oil self-sufficiency; thereafter, any imports to region I would have to be made at the expense (in terms of supply) of region V (Af/SEA), which has the lowest purchasing power even at that time. A similar situation could exist for region III (WE/JANZ) if it were to

Figure 25-3. Interregional oil trade, regions I, III, V, High and Low scenarios, primary equivalent, 1975-2030.



import more oil than that projected for this region in our scenarios. Region III is particularly vulnerable to any instabilities in energy supply—be it for coal or for natural gas or oil—because of its limited indigenous supply situation.

- *The demand for liquid fuels is a principal driving force of the energy problem.*

In fact, meeting this demand may be the energy problem. Oil has been used mainly to meet fluid demands up to now. But as our study has shown, this precious fossil resource will become more and more difficult to get at and thus more expensive. Ultimately, it will become exhausted. Thus, for any energy strategy it is imperative that the uses of secondary liquid energy carriers (in all cases, hydrocarbons) be restricted to only the most essential sectors where nothing else can be substituted for it—namely, for transportation and feedstocks in the chemical industry. This is not to say that eventually transportation could not be accommodated by means other than by the use of liquid hydrocarbons. Later, when we unfold our technical vision, we shall picture a world in which hydrogen could provide such a service. But since the transition to a hydrogen economy will not happen before 2030, we must concentrate on what should be done until we reach this transition.

In both regions I and III, there must be a reversal of the trends of the 1950s and 1960s, when oil was used more and more to heat homes. (Note, however, that this is not the situation in region II (SU/EE). Indeed, it is remarkable to observe the degree of district heating there.) To gain perspectives on this issue, we have identified, in Table 25-3, the evolution of the uses of liquid hydrocarbons in the various IIASA world regions.

- *The structure of secondary energy demand over the next fifty years will not change very much, and the change that would be noted will take place at a very slow rate.*

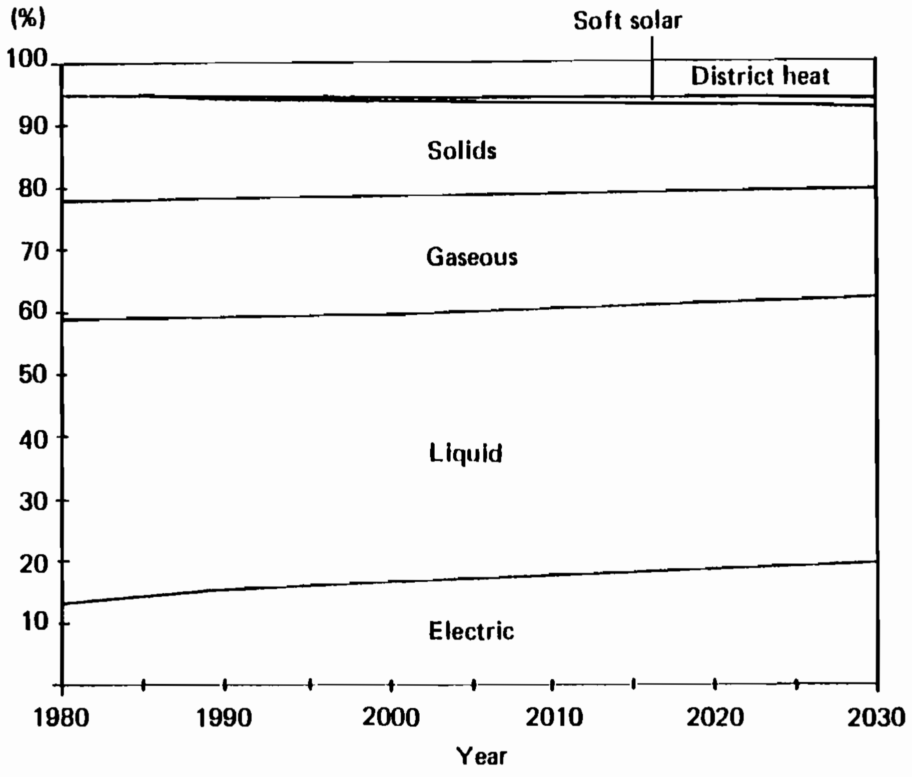
This major finding of our study is particularly relevant when we turn to electricity use. We saw, somewhat to our surprise, that the share of the demand met by electricity would grow more slowly than originally expected. Except for the 16 TW case, electricity's share in the secondary energy supply increased from 14 percent and to only 20 percent by 2030. Naturally, regional differences can be observed. For example, regions I and III have higher rates. But the overall trend is between 15 and 20 percent. The trend is certainly not toward an all-electrical society; the high investments (from generation to end use) that would have to accompany the use of electricity in other than its most appropriate sectors of demand cancel out such a trend.

The slow and moderate evolution of global secondary demand shares for the High scenario can be observed in Figure 25-4. Here too, we were surprised that our quantitative analysis did not turn up larger changes.

Table 25-3. Percentage of total use of liquid hydrocarbons for motor fuels and feedstocks, High and Low scenarios, 1975-2030.

Region	*Base Year 1975*	*High Scenario 2030*	*Low Scenario 2030*
I (NA)	74	94	91
II (SU/EE)	65	100	100
III (WE/JANZ)	52	86	76
IV (LA)	69	90	89
V (Af/SEA)	58	91	88
VI (ME/NAf)	74	94	91

Figure 25-4. Global secondary energy demand, High scenario.



ENERGY SUPPLY

- *Fossil fuels will continue to be available but will become unconventional and expensive.*

Both our High and Low scenarios are fundamentally fossil in nature, which may appear surprising if one considers the many statements being made today about our running out of fossil resources. As noted both in Chapter 2 on energy resources and in Chapter 17 on energy supply and conversion, the cheap, easily accessible fossil fuels are at a premium (Figure 25-5 and Tables 25-4 and 25-5). The world will have to look farther and dig deeper, which also means that costs will increase, as will environmental hazards.

The transition to low grade fossil fuels reverses a trend that began a few decades ago when oil became the reference carrier because it was a clean, cheap, and easy to handle fuel. Previously, investments were in the range of, say, $3000 per barrel of oil per day or less; today, these investments have

Figure 25-5. Shares of global fossil fuel supply, High scenario, 1980-2030. (For definition of resource categories see Table 25-5.)

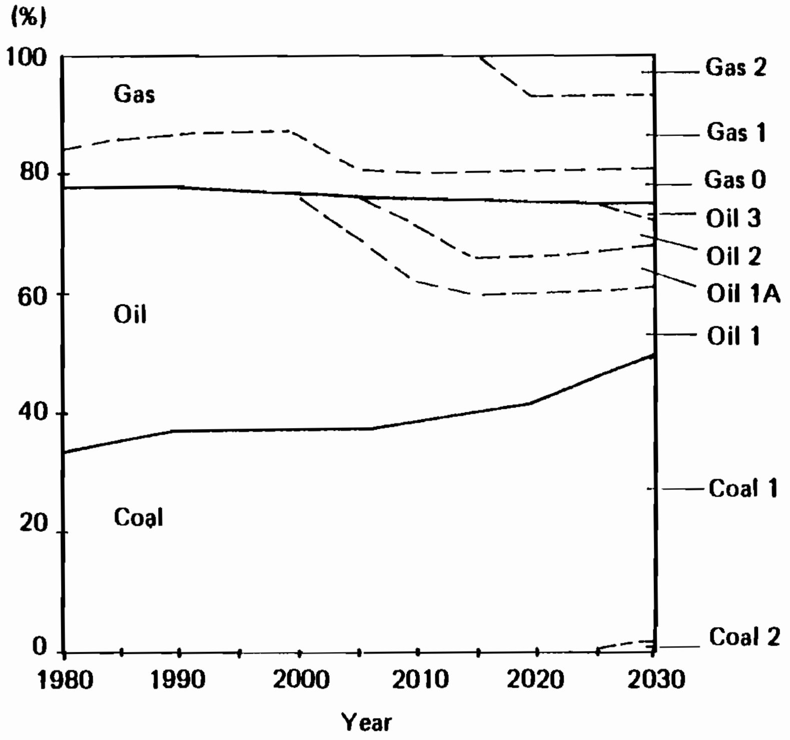


Table 25-4. Cumulative uses of fossil fuels, High and Low scenarios, 1975-2030.

	Total Resource Available[b] *(TWyr)*	*High Scenario*		*Low Scenario*	
		Total consumed (TWyr)	*Remaining resource (yr)*[c]	*Total consumed (TWyr)*	*Remaining resource (yr)*[c]
Oil					
Categories 1 and 2[a]	464	317	22	264	40
Category 3	373	4	45	0	62
Gas					
Categories 1 and 2	408	199	35	145	76
Category 3	130	0	22	0	38
Coal[d]					
Category 1	560	341	18	224	52
Category 2	1019	0	85	0	158

[a] For definition of terms and cost categories, see Table 25-5.

[b] Total resources, including those to be discovered, as of 1975.

[c] Number of years that the remaining resource would last if it were consumed at the 2030 annual rate of fuel use and if all of the resource came from the designated category.

[d] Coal use includes coal converted to synthetic liquids and gas.

Table 25-5. Summary of estimates of ultimately recoverable resources by cost category.

Resource[a]	Coal[b] (TWyr)		Oil (TWyr)			Natural Gas (TWyr)			Uranium (TWyr)	
Cost Category[c]	1	2	1	2	3	1	2	3	1	2
Region										
I (NA)	174	232	23	26	125	34	40	29	35	27
II (SU/EE)	136	448	37	45	69	66	51	31	ne	75
III (WE/JANZ)	93	151	17	3	21	19	5	14	14	38
IV (LA)	10	11	19	81	110	17	12	14	1	64
V (Af/SEA)	55	52	25	5	33	16	10	14	6	95
VI (ME/NAf)	<1	<1	132	27	ne	108	10	14	1	27
VII (C/CPA)	92	124	11	13	15	7	13	14	ne	36
World	560	1019	264	200	373	267	141	130	57	362

[a] For oil, gas, and coal, see estimates given in the text (translated here into units of TWyr); for uranium, see estimates given in Chapter 4.

[b] For coal, only a part of the ultimate resource (~15 percent) has been included because the figures are already very large for the time horizon of 2030 and because of the many uncertainties about very long-term coal resources and production technologies.

[c] Cost categories represent estimates of costs either at or below the stated volume of recoverable resources (in constant 1975$).

For oil and natural gas: Cat. 1: 12$/boe
Cat. 2: 12–20$/boe
Cat. 3: 20–25$/boe
For coal: Cat. 1: 25$/tce
Cat. 2: 25–50$/tce
For uranium: Cat. 1: 80$/kgU
Cat. 2: 80–130$/kgU

A subcategory of oil, 1A, exists only for regions I (NA) and IV (LA) and includes oil available at production costs of $12 to $16/boe. Also, a subcategory of gas, O, exists only for region VI (ME/NAf), with gas available at $2/boe.

ne—no estimate.

Note: For conversion to other units see Appendix B to Chapter 1.

Sources: Ashley, Rudman, and Whipple (1976); Eckstein (1978); Grenon (1977); Grossling (1976); Institute of Geological Sciences (1978); Lambertini (1976); Meyer (1977); *Oil and Gas Journal* (1978); O'Shaughnessy (1976); Penner and Icerman (1975); Perrine (1978); Uhl (1977).

risen three to six times, with $10,000 to $20,000 per barrel of oil per day being encountered. The costs and complexity of obtaining oil from Alaska and the North Sea are examples of what we will probably have to expect.

Let us look at these investments in still another light. One barrel of oil per day is equivalent to some 71 kW of caloric power. Presently, costs of $20,000 per barrel of oil per day correspond to $300 per kW(th), which can be related to $1000 per kW(e). Indeed, we came close to this figure in our discussion in Chapter 17 of capital costs of electrical power generation. Future abatement measures that would have to go along with the use of low grade fuels may bring investment costs to as high as $500 per kW(th) or even higher over the longer term. Ultimately, it would seem that the use of unconventional oil will probably approximate the use of other primary energy sources, and oil's inherent advantage will most likely fade away.

