# THE COMPARISON OF ENERGY OPTIONS: A METHODOLOGICAL STUDY

Report by the Energy Systems Program Group
of the International Institute for
Applied Systems Analysis

Wolf Häfele, Program Leader

Prepared for the United Nations Environment Programme

Status Report
SR-80-3
November 1980

International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria Telephone: 02236/71521*0

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## PREFACE

Very soon after the Energy Systems Program (ENP) of IIASA had been set up to work on the energy problem, close links were established with the United Nations Environment Programme (UNEP) in Nairobi. UNEP had recognized at an early stage our generation's worldwide responsibility to secure and preserve a sound and sustainable environment for mankind and the necessity for responsible action. This perspective coincided with the aims of IIASA's ENP, which was confronted with the task of elaborating a concept permitting us to provide a world of 8 billion people or more with enough energy to live under economically and environmentally acceptable and fair conditions.

This close cooperation with UNEP, therefore, has been a great opportunity for us at IIASA; it has not only helped us to gain new insights but has also been a tremendous stimulus to our work in general. We recall this collaboration with high appreciation and sincere gratitude.

The present report summarizes the major portions of the research work of some 140 scientists from over 19 countries who have contributed to the long-term global energy study carried out by the Energy Systems Program at IIASA. Above all it highlights those elements of research which are of particular interest and relevance to the joint UNEP/IIASA Project "The Comparison of Energy Options: A Methodological Study."

In addition, this status report goes beyond the content of this project in that it also attempts to place the project-related research into the context of the other findings of the Program. (The overall findings of its study on the global energy system, Phase I, are fully reported in "Energy in a Finite World," report by the Energy Systems Program Group of IIASA, Wolf Häfele, Program Leader, to be published by Ballinger Publishing Co., Cambridge, Massachusetts, U.S.A.) Thus, in a synthetic manner, it describes the general global long-term concept of the energy problem that has evolved in IIASA's Energy Program over the past eight years.

The reader will be offered an overview in the Introduction to this report (Chapter 1). This chapter illustrates the evolution of the work performed under the UNEP/IIASA contract and its links to the evolution of ENP's findings in general, and guides the reader to the substantive qualitative and quantitative results obtained.

The chapters on energy demand and on energy options and resources (2 and 3) lay the groundwork for comparing technological strategies in an appropriate quantitative framework. This framework results from anticipated demographic infrastructural and economic developments as well as from the physical conditions of the globe's energy resources and technological progress to harness them at the scale needed.

Some of the "human constraints" to expanding purely technical solutions of the energy problem are investigated in Chapter 4 on risk and health.

Two global energy demand/supply scenarios are detailed in Chapter 5 on energy strategies. These scenarios interlink qualitatively the technical possibilities of extending the present global energy system within a range of economic evolutions in a principally stable and cooperating world.

Conclusions from the analysis and comparison of long-term global energy options are finally drawn and assessed in a synthesis chapter (6).

The results reported here could not have been achieved without the aid and assistance of many institutions and individuals whose support we gratefully acknowledge.

Wolf Häfele
Deputy Director,
Program Leader, Energy Systems Program

## NOTE ON THE AUTHORSHIP OF THIS REPORT

No single author can be named for the present report as it represents a synthesis of the work of all 140 scientists involved in the Energy Systems Program. The difficult and demanding task of compiling, extracting, and presenting the results as well as actually formulating the text of the report was accomplished by Hannes Porias, former Assistant to the Deputy Director of IIASA, with the help and guidance of Wolfgang Sassin, IIASA Research Scholar. The editing and final polishing was provided by Maria Bacher-Helm. Last but not least, a word of thanks must go to Alan McDonald, who devoted much effort to checking the contents of this paper from a substance point of view.