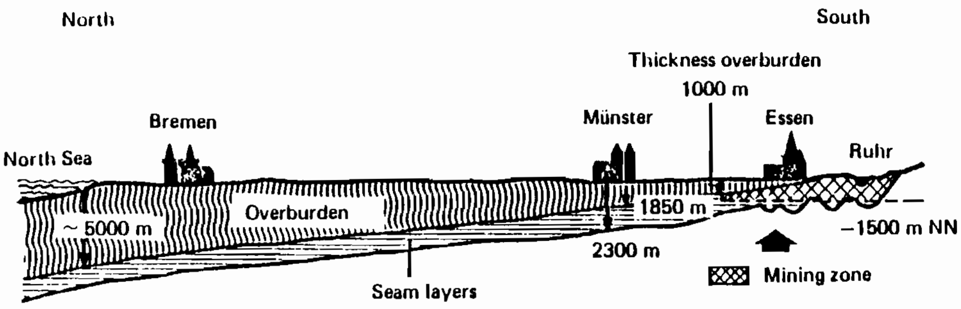
There is yet another dimension to the problem of harnessing low grade fossil fuels—the environmental impacts. We are not sure how large the impacts will be from the requisite surface mining or deep sea operations. The future coal-mining operation in the Federal Republic of Germany may provide some insights into what we might expect (Figure 25-6). Only the last "bit" of the coal stratum underneath northern Germany reaches the surface and is therefore accessible, which means mining to depths of some 1200 meters. At this level, some 25 billion tons of coal equivalent could be tapped. But according to estimates, more than 300 billion tons of coal equivalent lie beneath this area. To harness this amount would probably mean having to dig as deep as 3000 to 5000 meters: whole cities, villages, and landscapes could possibly be destroyed and would then have to be reclaimed. The Garsdorf open lignite pit, regarded today as one of the most modern and advanced mining operations, must be seen as only a small beginning of such large-scale operations.

By bringing in this example we are not trying to actually propose such operations. Rather, our intent is to show that the world cannot continue to look the other way as more and more fossil resources are used up in this "consumptive" mode. How this mode of consumptive resource use can be reversed has been discussed in Chapter 21, where we introduced the notions of negentropy and endowments; we shall treat this subject in depth when we come to our technical vision later in this chapter.

- *Our two reference scenarios are in the middle of the road and imply two overlapping transitions.*

The realization that there would have to be two overlapping transitions was also one of the unexpected findings of our study. When we began our study of the global energy system, we anticipated that there would be only

Figure 25-6. Schematic vertical section of northern area of the FRG. *Source:* Rürup (1978).



one major transition, which could be completed in fifty years. But by 1978–1979, as our analysis developed further, we realized that the transition to a sustainable energy system would not happen within our fifty-year time frame.

We have just referred to the consumptive uses of resources as unjustifiable. Yet our two supply scenarios and alternative cases call for a high degree of consumptive resource uses. How did this happen? Here, as elsewhere throughout this book, we must point to the inherent dualism between realism and a vision. The objective of our quantitative analysis was to be realistic and pragmatic; thus, we were led to supply structures with low investments. We consider this a confirmation of our intended realism; still, we see it also as support for our technical vision.

The second reason why we were driven to such fossil supply scenarios has to do with our assumed production profile for the seven world regions (see Figure 25-7). It was not possible to allocate a higher role for nuclear and solar power over the next fifty years, because energy production during this period will be constrained mainly by the rate of buildup of production capacities and not by resource scarcity. As Table 25-4 indicates, even for the High scenario only 68 percent of oil categories 1 and 2, 49 percent of gas categories 1 and 2, and 61 percent of category 1 of coal would be used up by 2030. Indeed, it is only in the second half of the twenty-first century that resources become an active constraint. Realistically, then, because neither nuclear nor solar power will be able to reach a high share of the energy market until after 2030, we had to rely on fossil fuels (albeit unconventional ones) to carry us through this period smoothly. However, this necessitates a second, more fundamental transition to a nonfossil world, in which there are "investive" uses of resources. Again, we shall elaborate further on this in our discussion of the technical vision.

- *Our scenarios are globally comprehensive and allow for no escape.*

The foregoing observations, when translated into national dimensions, often evoke concern, if not objection. The question arises, Is there no other solution than that being advanced here? We do not claim to have provided the "only" solution, but our scenarios are comprehensive enough to demonstrate that there is no way to escape the hardships. Let us look at the primary energy sources for the two supply scenarios, summarized in Table 25-6. One might immediately question the high coal figures, given today's production levels. But if these coal figures are reduced, then some other fuel must be increased. Unconventional oil? Gas? Or is demand to be reduced?

Equally, both the figures for unconventional oil and those for nuclear power could be questioned; some consider them too high. Contrary to what many believe, we cannot continually expect to discover yet still more resources by, say, "going further west." The global comprehensiveness of our study has shown that there is no escape from the finiteness of the earth's fossil resources. We must reach out and tap the infinite resources of the sun and the de facto infinite resources of the nuclei of the atom.

Figure 25-7. Domestic fossil fuel production, High scenario, 1980-2030.

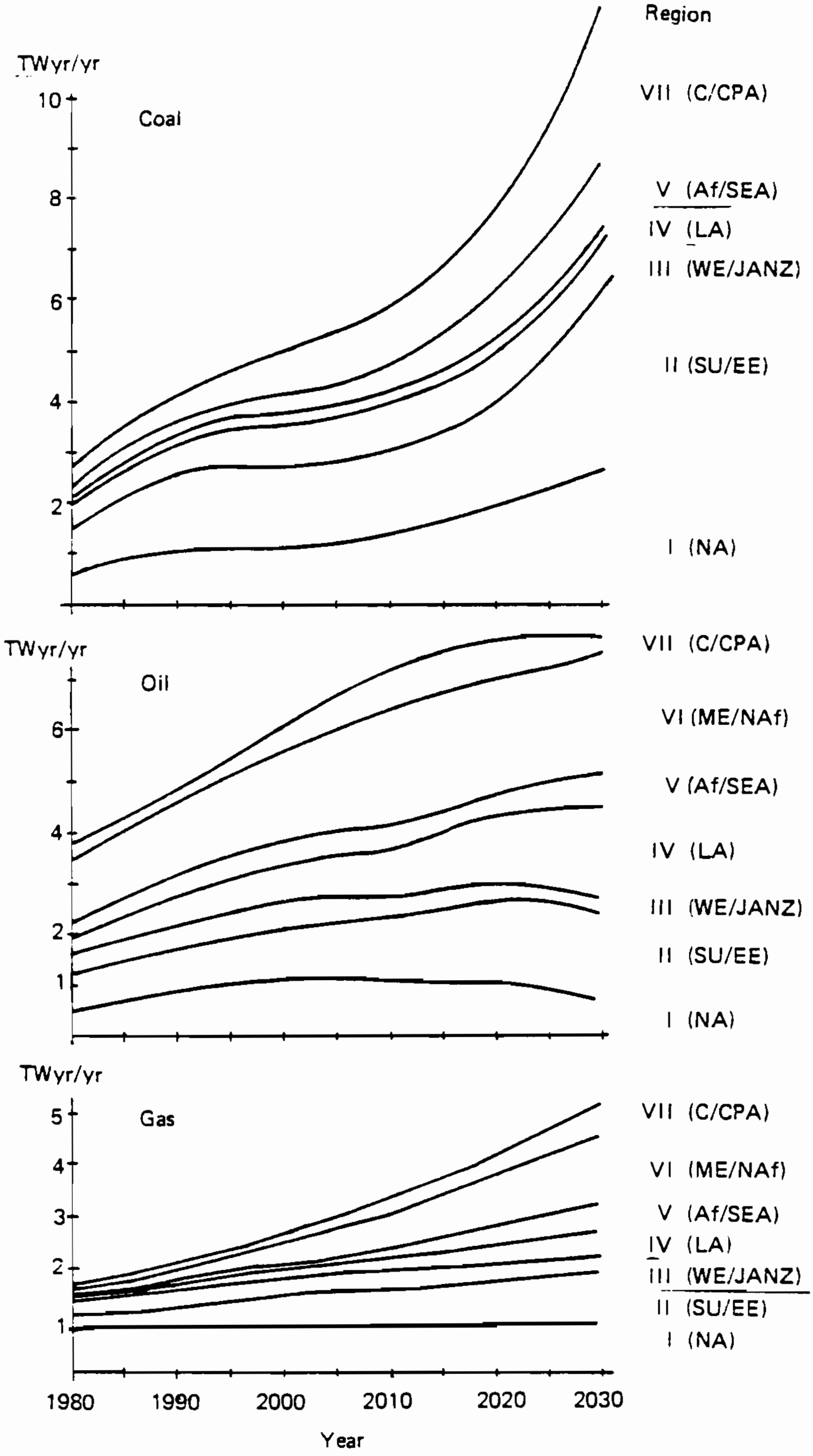


Table 25-6. Two supply scenarios, global primary energy by source, 1975–2030 (TWyr/yr).

Primary Source[a]	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
Oil	3.83	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar[b]	0	0.10	0.49	0.09	0.30
Other[c]	0	0.22	0.81	0.17	0.52
Total[d]	8.21	16.84	35.65	13.59	22.39

[a] Primary fuels production or primary fuels as inputs to conversion or refining processes—for example, coal used to make synthetic liquid fuel is counted in coal figures. (For definition of energy types, see Figure 1-1.)

[b] Includes mostly "soft" solar—individual rooftop collectors—also small amounts of centralized solar electricity.

[c] "Other" includes biogas, geothermal, commercial wood use.

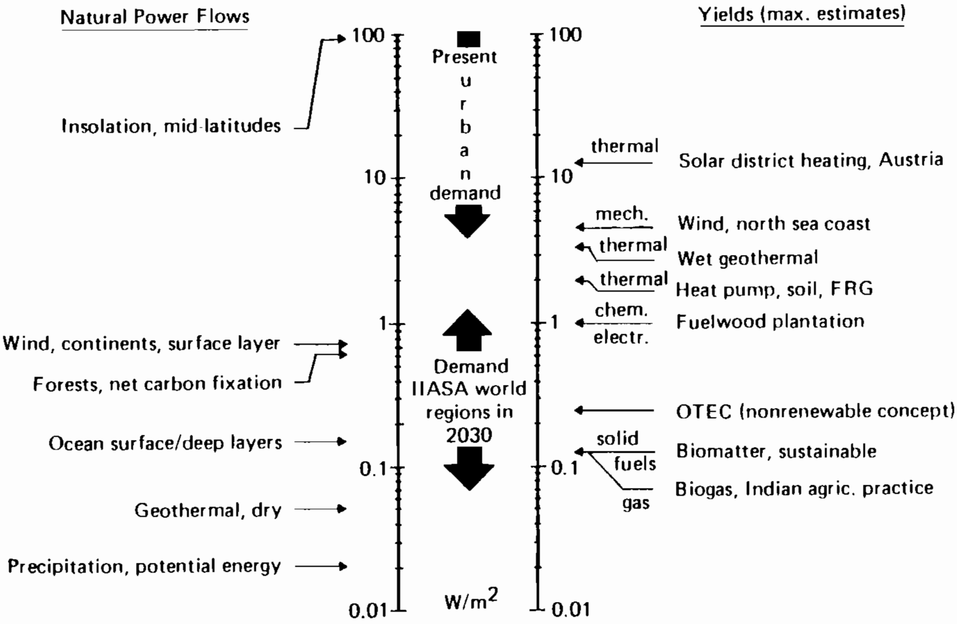
[d] Columns may not sum to totals because of rounding.

- *Renewable energy sources can contribute in an important, albeit limited way to meeting demand.*

For our supply scenarios we have argued for conventional and unconventional fossil resources as well as for solar and nuclear power. Obviously, there is also a role for renewable sources—specifically for the local uses of solar power, wind, hydroelectric power, and the power from biomass.

In Chapter 6, we have assessed the upper potential of renewable sources to be on the order of 15 TWyr/yr or about twice the present global primary energy consumption. One of the attractive features of renewable energy sources is that potentially they are endogenous, decentralized supply sources. But harnessing some 15 TWyr/yr from these sources has many serious implications. A crude but nevertheless good indicator is the production densities of renewables. If we assume that the average production density is 0.5 W/m^2, we see that some 30 million km^2 of land would be needed for producing 15 TWyr/yr—be it for wood gathering, sunshine, wind, and the like (Figure 25-8). For comparison, the amount of land being used today globally is some 13 million km^2. Thus the larger the output expected from renewables, the more difficult this option becomes; similarly, the less that is expected from these sources, the more they are likely to retain their attractive features of decentralization and local availability. This is a general observation that of course may vary according to local conditions. Nevertheless, we maintain that realistically the potential for renewable energy sources is significantly smaller than 15 TWyr/yr—say, between 6 and 10 TWyr/yr.

Figure 25-8. Energy densities.

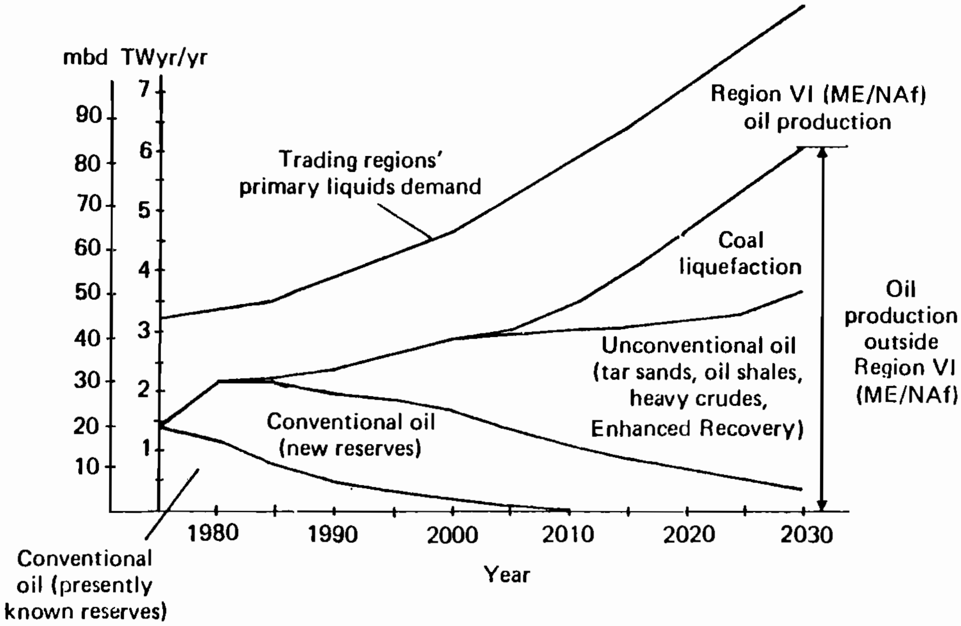


- *The oil exporting countries will continue to dominate the oil market.*
- *Accordingly, an international coal market must be developed.*

One important feature of our quantitative analysis is the trade links among regions, primarily for oil but also eventually for gas. We developed our assumption somewhat formally along the lines of a gaming approach where revenues for dominant suppliers are maximized. We did not, however, apply these procedures for the coal trade. It might be said that our assessment of future energy trade worldwide was not very sophisticated. Perhaps it would have been best to focus directly on world trade and not only on energy trade. But with our limited means this task was too complex.

Our goal was to add it all up and to assess a world energy trade pattern, using identifiable rules. A salient finding is that region VI will continue to dominate the market. As can be seen from Figure 25-9, the production of oil outside of region VI is relatively large. Yet because of the inelasticity of demand, current fluctuations in the contribution of region VI to world energy supply account for the differences between a glut and a shortage. Even by reducing the use of liquid hydrocarbons to those that are nonsubstitutable (transportation and feedstocks) and by taking into account the contributions of a young coal liquefaction industry, we still see a major contribution from region VI. We likewise assumed that region VI will

Figure 25-9. Oil supply and demand, 1975-2030, world (excluding centrally planned economies), High scenario.

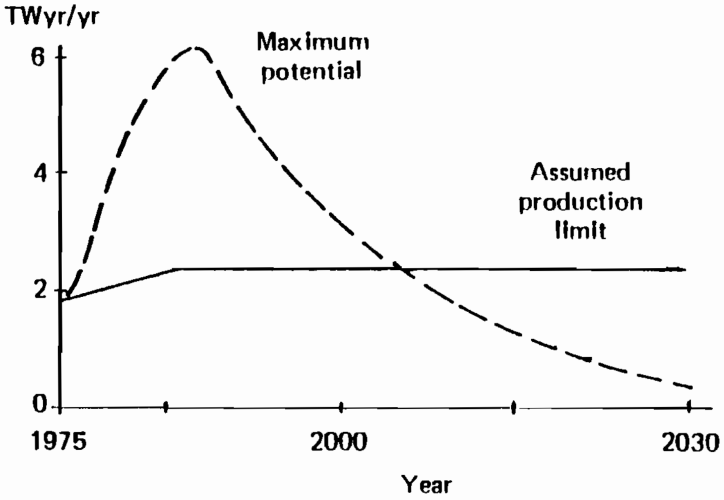


establish an oil production ceiling of 33.6 million barrels per day. This is crucial, since it allows for a stretching out of the oil resources of region VI (Figure 25-10). In Table 25-7, we relate the oil production in 1975 of region VI with that of the other OPEC countries and that of the OPEC countries not included in region VI. Essentially, the oil ceiling for region VI means that the amount of oil for export will be determined by political forces and not by the market.

The world trading relationship becomes even more problematic when we consider the allocation of oil exports and imports among world regions (Figure 25-11). Although regions V and IV (LA) were exporting oil in 1975, by 2030 the scenarios call for a significant oil import into region V. But where will this oil come from? How will region V, which has the lowest purchasing power, be able to pay for this oil?

In our two scenarios we assumed that not only regions I, II, IV, and VII would be self-sufficient in oil supply after the year 2030 but also that region III would decrease its oil imports and thus set free the oil for region V. When referring to our allocation procedures (Figure 25-11), we see that there is only one mechanism for accomplishing this—large-scale coal liquefaction. This is true for regions I and II, and especially for region III, the latter continuing to be a major oil importer throughout our fifty-year study period. Thus, for region III, and to a lesser extent for region I, coal liquefaction

Figure 25-10. Oil production, region VI (ME/NAf), 1975-2030.



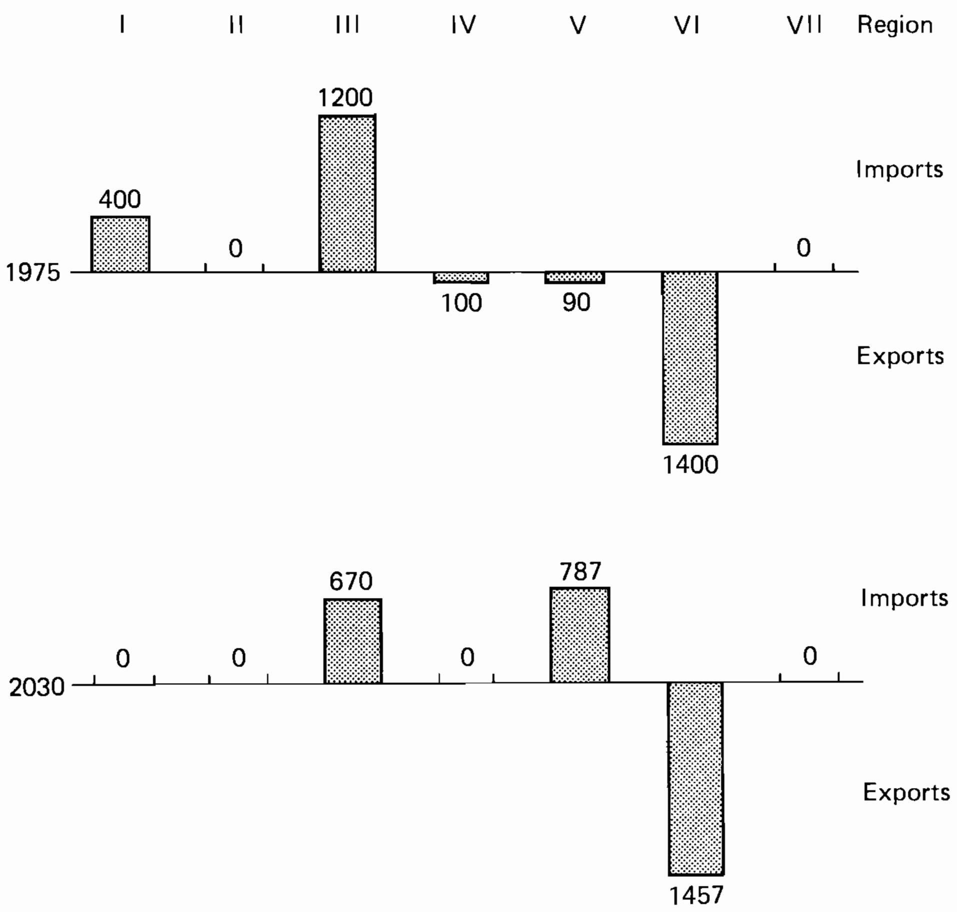
becomes a means for holding down the costs of imported oil. Our scenarios clearly demonstrated that beyond the year 2010, region III will have to import coal on a large scale, with regions I and II being the principal suppliers. Will regions I and II be willing to provide such exports? In what form? As coal or as a liquid synthetic hydrocarbon? By what means—autothermal or allothermal liquefaction? We can now observe a fundamental new interplay

Table 25-7. Oil production in 1975 (thousand barrels per day).

Region VI Countries (excluding OPEC member countries)		*Region VI and OPEC Member Countries*		*OPEC Member Countries (excluding region VI countries)*	
Bahrain	6.1	Algeria	1020.3	Ecuador	160.9
Egypt	23.3	Iran	5350.1	Gabon	223.0
Syrian Arab Republic	18.2	Iraq	2261.7	Indonesia	1306.5
Jordan	0	Kuwait	2084.2	Nigeria	1783.2
Lebanon	0	S.P.Lybian A.J.	1479.8	Venezuela	2346.2
Oman	34.1	Qatar	437.6		
Yemen	0	Saudi Arabia	7075.4		
Yemen, Democratic	0	United Arab Emirates	1663.8		
Total	81.7	Total	21,372.0	Total	5819.8
Total region VI: 21,453.7			Total OPEC: 27,192.7		

Sources: Data for region VI countries from United Nations (1978); data for member countries of OPEC from OPEC (1978).

Figure 25-11. Oil trading between regions, High scenario, 1975-2030.



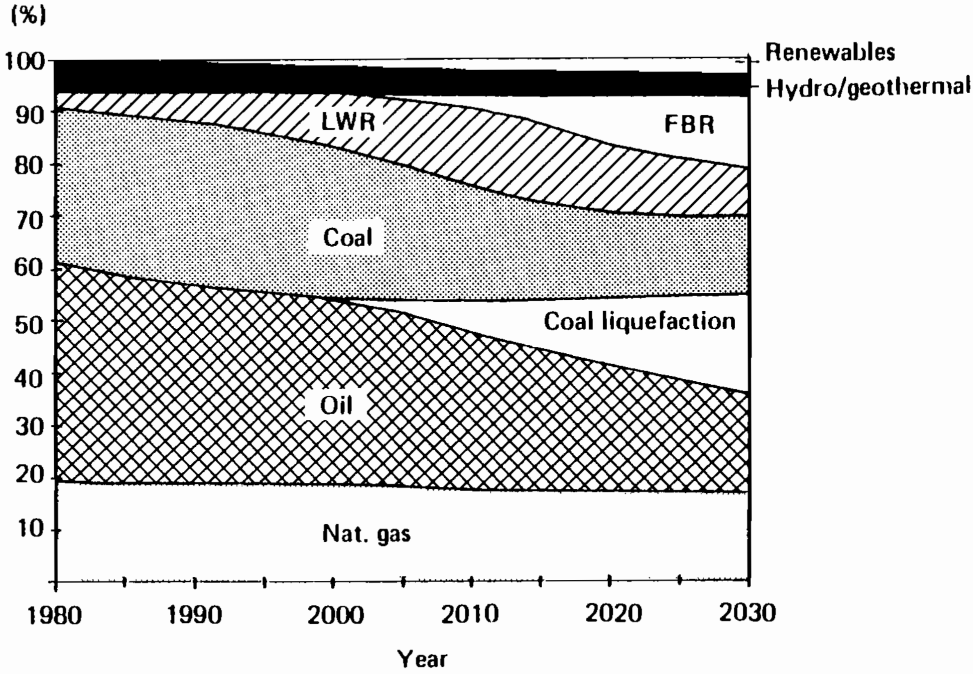
between region VI (oil supply), regions I and II (coal supply) and regions III and V (demand).

Again, it will be political forces that govern the quantity and price of oil (and later probably coal) in world markets. This is a new situation that existing economic and political institutions are not yet able to handle. It is therefore imperative that there be a conceptual framework for viewing the evolution of energy systems worldwide, which would give some perspective and thereby foster the mechanisms for managing the situation. It is with such goals in mind that we designed our scenarios.