Wolf Häfele
Deputy Director,
Program Leader, Energy Systems Program

# ABSTRACT

This report examines the dimensions of the world's energy problem as it might evolve over the 50 years from 1980 to 2030. The potential contributions to the global energy systems during these 50 years and beyond that might be made from renewable energy resources, from fossil resources (including especially coal), from the solar resources, and from nuclear resources are explored. The impacts of energy technologies on human health and the global environment are addressed. In particular the problems associated with analyzing and managing these risks are examined. Two quantitative, internally consistent scenarios of feasible balances between worldwide energy supply and demand during the next 50 years are reported in detail. Certain global environmental impacts associated with these scenarios are also determined. Finally, the methodological approach of this study is reconsidered and assessed by a critical comparison of the conclusions drawn and their wider implications--implications which must also be considered in energy systems planning and for policy decisions.

Contents

# 1 INTRODUCTION: THE ENP AND THE IIASA/UNEP CONTRACT IN THEIR DYNAMIC CONTEXT

## OVERVIEW

*How can the world move from its present energy system, relying on cheap but scarce fossil resources, to one sustainable over the long run?* This question stood at the beginning of the energy activities of the International Institute for Applied Systems Analysis (IIASA). It prompted a global and long-term orientation of IIASA's Energy Systems Program (ENP) right from its start.

This approach takes into account that the world's energy system is global in nature already now, with strong interdependencies between developing and developed regions. Out of a worldwide energy consumption of approximately 8 TWyr/yr, more than one third is provided by hydrocarbon export to the industrialized countries. These amounts would not be accessible without the help of a sophisticated technological system and through large investments by the industrialized nations.

The time scale appropriate for such investigations appears to be a period of 15-50 years. Studies by Marchetti et al. (1978, 1979) clearly point to the fact that it takes several decades for a new primary energy source to capture a significant share of the energy market (Figure 1). Furthermore, 50 years is not very long for a radical change to take place, considering, for example, the time span of a human generation to be 30 years, or the lifetime of a nuclear reactor to be on the order of 20-30 years.

Yet it was clear to the ENP Group from the onset that this broad orientation in space and time necessitated development of an entirely new approach to the question of energy; the conventional scientific tools available, which involve a high degree of data disaggregation, did not appear suitable as a main line of study.

Therefore, ENP first attempted to *conceptualize* the energy problem, identifying its essential components and their interrelationship. The initial result is the concept outlined in Figure 2. Accordingly, one sets out to ask: how much energy is

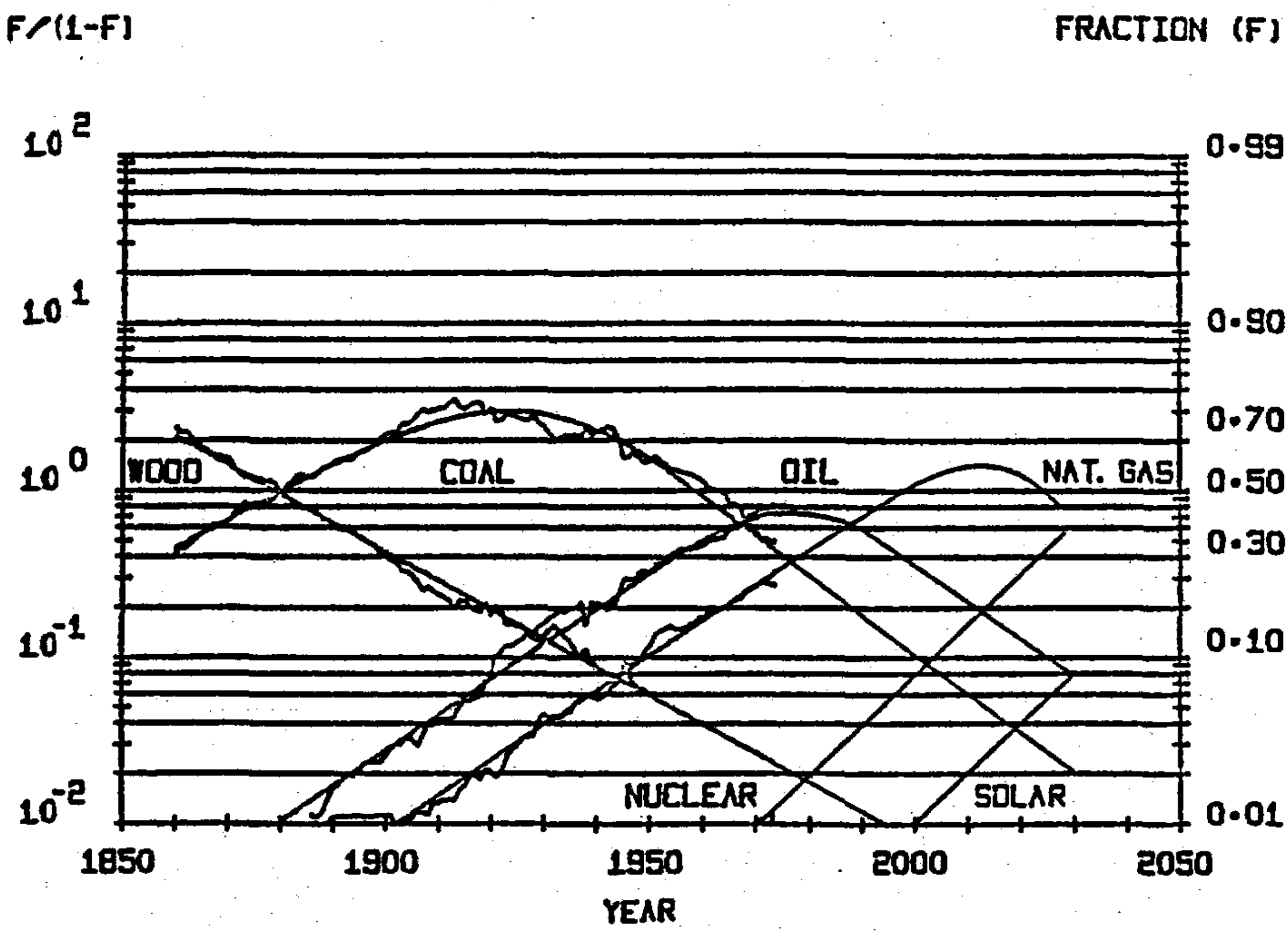



FIGURE 1 Global primary energy substitution, 1860-2030. Logarithmic plot of the transformation F/(1-F) where F is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show where energy sources follow logistic model substitution paths. Source: Marchetti and Nakicenovic (1979).

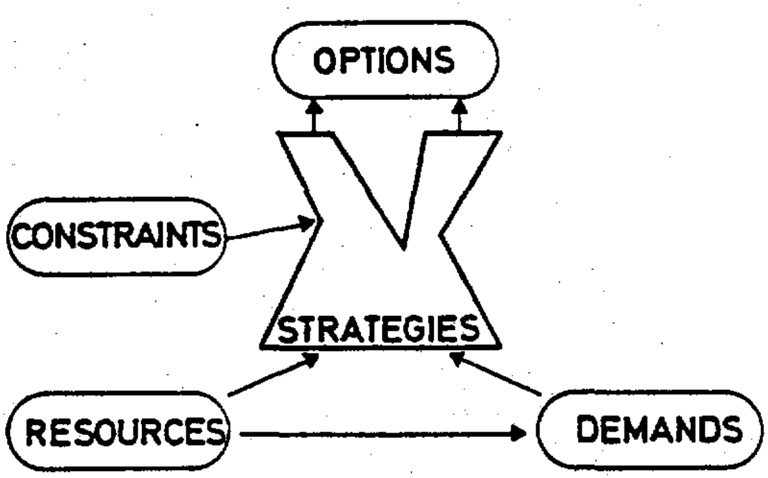



FIGURE 2 An approach to energy systems.

available in the world; where, in what form, and when; and how can it be obtained? Or, in short, what *energy resources* can we rely on? The answer is closely related to another question: what is the size of the globe's energy resources, and how does this volume compare to the actual needs? Thus *energy demand* comes to be the appropriate yardstick for the availability of resources as well as the principal force driving the energy system; the vexed question is whether this demand can at all be met by the supply. *Energy strategies* give the answers. Such strategies, conceived to strike a balance between expected demand and potential supply, describe possible pathways into an energy future. Comparing such paths helps to identify alternative *energy options*. Finally, this concept recognizes *constraints* limiting the scope of possible choices.