- *Coal liquefaction must be installed with a strategic view.*

Given the importance of coal liquefaction in balancing demand and supply of liquid fuels in regions I, II, and III, more must be said about it here. Coal

Figure 25-12. Primary energy (or equivalent) demand, High scenario, 1980-2030.



use in our two supply scenarios is on the order of 12 billion tons equivalent per year, most of it being used to meet internal energy needs of the various regions and with only moderate amounts left for trading on the world market. In Figure 25-12 we show the evolution of global primary energy shares for the High scenario. To decrease the relative share of oil, coal liquefaction must indeed come in. The necessary amounts of coal are made available from the traditional use of coal for electricity generation. This can be done by means of either the autothermal or the allothermal process.[d] Let us examine the possible implications of both of these processes.

In the related MESSAGE[e] supply runs for our scenarios we have assumed autothermal liquefaction; we did this in the best spirit of trying to be in the middle of the road, realistic, and pragmatic. As we explained in more detail in Chapter 22 on new old technologies, for coal liquefaction, the autothermal process implies the use of three to four carbon atoms for placing one atom into the right form of methanol. One carbon atom is used for shifting oxygen from two water molecules to one carbon dioxide molecule, thus freeing the

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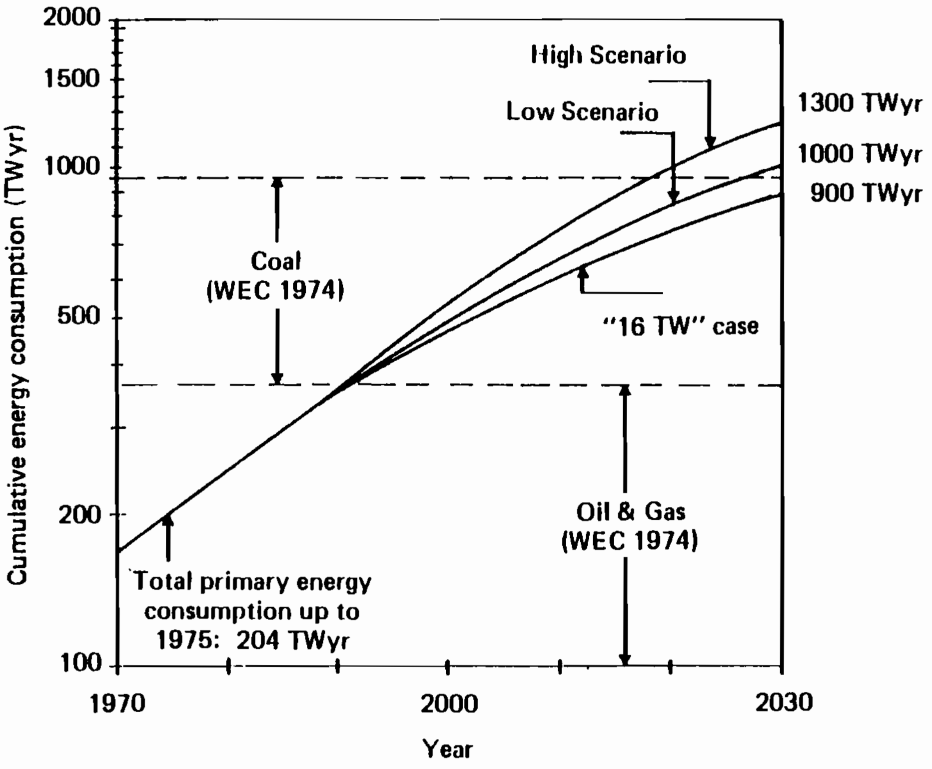
[d] For the autothermal method, the process heat comes from the coal itself, while for the allothermal method the process heat is supplied exogenously.

[e] For a description of the MESSAGE model, see Appendix 13A.

necessary hydrogen required for forming the one methanol (or methane) molecule in question. And one to two carbon atoms are burned into carbon dioxide to provide the necessary process heat for facilitating this chemical reaction.

However, we do not recommend autothermal liquefaction for several reasons. In addition to using three to four times more coal than necessary, the autothermal process of liquefaction also leads to the release of three to four times more carbon dioxide molecules into the atmosphere. And as explained in Chapter 10 on energy and climate, the buildup of atmospheric carbon dioxide must be restricted over the next decades to a prudent limit. We used a climate model to monitor the carbon dioxide buildup that goes along with the related reference supply scenarios. Here, it is helpful to recall the order of magnitude: the natural carbon dioxide content of the atmosphere is equivalent to the burning of roughly 500 TWyr of fossil fuels. If, however, 1000 TWyr of fossil fuels are actually burned (Figure 25-13), one can assume roughly that 50 percent of the carbon dioxide would remain in the atmosphere, thus doubling the natural carbon dioxide content. This is

Figure 25-13. Evaluation of integrated conceivable world energy consumption, 1970–2030.



certainly beyond the limits that we consider prudent. Later in this chapter, we shall discuss the carbon dioxide problem in more detail.

Thus, we believe that one should go to allothermal coal liquefaction. For this process, the hydrogen is provided without burning coal; instead, nuclear and/or solar power would be used for water splitting and accordingly for providing such hydrogen. In effect, only one carbon atom is required for producing one molecule of methanol (or methane). By using coal in this way during the period between the two transitions, we gain time.

- *If nuclear is used primarily, coal can be saved to produce liquid fuels during the next one hundred years or so.*

It was along such lines of reasoning that we conceived the Enhanced Nuclear Alternative Supply case (see Chapter 18). We envisaged allothermal coal liquefaction, using nuclear power close to the envisaged potential of 17 TWyr/yr given in Chapter 4. The coal supply situation was indeed relieved.

Nevertheless, our study revealed that the time is too short to come fully into the second transition. It is essentially after the year 2030 that the impacts of such strategies would be felt more strongly. Thus, from now until this time it is important to aim strategically not only to save the world's coal resources but also ultimately to eliminate the use of coal altogether. Of course, these observations hold for the world regions as a whole. On local or national bases, allothermal coal liquefaction schemes can become important much earlier—for example, in region III—when coal imports become less feasible than has been projected in our reference scenarios.

- *If there is a nuclear moratorium, the gas supply will be largely exhausted by the year 2030.*

The Nuclear Moratorium case, as discussed in Chapter 18, is based on the use of gas, which is in line with our goal in the quantitative analysis of being realistic and pragmatic. Indeed, as can be seen from Table 25-4, only 49 percent of gas categories 1 and 2 will be consumed in the High scenario by the year 2030; 339 TWyr of conventional and unconventional gas are estimated to still be in place. However, for gas to be able to substitute for oil, it must be transportable either by large gas pipelines or, if transported in liquid form, by cryogenic means or by chemical means. These all will require large-scale capital investments and considerable technological progress.

The forward application of our market penetration techniques (see Chapter 8) also indicates enhanced uses of gas. It is likely that the role of natural gas will be more important than that projected in our reference scenarios. However, unless gas resources are found in excess of the 538 TWyr currently estimated, then such a gas era will be of limited duration.

There is yet another condition of the Nuclear Moratorium case that concerns us: it appears feasible only for the Low demand scenario, thus implying, among other things, low economic growth rates. Earlier in this chapter we discussed some of the implications of this case. Here, we conclude that while the Nuclear Moratorium case could be perhaps an interim solution, it would have a price when viewed over the longer term—that is, beyond 2030.

- *Gas will have to be shipped long distances and in international commerce.*

Gas could play a major role, provided the problem of transporting gas can be overcome. Although our explorations of the technical possibilities have not been extensive, in Chapter 22 on new old technologies we have briefly examined the possible mechanical liquefaction and transportation of liquefied gas in large tankers. Transporting gas by pipelines is yet another possibility that could be significantly improved by going to large diameters (1400 mm), or high pressures (70 atmospheres), or both. Such a solution could be particularly applicable to the Middle East (where the flare gases alone are currently on the order of 0.25 TW/yr) and to the Soviet Union. Conceivably, the chemical liquefaction of natural gas (methane to methanol) could also solve the problem of transporting gas over large distances.

CONSTRAINTS

- *Energy investments will grow significantly but will not be a large portion of GDP in the developed countries.*

Ideally, the problem of investments should involve an input-output procedure that embraces not only the energy sector but all economic sectors. The pilot model of G. Dantzig of Stanford University is a prominent example of such a procedure. But such models are very data intensive, and the use of a similar model on the global level would present insurmountable problems. Thus, in Chapter 19, we examined only the direct investments in the energy sectors as well as those in the energy-related sectors that indirectly contribute to the energy development. We made a number of assumptions; a summary of the major ones are given in Table 25-8. We

Table 25-8. Capital cost assumptions for major energy supply and conversion technologies.[a]

	Capital Cost (1975 \$/kW(e))
Electric Generation	
Coal	480-550
Nuclear	700-920
Hydroelectric	620
Oil- and Gas-fired	325-350
Gas turbine	170
Other	
Coal gasification, liquefaction (autothermal)	400
Crude oil refinery	50

[a] For more details see Table 17-4.

Table 25-9. Cumulative energy sector capital cost requirements, 1981-2030 (10^{12} \$).

	Developed Regions[a]	*Developing Regions*[b]	*World*
High scenario	28.0	18.5	46.5
Low scenario	18.8	10.9	29.7
Nuclear Moratorium case	22.0	12.0	34.0
Enhanced Nuclear case	28.4	15.3	47.7

[a] Regions I (NA), II (SU/EE), III (WE/JANZ).
[b] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

assumed that costs would remain the same throughout the period up to 2030. We did so not because we felt this would actually happen, but rather, because assuming otherwise would have been less accurate. This led to some rough overall orientations. Table 25-9 lists cumulative investments for the High and Low scenarios and for the Nuclear Moratorium and Enhanced Nuclear cases. Comparing the data for both cases and scenarios, we see that the Nuclear Moratorium case has higher investments than, say, the Low scenario, which has some 23 percent nuclear power by 2030.

The absolute sisze of the cumulated energy investments for this period would range between \$29 and \$48 trillion (10^{12}). This is very much in line with our propositions presented at the World Energy Conference in Istanbul in 1977 (WEC 1978). We used the IMPACT model[f] to relate the yearly energy investment to yearly GDP. As can be seen from Figure 25-14, today's share of energy investments of 2 percent can be considered typical. For the developed regions (I, II, and III) such investments increase, peaking at about 4 percent around 2015. For the developing regions (IV, V, VI, and VII) investments rise more sharply, coming close to 7 percent around the year 2020. Globally, the investment maximum is about 4.5 percent. Is this large or small? The more we tried to answer this question, the more complex it became. If we compare this 4.5 percent with, say, military expenditures worldwide, we see that they are both of the same order. Then too, changes in the savings rate over the last decades have also been of that order. In Japan, for example, during the 1960s the savings rate has been between 30 and 35 percent, although presently it is closer to 30 percent. Roughly a 5 percent difference decrease has occurred there, with no fundamental changes. In our scenarios we assumed constantly declining economic growth rates globally. When integrated energy investments are then compared with integrated GDP, the ratio turns out to be rather low because of the pocket of relatively large GDP that existed before 2030. This ratio would definitely be higher if we were to have assumed constant growth rates (which we did earlier in 1977 in our presentation to the World Energy Conference).