This was, in brief, ENP's comprehension of the energy problem at the time when the contract on "The Comparison of Energy Options: A Methodological Study to the United Nations Environment Programme" was proposed in 1975. The concept described above was adopted to serve as the main structure of approach. The study, which began in 1976, is subdivided into several tasks: TASK 1 of the UNEP/IIASA study relates to energy demand; TASK 2 is concerned with energy resources and their accessibility; TASK 3 centers on the analysis of two constraints, namely risk and health; TASK 4 studies the balancing supply and demand. The present paper closely follows this setup; it reports on the work done and concludes with an attempt at synthesizing the results obtained in the various tasks.

For an appraisal of this study, one may also want to know the amount of work put in and the type of support received. In fact, the results to be presented are based on an effort totaling almost 10 years of work or some 200 person-years. These results are an outcome of work that, besides the main support it has received by UNEP and IIASA, has also been sponsored by several other organizations, such as the Ministry of Research and Technology and the Volkswagenwerk Foundation, FRG; the Austrian National Bank; and the Electric Power Research Institute and the Ford Foundation, USA. It has involved active participation by more than 20 international and national institutions all over the world.

The second step for ENP venturing to grasp the energy problem was to qualitatively assess the various elements of the energy system. First the approach outlined in Figure 3 was developed. It indicates that, unlike the procedure in other studies, our approach was not to project the present development into the future. Rather, the goal was first to discern the potential long-term requirements and possibilities and only then to try to conceive suitable pathways into the long-term future.

During this phase, lasting until the turn of 1977/78, our efforts focused on examining the potential of the various energy technologies and their systems implications. Before the general backdrop of investigations on resource availability, task forces looked into questions of nuclear energy and coal, and other options such as solar energy were evaluated. Consideration of major constraints to the introduction of energy technologies included the study of issues relating to risk, health, standards, and the climate. For our climate work until the end of 1978, UNEP awarded us a contract on "A Systems Study of Energy and Climate".

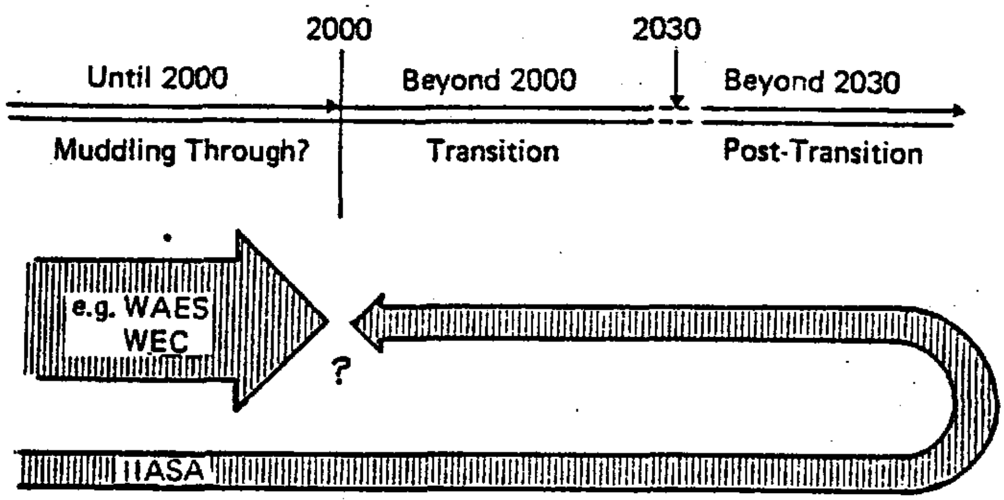



FIGURE 3 Time phases of energy.

The question of energy demand was approached from various vantage points. A first-order approximation of the analysis clearly indicated that more formal tools would have to be developed if long-term energy strategies were to be designed. Then a suggestion by Academician Styrikovich, Member of the Academy of Sciences of the USSR, was taken up to study the evolution of the energy systems in several world regions and their aggregation into a global strategy. Thus, in parallel to the qualitative work under way in the various tasks, a methodological activity was initiated to produce a set of models capable of handling long-term, world-regional energy strategies.

A prerequisite for dealing with such a group of models in a sensible way was to develop a "mental model," on the basis of which the qualitative findings of the Program could be translated into a comprehensive and consistent vision of the future. This first synthesis was completed by the end of 1977. It was presented to the World Energy Conference in Istanbul in the format of a handwritten 35 TWyr/yr demand and supply scenario for seven world regions for the year 2030.

This reference scenario--the figures of which were to be understood as quantitative indicators of qualitative conclusions--led us to one fundamental observation: that it is unrealistic to expect any single energy technology to be capable of meeting the overall energy requirements of the coming 50 years. On the contrary, all the supply technologies that can prudently be used will have to be employed to meet the demand. Conservation, reduced economic growth, etc. may lower the demand, but will not solve the energy crisis in the long run; while it would seem easier to strike the supply and demand balance in this case, the price to be paid in terms of overall economic development will be high. And still, every supply source will be needed to meet the energy demand.

This first assessment was the point of departure for the conception and development of two detailed scenarios that were to provide a consistent quantification of our qualitative visions. This activity took up all of 1978 and 1979. In 1978, the methodology and, in particular, the model set was tested and first approximations were computed; in 1979 the runs were completed and an overall qualitative and quantitative synthesis was undertaken.

The focus of that third and last stage was on the model set. These models, which are interlinked but individually operable, serve to determine a consistent view of the development of the energy sector in relation to the general economic development in the various world regions. "World region" in this context should be understood in an economic sense rather than in a strictly geographical sense. Seven such regions were identified that allow for a certain amount of disaggregation, in order to reflect specific and particular conditions, and that take account of the constraints due to the necessary large amounts of data. The regions are (see Figure 4):

- I North America
- II USSR and Eastern Europe
- III Western Europe, Israel, South Africa, Oceania and Japan
- IV Latin America
- V South and East Asia, Africa excepting both South Africa and the oil producers in North Africa
- VI The Middle East and North African oil producers
- VII China and the other centrally planned Asian economies.

Figure 5 is a schematic representation of the model set. On the basis of scenario projections of the economic development and of projected population growth, the energy demand model MEDEE (modèle d'évolution de la demande d'enérgie) computes the secondary energy demands, using assumptions on lifestyles, technical efficiencies, etc. The linear programming model MESSAGE (Model of the Energy Supply System and its General Environmental Impact) then determines the optimal strategy for meeting the demand. Buildup rates, costs, and resource availability act as constraints. IMPACT, an input-output model, finally determines the investment, labor and materials requirements of the strategy. These data are compared with the initial scenario assumptions, the latter are reviewed and by way of additional iterations the loop is completed. By this iterative procedure, provision is made for the consistency of the scenario data obtained. For more information on the models, see the respective chapters.

This methodological approach aims at four objectives:

1 to study the *long-term, dynamic, and strategic dimensions* of regional and global energy systems;
2 to explore the *embedding of future energy systems* and strategies into the economy and to some extent into the physical and societal environment;
3 to develop a *global framework* within which the global implications of long-term regional or national energy policies can be assessed;
4 to evaluate *alternative strategies*--to compare options--in physical and technological terms, including their economic impact.