A serious comparison would have to be made sector by sector, followed

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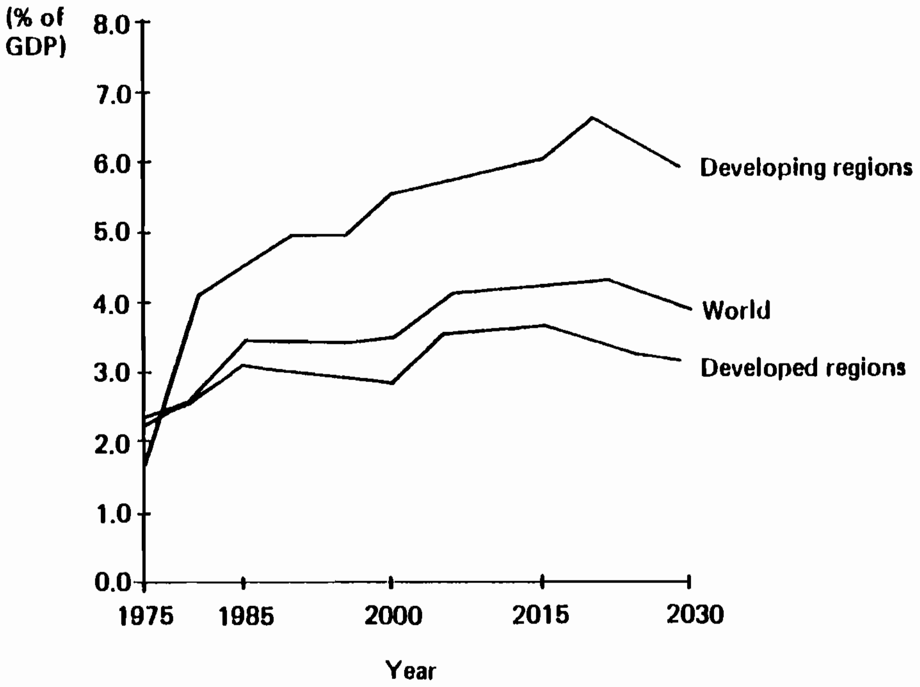
[f] For a description of the IMPACT model see Appendix 13A.

Figure 25-14. Share of total energy investment in GDP, High scenario, 1975-2030.



by the above-mentioned input-output analysis covering the whole of the economy. For the world trade situation, the problem of analysis becomes particularly complex, and we were not in a position to undertake such an extensive analysis. We observe, however, that the macroeconomical impacts (globally) will not be too large, while the sectoral impacts will probably be very pronounced. Such a statement is consistent with our earlier observations about the pragmatic and realistic nature of our two scenarios, since they defer the second transition to beyond 2030 and only prepare smoothly for this transition at best.

- *Global impact of waste heat is probably a nonproblem.*

We were concerned about constraints on energy supply that only became explicit when the energy problem was viewed globally. We therefore considered the interaction between energy and the climate system.

We became increasingly aware of the complexity of the climate system. Climate is a very "noisy" phenomenon. In addition to changes of averages of quantitites, such as temperature, pressure, and humidity, there are fluctuations and, indeed, changes in these fluctuations that make up the temporal and spatial patterns of climate. It is the changes in these patterns that interested us.

Using numerical models of global atmospheric circulations (at present the best means available), we simulated the climatic effects of energy release ranging from 30 to 300 TWyr/yr, from certain geographical locations and areas. We observed that the thermal pollution effects from such waste heat releases were not greater than the inherent noise level of the model. In fact, it appears that only when very large amounts of energy (several hundreds of terawatts) are released under certain circumstances (e.g., from small concentrated areas) are there significant changes in the global average climate state. Thus, when considering the global energy consumption levels of the High and Low scenarios (36 and 22 TWyr/yr, respectively), waste heat releases do not appear likely to perturb the global average climate state in the foreseeable future. Of course, this is not to say that impacts on the local and regional levels from waste heat releases could not be serious in the vicinity of such operations.

A second line of investigation of the climate-energy interface led us to a more serious conclusion.

- *The carbon dioxide buildup caused by fossil fuel consumption is probably the most severe climate issue.*

While it is too early to make alarming statements about the specific climatic impacts of large-scale deployment of any of the major energy strategies, our study revealed that the climate impact caused by carbon dioxide buildup over the next fifty to seventy years could lead to a global average temperature increase from 1 to 4 K. This would have different effects on different parts of the globe: some areas would benefit from these changes, whereas others would experience negative impacts. For example, increased precipitation (rainfall) in certain areas could result in changes in regional agricultural practices, with hitherto arid areas flourishing agriculturally while others struggle to adapt their cropping patterns to more arid conditions. The hydrosphere, too, could undergo changes. Certain rivers could be enlarged, whereas others would become smaller. The implications of these climatic changes are potentially large.

Ideally, the impacts of carbon dioxide should be monitored early enough to allow for actions that would ward off any negative effects. But reality is sometimes far from the ideal. Present knowledge about the climatic implications of raising the carbon dioxide level is limited, and according to our estimate a period of five to ten years is probably needed to narrow down these uncertainties.

It does not appear realistic to assume that there will be political agreement among nations on the avoidance of carbon dioxide impacts, as climatic changes would in fact be welcomed in some areas. We are faced with the dichotomy of having a highly disaggregated political power on the globe and a truly global problem of carbon dioxide buildup. Are we doomed to encounter this dilemma? Probably, yes. Nevertheless, maintaining flexibility in designing energy supply policies to delay the buildup of carbon dioxide beyond certain levels is prudent and advisable.

- *Low density energy collection devices spread over large areas could have climatic impacts as well.*

As noted above, it is the changes in spatial and temporal climate patterns that matter. It is in this light that we examined other possible climatic impacts from energy conversion and use—namely, changes in the earth's surface characteristics. We delved into this issue by examining the possible effects on surface conditions of vast areas as a result of low density civilization activities. These include large-scale deforestation in tropical or subtropical areas, large-scale harnessing of energy from thermal gradient of tropical oceans, large-scale deployment of wind mills, and even the tens of terawatt scale of production of unconventional fossil fuels.

There are indications that such changes are to be expected with dispositions of energy flows on the order of 100 TWyr/yr. Agriculture is a case in point. Albedo changes of 0.1 seem to take place with the establishment of farm land. Envisaging 10 billion km^2, one arrives at resulting dispositions of energy flows on the order of 100 TWyr/yr. Given the influx of 178,000 TWyr/yr of solar power, one might consider that 100 TWyr/yr is only a minute fraction and therefore too small an amount to warrant concern. But because climate is a noisy phenomenon, it does not take much to change the climate pattern, and that is what matters. For example, precipitation and cloud formation patterns change upon such dispositions of energy flows.

Unfortunately, the state of the art did not permit us to set upper limits on the uses of these energy collection devices or to translate our concern into operational constraints. Nevertheless, the concern remains.

- *Nuclear waste and proliferation issues could limit the buildup of nuclear energy over the next fifty years.*

The handling of nuclear waste and the proliferation of nuclear weapons are the principle concerns that go along with the use of nuclear fuels. The worldwide, oeften heated debate about these issues reflects the size of the related concerns and, as such, has become a constraint.

The IIASA Energy Systems Program did not deal with these issues explicitly for two reasons. The first reason is a pragmatic one. A large number of capable and sizeable groups are already studying these problems, and we did not judge it practical for the relatively small groups of IIASA scientists, from many nations, to compete with these efforts. This is not to say that individual members of the IIASA Energy Systems Program are not personally involved with or at least well informed on these matters. But as a group we decided to abstain. It is in this light that we wish to mention here the work of the International Fuel Cycle Evaluation (INFCE), which was carried out, mostly in Vienna, at the same time as our global energy study.

The second and more commanding reason for abstaining is that we regard the problems of nuclear waste handling and proliferation as primarily political ones. Indeed, the process of establishing the related standards and regulations is largely a sociopolitical one. We did, however, look into the related risk problem, but obviously the issue is far more complex. The political nature of the proliferation problem is more obvious. We hope that indirectly we have contributed to the debate on this subject by clarifying the factual lines of the energy problem as a whole. Is civilian nuclear power needed or not? This question was upmost in our minds throughout our investigations as we sought to provide decision- and policymakers with the information they need to make strategic choices.

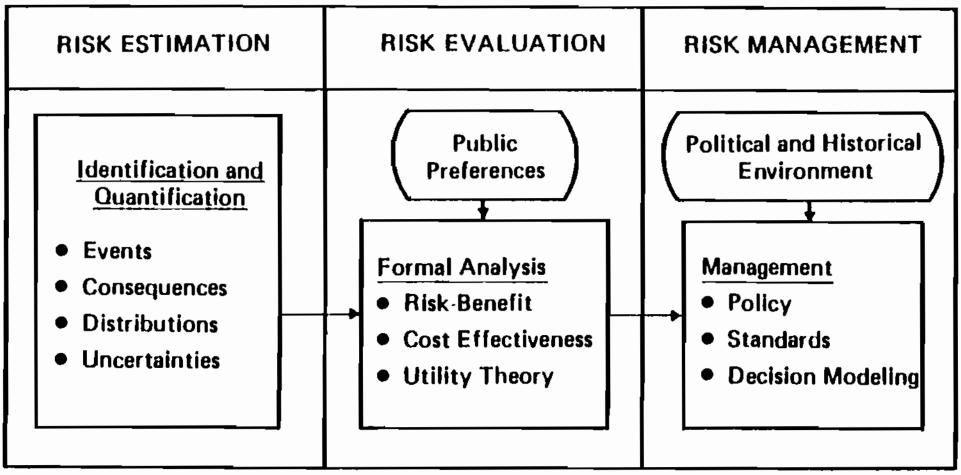
- *Society has not yet developed adequate mechanisms for treating the risks associated with energy supply technologies.*

Risk analysis is a relatively young field, and the lack of data and the inadequacy of both evaluation techniques and the decision-making formalisms for standard setting complicate the problem of understanding the risks of energy strategies. By conceiving a risk assessment framework (Figure 25-15), we have established categories so as to provide a meaningful debate on this subject and to allow for more formal research in this field.

While the risks of nuclear energy have received the most attention, there are other risks from society's activities and particularly from its energy activities that should be examined. We have done this and reported on our findings in Chapter 11.

Our research on public attitudes toward energy-related risks revealed that the public is more concerned with the risks of low probability, large consequence events than with those of high probability, low consequence events. Indeed, there is a large discrepancy between the public's perception of the risk and the risk as expressed in linear expectation values. Psycho-

Figure 25-15. Risk assessment framework.



logical and sociopolitical factors have been shown to greatly influence the beliefs of individuals and societies toward certain risks. This is an important finding that has bearing on the essentially political process of establishing the standards and regulations for energy technologies.

The importance of having established standards and regulations for modern technologies cannot be overestimated: they are, in fact, the real driving forces for these technologies. This is in contrast with the past when optimization was the driving force. Optimization, usually for minimal costs (while observing certain constraints), has been the traditional engineering approach. We maintain, however, that this often no longer prevails. Costs have become at best a constraint (if at all). Today, the principal criterion is the ability to "carry through" a particular engineering design and not to prove in theory that this design is optimal in some sense. "Carrying through" a design largely means obtaining the necessary licenses and permits. Consider, for instance, a particular nuclear reactor designed in country x. In most cases, this reactor will not be licensed in country $x + 1$, even though it is successfully operating in country x. The reasons for this seemingly illogical situation point to the complexities of the sociopolitical domain, as the factors affecting decisions about licensing a technology are, in fact, influenced by the many different perceptions of reality held by the societies of the different countries.

There is a further dimension to the problem of obtaining a license. Lead times for constructing, say, a nuclear power station are increasing. Currently, the time between the decision to build and the putting into operation is close to ten years, five of which go for construction and the other five for completing the necessary paperwork for licensing and permits.

This problematic situation is indeed not helped by the fact that the regulatory bodies often do not know how to arrive at such regulations and standards. Engineers become confused as to what standards and regulations they should aim to meet. Several examples come to mind here—nuclear waste disposal, pressure vessel safety codes, and codes for the design of fatigue ruptures. All too often, codes, regulations, and standards are contested in the courts, which are being used inappropriately for de facto legislative and standard-setting purposes. This not only intensifies the uncertainty about what standards and regulations apply, but also inhibits the responsible bodies from functioning properly. Here again, we see the prominent role played by psychological and sociopolitical factors in fostering fear and uncertainty about the possible risks of certain technologies.

A "language" is needed to overcome such fears—that is, there must be some means established for consciously addressing these fears and, in so doing, managing risks. For in the absence of such means, the problem of managing risk is often reduced to dealing with numerical information. (Numbers appear easier to deal with than deep-seated beliefs, although in the long run dealing with such numbers is not helpful.) One has only to look at the Gofman-Tamplin debate of the late 1960s and early 1970s about permissible dose rates, held at the fence of a light water reaction nuclear power station, to see the problem of such a numerical approach.

Although adequate mechanisms for treating energy-related risks have not yet been developed, we felt we could not stand by idly without trying to give some insights into how to deal with this dilemma.

THE TECHNICAL VISION

- *It is possible to have a sustainable global energy system.*

When we began our study of the global energy system in 1973, we were looking for ways of moving from the present system, based on the consumption of resources by the burning of fossil or nuclear fuels, to a world that could sustain the energy needs of a global population even larger than the eight billion people we project for the year 2030. In this sustainable system, resources would be used for investments that permit both nuclear breeding and the use of solar power directly and through renewable means.