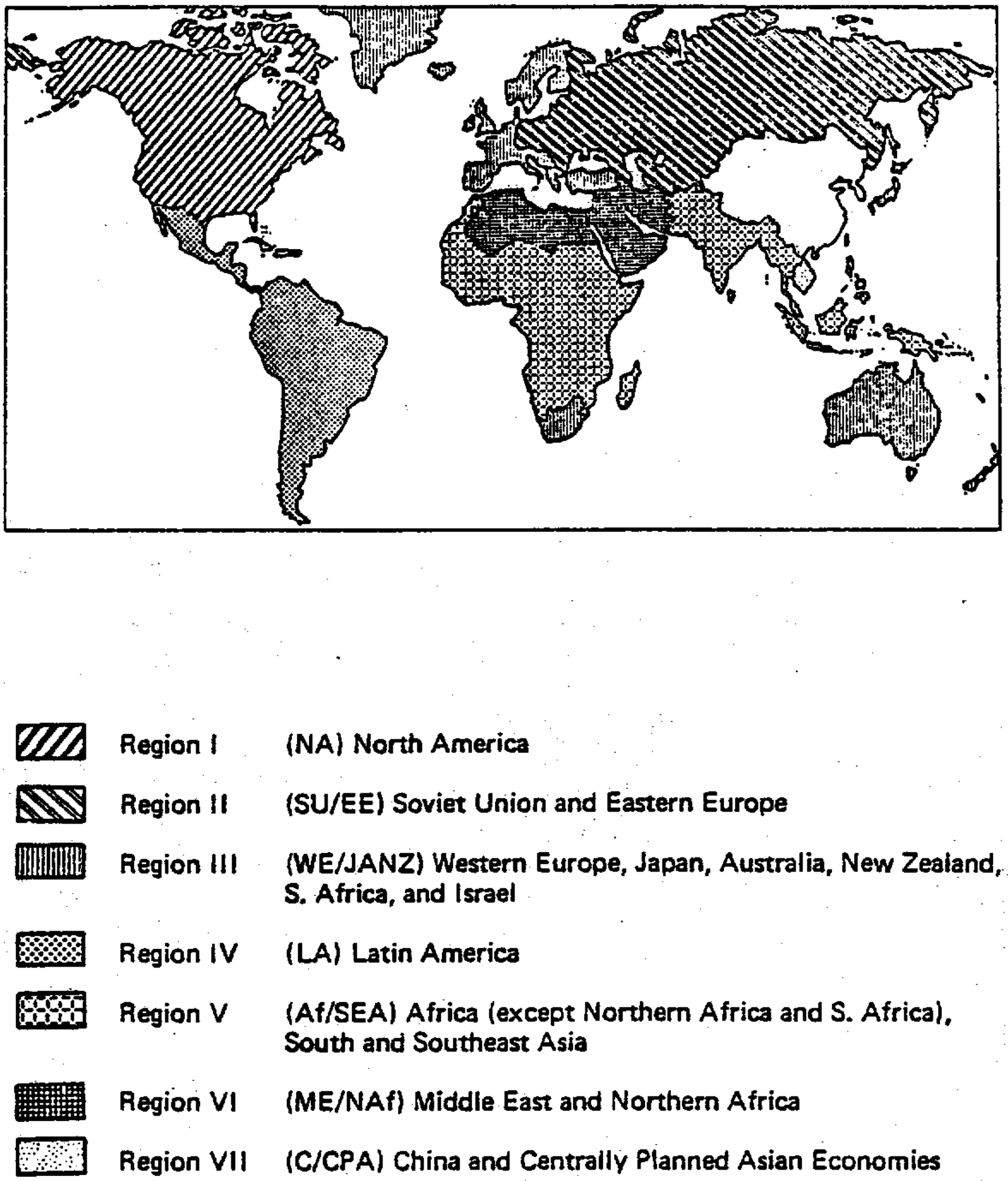



FIGURE 4 The IIASA world regions.

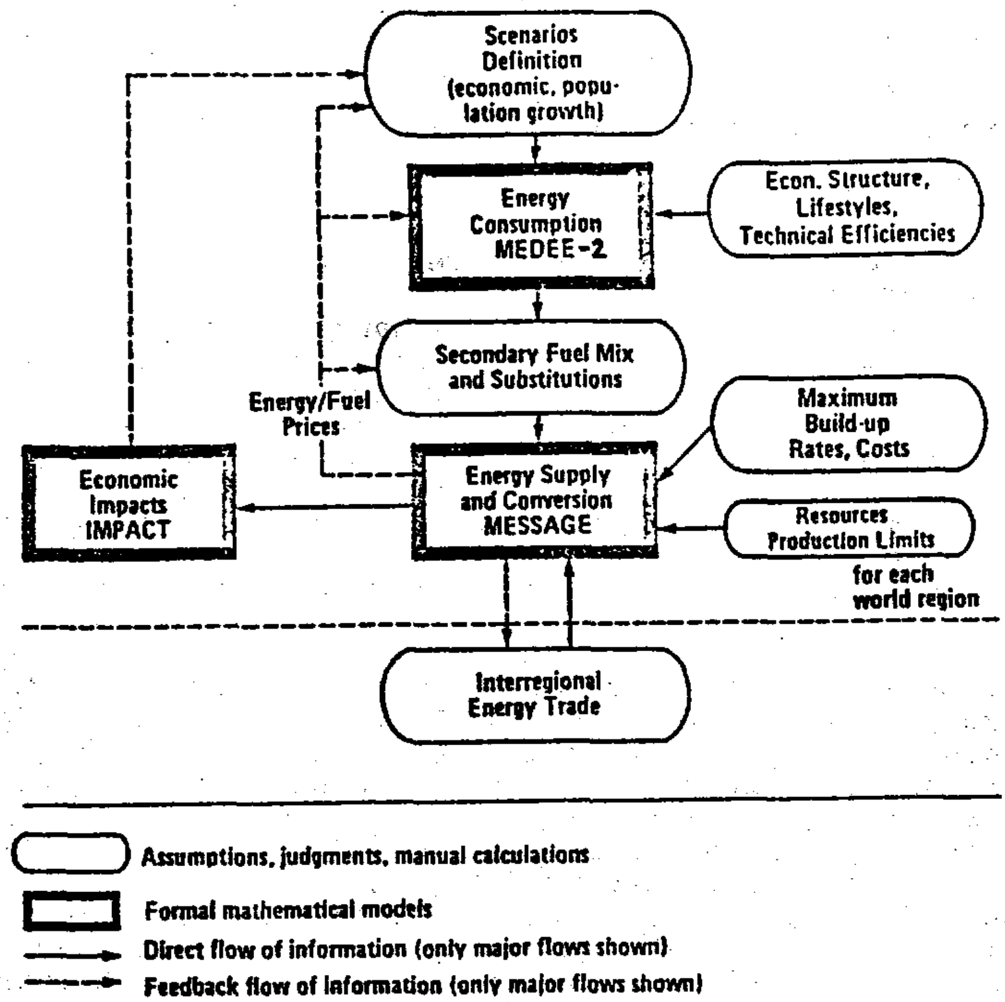



FIGURE 5 IIASA's set of energy models: a simplified representation.

It would be wrong, however, to expect the model set to deal with all the important issues of the energy problem or to consider the model loop to be an automatic procedure. In some respect, comprehensiveness had been traded in for flexibility and manageability of the models. Generally speaking, models are instruments that are limited in scope by definition. Modeling can certainly not substitute for judgment, intuition and common sense. Thus, a lack of comprehensiveness and the necessity for operator intervention are features purposely built into the modeling loop. They allow one to retain control and understanding throughout the procedure and to avoid the fallacy of ascribing to the models a false sense of "totality."

The set of models *does not:*

1 *take* into account most institutional, societal, and political issues;
2 *predict* energy pricing policies, market fluctuations, interest rates or multisectoral economic dynamics;
3 *focus* on great, multisectoral detail of useful energy demand;
4 *treat* technological details of small scale;

5 *simulate* carefully the full nuclear fuel cycle or questions of safety or arms control;
6 *evaluate* the effects of specific tax, quota, regulatory and financial incentive policies in detail.

The set of models *does*:

1 *describe* the potential of a reasonable evolution of global and regional energy systems;
2 *capture* the long-term, slowly changing macroeconomic characteristics of developed and developing economies;
3 *forecast* aggregate final energy demand (fuels);
4 *model* the evolution of the energy supply, conversion and distribution systems and, in so doing, incorporate resource, capital cost, environmental, and some political constraints;
5 *calculate* the economic impact--capital, manpower, materials etc.--of alternative strategies;
6 *produce* consistent scenarios on global and world-regional levels.

In summary, the work accomplished by the Energy Systems Program Group (and with it the IIASA/UNEP contract) has undergone three stages: the conceptualization providing the framework for the study; the qualitative assessment necessary to understand long-term systems implications of energy production and consumption; and the translation of this vision into quantitative scenarios, which indicate pathways for the next 50 years. Thus the conditions for an acceptable future have been found to be the following: in the next half a century, the world will have to switch from fossil fuels that are easily accessible and scarce to fuels that are more abundant but less easily accessible. At the same time the groundwork will have to be laid for the post-2030 transition to energy systems that are capable of providing large amounts of energy over very long periods of time without exhausting the earth's natural and human resources.