Initially, we had hoped this sustainable system would be reached by the year 2030. However, both our pragmatic quantitative analysis and our more exploratory look at energy constraints and options showed us the reality of the situation: over the next fifty years the world will continue to rely on fossil fuels, albeit unconventional ones, owing to the limitation on the buildup rate of energy technologies. Indeed, our two reference scenarios are primarily fossil in nature, reflecting this reality.

We also observed that resource limitations would be felt only after the year 2030, occurring sometime during the second half of the next century. How does all that fit together? Here, it is useful to elaborate on the nature of this ultimate, sustainable energy system, which would rely on both nuclear and solar energy for primary energy supply and would be complemented by electricity and hydrogen as secondary energy carriers.

What will an electrical-hydrogen world be like? It would necessarily include the generation of vast quantities of electricity. Part of this electricity would provide direct energy services, part would run the processes of production, part might run local transportation (electric cars and trains), and part would be used for water splitting to produce great quantities of hydrogen (and oxygen). When we speak of vast quantities of electricity, we are making an important distinction in relation to the energy world of today. We are speaking of such an abundance of electricity that it comes to be seen virtually as the primary energy source. Today, we think largely of using coal, oil, and natural gas, as well as hydroelectric power, as primary forms of energy for generating electricity as a convenient form of secondary energy. In the future, electricity would become primary in the sense that it would become the source of gas and liquid fuels. It could become the "standard" or reference against which all substitutions would be measured; in both a literal and a figurative sense, it would be the "currency" of the future world. Indeed, electricity could become the basis of new infrastructures and the common ground for industrial processes and residential needs.

With large amounts of electricity being generated in all world regions, a totally different complexion to world politics would undoubtedly develop. Instead of the world being focused mainly on one major oil-producing region, the Middle East and Northern Africa (region VI), as is the case today, one can imagine that a multiplicity of energy sources might encourage a more dynamic stability among the world's trading partners. Whether such things could come to pass are, of course, pure conjecture; technically, they are more than conjecture, they are real possibilities.

The other "half" of the future energy structure would be hydrogen. With a large worldwide electrical basis, the production of hydrogen could be practical and probably economic. Thus, if the use of natural gas grows over the next fifty years, as projected in our reference scenarios, the piping systems for its long-distance transmission and local distribution networks could come into place. Along with the physical gas networks would come the institutional infrastructure and the skills of building, running, and maintaining such systems. And as natural gas is phased out—through scarcity and rising cost—hydrogen could be phased in, flowing through essentially the same distribution systems, managed and maintained by the same cadres of specialists. Unlike natural gas, which produces carbon dioxide when burned, hydrogen gas produces pure water when burned (the recombination of hydrogen and oxygen). Pure water, it hardly needs to be remarked, is certainly not an environmental pollutant.

The other essential arm of this hydrogen structure would be its use for the creation of hydrocarbons for vital needs. The necessary carbon for these substances could presumably come from biomass plantations of various kinds and ultimately even from technical recycling of carbon dioxide.

Ideally, the ultimate transition to the hydrogen-electricity economy should progress smoothly. To do this would require a strategy for the interim period that would allow decisionmakers to plan for the kinds of technologies and investments needed to achieve such a sustainable energy system over the next one hundred years or so. It is within this broader context that we make our observations.

- *"Sustainability" of the ultimate global energy system means living from the interest generated from endowments: resources are then used for investments and not (as currently) for consumption.*

In Chapter 21, on energy, endowments, and negentropy, we outlined in thermodynamical terms how services provided by inputs of resources, energy, labor, and skill are partly substitutable. We saw that these inputs have the common denominator of negative entropy (which we defined as negentropy) or, in a more general sense, of "order states." It was along such lines that we introduced the notion of "endowments"—that is, an investment of resources, energy, labor, and skill. And because capital is a stored form of negentropy, it too is an input to an endowment system. It is the interest generated from these endowments that would be used for consumption.

Since no law of conservation exists for entropy and thus for negentropy, we feel fully justified in speaking here of "energy consumption." Indeed, the negentropy carried by energy is then consumed. These relations, in turn, then also allow for the generation of negentropy. Based on this heuristic reasoning, we suggested using only the interest from endowments to meet the demand for services.

While this reasoning is abstract and perhaps enlightening only to physicists, it nevertheless led us to make the operationally important distinction between the consumptive and the investive mode of resource use. For breeder reactors, the investive use of resources would mean the use of fissionable isotopes only as catalysts for the breeding of practically unlimited amounts of fertile material. For solar power, the investive mode would call for the use of 10 to 100 kg/m^2 of materials (e.g., steel, concrete) needed for the installation of solar facilities as explained in Chapter 5. Thus, the sustainability of our ultimate global energy system, based on nuclear breeders and solar power as primary energy sources, rests solely with the investive use of resources, which in turn rests with the abstract nature of the services civilization requires.

- *The buildup and operation of a sustainable global energy system must make prudent use of the carbon atom.*

We observed that the transition to the sustainable energy system—to the hydrogen-electricity world—will have to proceed through various stages, which we refer to as the first and second energy transitions. While these transitions would, in fact, overlap, the first transition (lasting until around the year 2030) would be one from the present carbon-based economy to a carbon-based economy with different features. It is useful here to describe briefly some of the features of both the present and the future carbon-based economies.

Today's carbon-based economy uses mostly oil and to an extent gas. It employs not only the energy content of oil and gas but also the many additional services that go along with the use of versatile and clean oil and gas resources. Until recently, the use of oil and gas had been driven mostly by prices and market forces, implying essentially that strategic considerations about long-term supply limitations have not, and still do not, determine the situation.

One major characteristic of the future carbon-based economy is the short supply of fossil fuels, including coal. (Indeed, our reference scenarios have shown that the amounts of coal and unconventional oil that would have to be harnessed are almost inconceivable by current standards.) At this time, fossil waste disposal (i.e., carbon dioxide) is likely to be a global problem. Because of these two factors, the carbon atom would have to be used strategically, and allothermal coal gasification and liquefaction would be employed for producing liquid fuels. Along with this prudent use of the carbon atom, there would be the saturation buildup of both nuclear and solar power to meet demand left unfulfilled by the dwindling fossil fuel resources.

This transition to the modified carbon-based economy of the world of 2030 can be viewed in yet another light: it would require a change in the mix of the inputs of resources, capital, labor, and skill needed to substitute for energy services that go along with the use of oil and gas today. As we go from today's cheap, relatively clean, and easy to move fossil fuels to the world of more expensive, dirty, and harder to get at and to transport unconventional fossil fuels, there will have to be greater inputs of both capital and skill to maintain services at acceptable levels. The most readily visible aspect of that is the incoming abatement measures for the protection of the environment. They are, among other things, capital intensive.

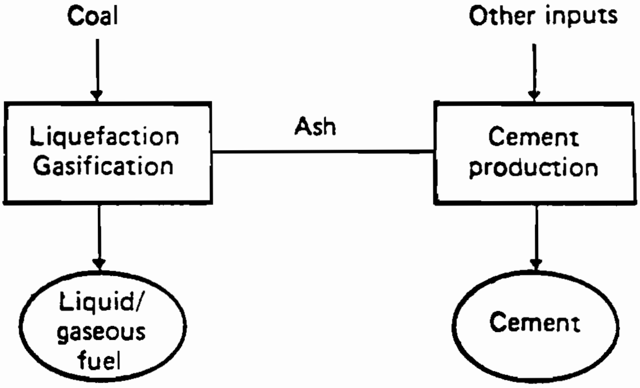
Earlier in this chapter we elaborated on the strategic view with which coal liquefaction must be installed. Both the relative scarcity of coal and the carbon dioxide problem led us to strongly invoke allothermal rather than autothermal coal liquefaction (or gasification) schemes. But we now realize that there is even more to such a strategic view. For allothermal schemes the generation of large amounts of exogenous hydrogen from nonfossil energy sources is required. In fact, about 50 percent of the energy content of the hydrocarbon molecules in question is because of their hydrogen content.

Thus, having established more explicitly our vision of the ultimate sustainable energy system and having realized that hydrogen should serve as the principal secondary energy carrier, besides electricity, we can envisage the use of such exogenous hydrogen in an even wider context—namely, to facilitate the early and smooth introduction of the ultimate secondary energy carrier, hydrogen. The existing difficulties in today's use of hydrogen relate to its volatile form and to its other thermodynamical and chemical properties. Our present infrastructure on the end use side relies greatly on the liquid nature of the hydrocarbons in use, and to change that requires time. Therefore, the carbon atom can be seen as a carrier of hydrogen during the transition periods, thus permitting for the continued use of that infrastructure. In Chapter 5 we observed that large-scale energy storage of solar power leads most probably to the use of hydrogen, and we welcome this view of the role that hydrogen plays in our vision. Further, in Chapter 22 we pointed to the molten iron bath technique for generating clean synthesis gas, a fairly specific technology. While the actual development could well evolve along somewhat different lines, it nevertheless is heuristically helpful to realize system opportunities that foster the second transition and reconcile the first and the second transitions.

For the molten iron bath technique, the cleaning of the low grade fossil fuels takes place automatically, almost as a by-product. Slag is formed on the surface of the bath and must be removed (see description in Chapter 22). Systems opportunities come up when this slag is, for instance, used to produce concrete, which in turn would be used to install large-scale solar facilities (see Figure 25-16). It is indeed surprising that the orders of magnitude fit. The amount of ashes of the low grade fossil fuels to be expected in our reference scenarios allows for a very desirable buildup of solar facilities.

Two observations must be repeated here—the integrating and fostering role of the hydrogen atom and the mediating and smoothening role of the carbon atom that should be understood when energy strategies for the next decades are to be conceived.

Figure 25-16. Hypothetical production chain: coal liquefaction/gasification-cement-solar conversion systems.



Year	*Coal Liquefaction/ Gasification*[a] *(10^6 tce)*	*Resulting Cement Output (10^6 tons)*	*Resulting Yearly Buildup of Solar Conversion Systems*[b] *(GW(e) installed)*
1980	0	0	0
1985	0	0	0
1990	0	0	0
1995	10.3	2.1	5.5
2000	114.3	22.9	61.0
2005	452.3	90.4	241.2
2010	1,385.6	277.1	739.0
2015	2,606.9	521.4	1,390.4
2020	3,893.8	778.8	2,076.7
2025	5,481.0	1,096.2	2,923.2
2030	7,222.7	1,444.5	3,852.1
Total			11,288.9

[a] High scenario.

[b] Assuming total material requirements of 750 kg/kW(e), 50 percent of which would be cement.

All these considerations point to the buildup of the sustainable ultimate energy system. But even for the operation of the completed system, the carbon atom could play an important role—namely, along the lines of its investive uses. In Chapter 3 on the coal option, we noted the value of considering the use of hydrocarbons in a closed cycle where the carbon dioxide is technically recycled. For this scheme, the carbon atom would no longer be consumed; rather, it becomes part of the endowment vision explained above.

- *Realistically, the buildup of nuclear and solar power in our two reference scenarios can be seen only as a beginning of our second transition.*

We ask ourselves, How close did our two reference scenarios come to our vision of a sustainable energy system? To answer this question, we refer to the insights gained in our quantitative analysis, specifically to those for the future role of nuclear and solar power.

In our two reference scenarios, the breeder reactor starts coming into the energy picture around the year 2000; by the year 2030, it has taken over some 70 percent of the nuclear share of energy production (see Figure 25-12). What near- and medium-term implications does this have for our endowment vision?

For the breeder reactor to be considered a serious energy contender in the terawatt demand range, it should be contributing in the hundreds of gigawatt level by the early years of the next century. For this to be possible requires vigorous action today.

Different assumptions about the rates of the potential development of breeder reactors were used in our two reference scenarios. For region I, the breeder enters the picture sometime around 2010, whereas its entrance in region III occurs around 1995. Viewed against today's actual situation, this would mean that region III would now have to deploy breeder technology more aggressively.

In developing our quantitative analysis we were surprised to see the limited share that nuclear power made to energy production by the year 2030, for both reference scenarios. Again, it is the limitation on the buildup rates of these technologies over the next fifty years that is responsible for these disappointing figures. Nevertheless, during the period 2030 to 2080, when the world is making its second energy transition, the energy burden should shift progressively onto the sustainable system, and nuclear power would then be able to play its major role in energy supply.

For building our endowment system, we include all feasible types of breeders. (See Chapter 4 for detailed information on breeder strategies.) Technically, the liquid metal cooled fast breeder reactor (LMFBR) is currently the most advanced technology and has accumulated the most operational experience. Fast breeder technology is in advanced stages both in France and in the Soviet Union.

The traditional, middle of the road approach (which our two reference scenarios adopted) is to consider the recycling of bred plutonium to the fast breeders. But over the long run it may be more advantageous to use the radial blanket of FBRs for breeding ^{233}U. For instance, the use of ^{233}U in the original light water reactors that fed the FBRs their first core plutonium inventory could enhance the LWR conversion ratio, thereby reducing their demand for new natural uranium and ultimately allowing the breeding gain of the FBR to support the LWRs entirely. In fact, such a LWR-FBR complex could become part of our endowment system. Similarly, one should consider the crossing of fuel cycles of LMFBRs and high temperature reactors (HTRs) that use ^{233}U.

The fusion reactor also fits into the picture. Be it the present D-T version, which breeds lithium, or the much more futuristic D-D version, for both cases the reactor is de facto decoupled from the problem of fuel supply.

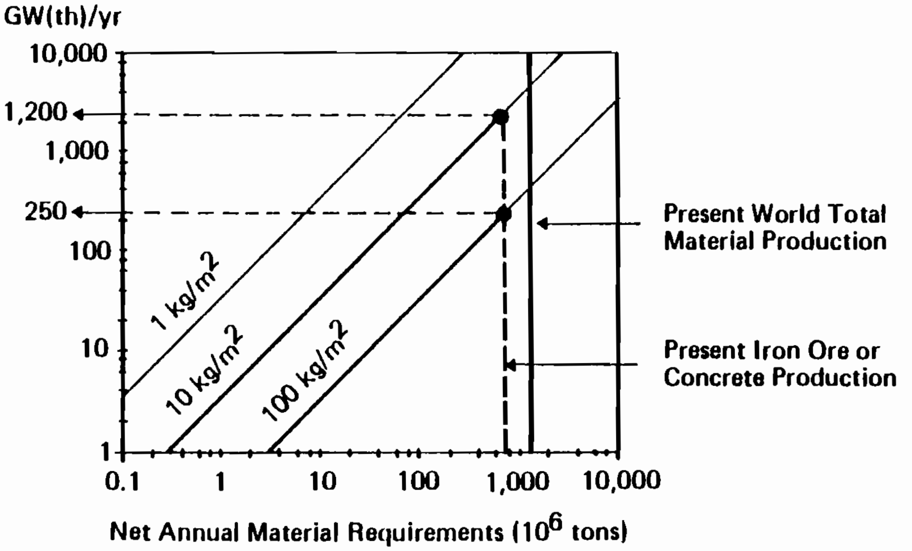
Although both the fission breeder and the fusion reactor handle large amounts of radioactive inventories and produce radioactive wastes, the fusion reactor holds the promise of being better than the FBR in environmental terms, although it remains to be seen at what cost. It would be a mistake, considering the differences between these developing technologies, to get lost in marginal technological issues and to lose sight of their important potential contribution to meeting the large energy needs of the world after the year 2000.

While solar and nuclear power will have different patterns of evolution, they share the same ultimate goal—the establishment of endowments on whose interest rates future societies would live indefinitely. Figure 25-17 illustrates some of the material requirements for solar conversion systems of various net densities. We cannot understand all the implications of such large inputs of human and physical resources. But it is these investive uses of large amounts of resources that are the essential issue, as well as the time element. Then too, there will be institutional barriers that we are not sure can be overcome. Nevertheless, let us assume here that they can be mastered.

We are faced with yet another problem—energy storage. In the very near term, storage will probably not be a serious problem provided that solar power contributes no more than 10 percent to the total primary energy sytem—an amount that can be absorbed by existing supply systems. But beyond the 10 percent level, solar energy storage problems must be put in focus.

The average insolation in the middle latitudes and the equatorial regions does not differ greatly; it differs no more than by a factor of two. Seasonal

Figure 25-17. Material requirements: solar conversion system of various net densities.



variations, however, differ by a factor of four. Thus the maximum-to-minimum ratio between the middle latitudes and equatorial insolation is eight. It would appear that storing energy for the winter during the summer is much beyond the possibilities of hydrostorage.

To make the long-term storage problem of solar power manageable, electrical-chemical processes are needed to transform solar power into either a gas or a liquid. In Chapter 22 we examined some of the various methods and schemes that are being considered as possible solutions to this problem. In practical terms, the technology of hydrogen production seems suitable for solving the problem of solar power energy storage. (This is indeed consistent with our vision of the ultimate electricity-hydrogen economy.

However, there are other major obstacles that will have to be overcome before there can be large-scale application of solar power. In fact, the physical embedding of solar power into the existing energy supply infrastructure appears to be more difficult than the embedding of nuclear power. Time in both cases, but especially for solar power, is a very precious element. Therefore, the development of significant amounts of solar power by the year 2030 appears unlikely. Still, this should not preclude aggressive actions now that might even hasten the final event.

- *Establishing the endowment system requires a degree of capital formation that can be obtained only through high productivity.*

Does the world possess the productive and institutional capabilities, the capital and material resources, and the discipline to achieve such goals? What does it mean to mobilize building programs on such a scale around the world or to build the productive plant to turn out the dozens of billions of tons of concrete and steel to build these grandeurous new plants? These are challenging questions that we hope the old and new generations will be able to tackle. Again, it will take time and material inputs, especially of capital; there will also be institutional barriers of all kinds at all levels to overcome. Above all, it would demand generally much greater productivity worldwide, and this would mean increased levels of interregional trading of all kinds—of labor, of skills, of technologies, of knowledge, of energy, of products, of food, and so forth. A world infrastructure of a new order would probably be required.

In capital terms, taking into account the construction of facilities for energy transmission and distribution, breeder technologies, and solar technologies, the investment may be on the order of \$2 to \$3 per watt of achieved capacity. Thus, even a 20 TWyr/yr energy demand world (which is lower than our Low scenario) would require an investment on the order of \$40 to \$60 trillion (10^{12}).

However, once this scale of investment has been made and the energy supply mode is de facto decoupled from the problem of resource supplies, the world would have crossed a distinct threshold. This threshold might be regarded as great as that passed by our distant ancestors when they launched the era of domestic agriculture, began the intensification of farming productivity, and started the process of aggregation of peoples into what would become cities. Below this distinct threshold, there would remain the problem of supply shortages, which may be experienced by "pockets" of mankind; above this distinct threshold, this problem would virtually disappear on a universal scale.

In economic terms, we must ask what this investment means as compared with world investments in energy today. If we take the average per capita demand of 3 kWyr/yr of our Low scenario in the year 2030, we arrive at a capital stock requirement of $6000 to $9000 for each citizen of the globe, should he or she wish to live on the basis of endowments for the energy supply. The present-day share of world capital stock in the existing energy system is 25 percent. If this share were to be increased to 33 percent, thus making the importance of energy relatively larger, the capital stock per person would still be somewhere between $18,000 and $27,000. This is indeed a high investment when compared with today's capital stocks, as Table 25-10 indicates, particularly for developing countries. Their average capital stock today is only $380, as contrasted with $8500 in the developed market economies and even with the $2700 of the centrally planned economies (Ströbele 1975).

If one looks at the world average of $2000 in capital stock and envisages the need to raise that to $18,000 to $27,000, then one sees that building the energy endowments system is not a straightforward possibility within the next one hundred years or so. This is why it is so important that the eight billion or more people living in the year 2030 be rich, not poor, and much richer than today. Only then will it be possible to break out of the consumptive mode of resource use and to cross the thresholds where, at least, the energy resources problem can for all practical purposes be forgotten.

To become so rich will require continued economic growth as well as ever-increasing productivity and technological sophistication. A science of "energy and society" should become a tool of that future society in many more respects than we can point to here. Such a science exists today only in a rudimentary form; it is still more an art and a craft than a science, and inasmuch as it incorporates broad social, cultural, and political issues, it cannot be called upon readily to acquire the general sophistication needed.

Nonetheless, even lacking such tools and without attempting to work out

Table 25-10. Energy consumption and capital stock.

	Energy Capital Input Ratio (W/1973$)	*Capital Stock Per Capita (1973$)*
Developed market economies	0.71	8500
Developing countries	0.77	380
Centrally planned economies (excluding China)	1.43	2700
World	0.87	2000

Source: Ströbele (1975).

a detailed plan as to how the world might rise to the high per capita investments in energy supply systems, we must conclude that endowments will require a degree of capital formation that can be obtained only through high productivity.

Once we were asked to identify three vital questions that we felt had to be answered regarding the global energy situation in the year 2030. We identified the following: How many people will live in urban areas? What is their demand for liquid fuels? What is their industrial productivity?

Where is the crystal ball?

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GLOSSARY

AC—alternating current, electric current that reverses direction periodically, usually many times per second.

AECL—Atomic Energy of Canada, Ltd.

AGR—advanced gas-cooled reactor.

AMP—ampere, the unit of electric current in the rationalized meter-kilogram-second system of units; defined in terms of the force of attraction between two parallel current-carrying conductors.

API—the American Petroleum Institute hydrometer scale for the measurement of the specific gravity of liquids.

atm—a unit of pressure equal to 1.013250×10^6 dynes/cm^2 (which is the air pressure at mean sea level).

bbl—barrel.

boe—barrel of oil equivalent.

BPA—Bonneville Power Authority.

Btu—British thermal unit [THERMO]. 1. A unit of heat energy equal to the heat needed to raise the temperature of 1 pound of air-free water from 60° to 61°F at a constant pressure of 1 standard atmosphere; it is found experimentally to be equal to 1054.5 joules. Also known as sixty degrees Fahrenheit British thermal unit ($\mathrm{Btu}_{60/61}$). 2. A unit of heat energy equal to 1/180 of the heat needed to raise 1 pound of air-free water from 32°F (0°C) to 212°F (100°C) at a constant pressure of 1 of 1 standard atmosphere; it is found experimentally to be equal to 1055.79 joules. Also known as mean British thermal unit (Btu_{mean}). 3. A unit of heat energy whose magnitude is such that 1 British thermal unit per pound equals 2326 joules per kilogram; it is equal to exactly 1055.05585262 joules. Also known as international table British thermal unit (Btu_{IT}).

BWR—boiling water reactor.

CANDU—A nuclear reactor of Canadian design, which uses natural uranium as a fuel and heavy water as a moderator and coolant.

CF—confinement factor.

cm—centimeter.

CPC—compound parabolic concentration.

CR—central receiver facility.

DC—direct current, electric current which flows in one direction only, as opposed to alternating current.

$/kW—dollars per kilowatt.

$/tce—dollars per ton of coal equivalent.

DR—distributed receiver facility.

EJ—Exajoule = 10^{18} J.

ERDA—Energy Research and Development Administration (U.S.).

ESS—energy supply system.

eV—electron volt; a unit of energy equal to the energy acquired by an electron when it passes through a potential difference of one volt in a vacuum; it is equal to $(1.602192 \pm 0.000007) \times 10^{-19}$ volt.

FBR—fast breeder reactor.

FCR—fixed charge rate.

GCM—general circulation model.

GCOS—Great Canadian Oil Sand.

GDP—gross domestic product.

GeV—giga electron volt, a unit of energy, used primarily in high energy physics, equal to 10^9 electron volts.

GM—gaming model.

GNP—gross national product.

GW—gigawatt, one billion watts, or 10^9 watt.

GW(e)—gigawatt electric.

GW(e)yr—gigawatt (electric) year.

GWP—gross world product.

GW(th)yr—gigawatt (thermal) year.

GWyr—gigawatt year.

GWyr(e)—gigawatt-year (electric).

h—hour.

ha—hectare.

HHV—high heating value.

HTR—high temperature reactor.

HTGR—high temperature gas-cooled reactor.

HWR—heavy water reactor.

IAEA—International Atomic Energy Agency.

ICRP—International Committee on Radiation Protection.

IEA—International Energy Agency.

IEJE—Institut des Etudes Juridiques et Economiques at the University of Grenoble, France.

IGT—Institute of Gas Technology, U.S.A.

IMPACT—economic impact model.

INFCE—International Fuel Cycle Evaluation.

INTERLINK—input/output model.

J—joule, the unit of energy or work in the meter-kilogram-second system of units, equal to the work done by a force of magnitude of one newton when the point at which the force is applied is displaced one meter in the direction of the force.

K—kelvin, a unit of absolute temperature equal to 1/273.16 of the absolute temperature of the triple point of water.

kcal—kilo calorie, a unit of heat energy equal to 1000 calories.

kcal/mole—kilocalorie per mole, mole [CHEM]. An amount of substance of a system which contains as many elementary units as there are atoms of carbon in 0.012 kilogram of the pure nuclide carbon-12; the elementary unit must be specified and may be an atom, molecule, ion, electron, photon, or even a specified group of such units. Symbolized mol.

kg—kilogram.

km^2—square kilometer.

kW—kilowatt, a unit of power equal to 1000 watts.

kW(e)—kilowatt-electric.

kWh—kilowatt-hour, a unit of energy or work equal to 1000 watt-hours.

kWh(e)—kilowatt-hour (electric).

kW(th)—kilowatt-thermal.

KWU—Kraftwerk Union, F.R.G.

kWyr/yr, cap—kilowatt-year per year and per capita.

ℓ—liter.

LMFBR—liquid metal fast breeder reactor.

LNG—liquified natural gas.

LWBR—light water breeder reactor.

LWR—light water reactor.

m—meter.

MACRO—macro-economic model.

mbd—million barrels per day.

mbdoe—million barrels per day oil equivalent.

MBtu—million Btu.

MEDEE—Modele d'Evolution de la Demande d'Energie.

MESSAGE—Model for Energy Supply Systems Alternatives and Their General Environmental Impact.

MeV—million electron volts, a unit of energy commonly used in nuclear and particle physics, equal to the energy acquired by an electron in falling through a potential of 10^6 volts.

MIP—molten iron process.

MPC—maximum permissible concentration.

mpg—miles per gallon.

mrem—milli-rem.

MSR—molten salt reactor.

mtce—metric ton of coal equivalent.

mtoe—metric ton of oil equivalent.

μm—micro-meter = 10^{-6} meters.

MW—megawatt, a unit of power, equal to 1,000,000 watts.

MW d/tU—megawatt days, thermal, per ton of uranium.

MW(e)—megawatt-electric, unit of the electric power of a nuclear reactor, as opposed to thermal power.

MWh—megawatt-hour.

NASA—National Aeronautics and Space Administration (U.S.).

NCAR—National Center for Atmospheric Research (U.S.).

NCRP—National Commission for Radiation Protection (U.S.).

NPT—Nonproliferation Treaty.

OAPEC—Organization of Arab Petroleum Exporting Countries.

OECD—Organisation for Economic Co-operation and Development.

OPEC—Organization of Petroleum Exporting Countries.

OTEC—ocean thermal electric conversion.

ppm—parts per million.

ppmv—parts per million volume.

PV—photovoltaic.

PWR—pressurized water reactor.

Quad—one quadrillion (10^{15}) Btu.

R—roentgen [NUCLEO] An exposure dose of x- or γ-radiation such that the electrons and positrons liberated by this radiation produce, in air, when stopped completely, ions carrying positive and negative charges of 2.58×10^{-4} coulomb per kilogram of air.

rad—the standard unit of absorbed dose, equal to energy absorption of 100 ergs per gram; supersedes the roentgen as the unit of dosage.

RBE—relative biological effectiveness. [NUCLEO] A factor used to compare the biological effectiveness of different types of ionizing radiation; it is the inverse ratio of the amount of absorbed radiation required to produce a given effect to a standard (or reference) radiation required to produce the same effect.

rem—a unit of ionizing radiation, equal to the amount that produces the same damage to humans as one roentgen of high-voltage x-rays. Derived from roentgen equivalent man.

rpm—revolutions per minute, a unit of angular velocity equal to the uniform angular velocity of a body which rotates through an angle of 360° (2π radians) so that every point in the body returns to its original position, in one minute.

SECURE—Swedish Nunclear District Heating Plant Study.

SIMA—economic and energy demand model for developing regions.

SIMCRED—Simulation Model based on Cross Country Regressions for Energy Demand.

SPE—solid polymer electrolyte.

SPI—Siberian Power Institute (USSR).

SSP—solar satellite power.

SSPS—solar satellite power station.
STEC—solar thermal electric conversion.
SWU/yr—separative working units per year.
TBR—thermal breeder reactor.
tce—ton of coal equivalent.
tC/yr—tons of carbon per year.
THTR—thorium high temperature reactor.
TVA—Tennessee Valley Authority (U.S.).
TW—terawatt, a unit of power, equal to 10^{12} watts, or 1,000,000 megawatts.
TW(e)—terawatt-electric.
TWh—terawatt-hour.
TW(th)—terawatt-thermal.
TWyr—terawatt-year.
TWyr/yr—terawatt-year per year.
UNCTAD—U.N. Council on Trade and Development.
UNEP—United Nations Environmental Programme.
USEPA—U.S. Environmental Protection Agency.
USNRC—U.S. Nuclear Regulatory Commission.
V—volt, the unit of potential difference or electromotive force in the meter-kilogram-second system, equal to the potential difference between two points for which one coulomb of electricity will do one joule of work in going from one point to the other.
VR—Voronezh reactor.
WAES—Workshop on Alternative Energy Strategies.
WEC—World Energy Conference.
WELMM—acronym of Water, Energy, Land, Materials, and Manpower.
W/m^2—watt per square meter.
W_p—watts peak.
Wt %—weight percent.

AUTHOR INDEX

SUBJECT INDEX

PROFILE OF THE INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS

The International Institute for applied Systems Analysis (IIASA) came into being officially on October 4, 1972. On that day, representatives of distinguished scientific bodies from 12 nations gathered at The Royal Society in London to sign its Charter. But the signing was only the last of several major steps in an international cooperative effort that had begun much earlier.

Another critical meeting had taken place in 1967, when two men met in Moscow and agreed that their nations would work to establish an international scientific institution. They were McGeorge Bundy, former national security adviser to President Lyndon Johnson of the US, and Professor Jermen Gvishiani, Deputy Chairman of the State Committee for Science and Technology of the USSR Council of Ministers. The idea that brought them together had been proposed by President Johnson, who had hoped that such an institution could serve as a way to bring peoples of the world together.

Progress came slowly. For more than five years, spurts of negotiation were followed by long periods of seeming inactivity. Yet progress was being made. During those years, ten more nations joined the discussions, and the Charter gradually emerged. It was a document designed to accommodate many points of view, and its provisions have shaped IIASA's evolution.

Principal Features of IIASA

A key provision of the Charter makes IIASA international without being governmental. Its members are not nations, but scientific institutions from each participating nation. This structure helps keep IIASA free of international political pressures.

IIASA's founders reached another important agreement on the name of the institute. With "systems analysis," they wanted to convey the impression that research at IIASA would apply modern analytic tools to address major problems of international concern. The word "applied" was meant to stress IIASA's concern with practical, real-life issues. "Applied Systems Analysis" is deliberately general—allowing the Institute to deal with a wide range of topics.

The agreement reached on financing the Institute was also important to its future. The scientific organizations from the US and the USSR had taken leading roles in establishing the Institute. They agreed to pay the largest amounts, which would be equal. Each of the scientific bodies from other nations would contribute smaller but equal amounts, 15 percent of the larger contributions. In 1980, the contributions of the two large category A members were some 32 million Austrian schillings. Category B members, currently 15 in number, each contributed some 4.8 million Austrian schillings in 1980.

Two other important decisions by the founders helped establish IIASA.

One was the decision to make English the Institute's sole official language, thereby facilitating working relations among its international staff. The other was to accept an offer by the Austrian government to locate the Institute at Schloss Laxenburg, a former summer residence of the Habsburgs, 16 kilometers south of Vienna. The palace has been generously restored and adapted to IIASA's needs by the Austrian authorities, who have made it available to the Institute for a symbolic rent of one schilling per year.

The Institute's governing body is its Council, comprising one representative from each National Member Organization (NMO). The Council approves the principal research directions and budget, sets financial and management policies, deals with questions of membership, and appoints the Director and Deputy Directors. The Chairman of the Council is Professor Jermen Gvishiani.

The Director of IIASA, its chief executive officer, is responsible for formulating, managing, and administering all the Institute's activities, including preparing the budget and research plan and implementing the plan after Council approval. Under the guidance of the Council, he represents the Institute in dealings with research agencies, governments, and multinational bodies, and he is also an ex-officio member of the Council. The Director of IIASA is Dr. Roger E. Levien, formerly of the Rand Corporation in the US.

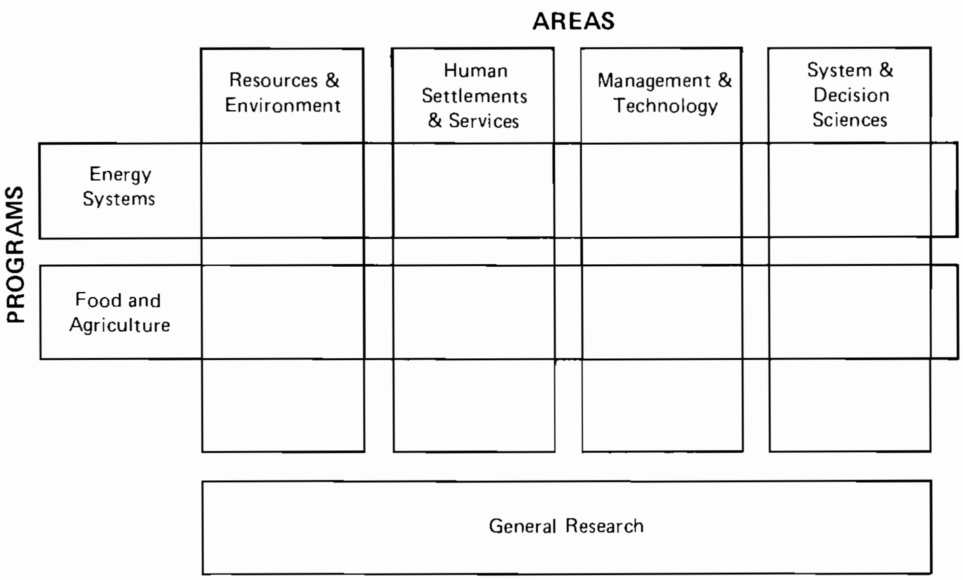
Structure of Research Activities

In 1973, IIASA's first Director, Professor Howard Raiffa from Harvard University in the US, welcomed the first scientists who came to Laxenburg to work on six applied projects (energy systems, water resources, management of urban systems, biological and medical systems, ecological systems, and integrated industrial systems) and three supporting projects (methodology, computer science, and design and management of large organizations). By the end of IIASA's second year—just 16 months after the arrival of the first full-time scientists—the Institute had established a full complement of research activities and a scientific staff of 80.

In 1975 IIASA's second Director, Dr. Levien, proposed a two-dimensional "matrix" organization for the Institute's research activities. The horizontal rows of this matrix represent the two major cross-cutting research Programs, which address major international issues. The *Energy Systems Program* examines strategies, at global, regional, and national levels, for achieving the transition from oil- and gas-based energy systems to those based on more sustainable sources. The *Food and Agriculture Program* is concerned with the development of effective national food policies and the international interactions among them. Each of these Programs has a four to five year lifetime. Programs on regional development, industrial change, and risk and hazards are under consideration.

The programs draw upon the broad range of talents that reside in the four continuing research Areas, represented by the vertical columns in the matrix. The *Resources and Environment Area* studies problems concerning the ex-

Figure 1. IIASA's research matrix.



ploitation of the earth's resources and the protection of its environment. The *Human Settlements and Services Area* investigates the earth's population, its distribution, and its needs for resources and services. The *Management and Technology Area* pays attention to the design and operation of organizations and the prospective development and consequences of technology. The *System and Decision Sciences Area* applies and develops the mathematical and computational tools that assist in the investigation of complex systems or decision problems. For activities that do not fit into the matrix, there is a *General Research* category.

IIASA's Mandate

IIASA has three principal objectives, which derive from the aspirations of its founders and the wishes of its members:

(1) To promote international collaboration, understanding and cooperation by bringing together scientists of different disciplines and nationalities for work on problems of concern to all mankind and by creating networks of scientific institutions for collaborative research.

(2) To advance both systems analysis and the sciences contributing to it.

(3) To apply IIASA's findings to problems of international importance by providing decision makers with relevant information and appropriate tools for dealing with these problems.