# 2 ENERGY DEMAND

## UNDERSTANDING ENERGY DEMAND: THE SETTING

Today's energy discussion centers more and more on the issue: how much energy does our world require to subsist? The discussion is fierce and often led with much bitterness. A broad range of figures is quoted, but there is no widely accepted estimate. Consensus is sadly lacking.

The reason for this strong and disruptive divergence lies primarily in the fact that all predictions of energy demand are based on fundamental value judgments. Ideological, political, ethical and other inclinations largely contribute to the development of views as to what future society should be and how it should be run; and on the basis of these societal perspectives, the assumptions on future energy demand are generally formulated. This process is in almost none of the cases explicit.

Still, even if we were able to create a common platform on which to plant our assumptions the problem would not be solved. If, supposedly, agreement could be reached on the services societies should provide, we still could not determine what the related energy demand would be. Theoretically, by way of a "Gedankenexperiment", it is possible to run a sophisticated and well developed economy with no energy use at all. C. Marchetti (see Häfele 1977) envisages a scheme (Figure 6) where the ocean thermal gradient utilized in a Carnot cycle procures compressed air, which in turn is used in a civilization center in order to move a car, for example. Accordingly, no energy is used but the entropy of the system is increased; what is consumed is a kind of "negative entropy".

Our economic systems rely, in the present as in the past, mainly on fossil resources which provide this "negentropy". Obviously, a technological scheme, such as the one outline above,

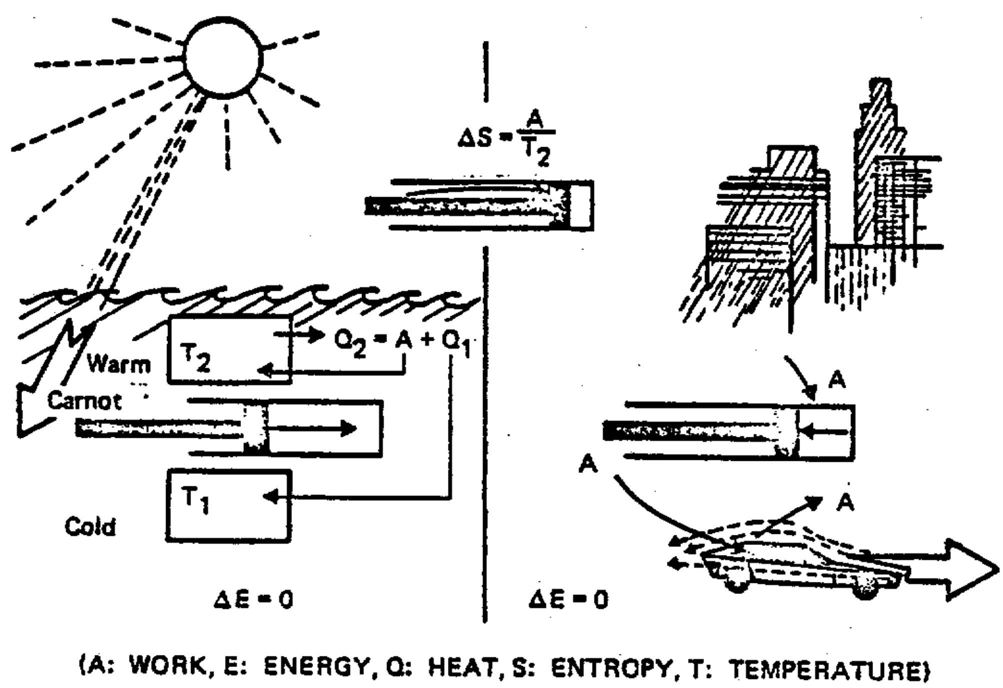



FIGURE 6 Negentropy city.

could not be implemented in practice for probably at least another century; yet Marchetti's notion indicates that there is no physical reason why economic growth should automatically presuppose growth of energy consumption. A decoupling of energy use from general economic activities is in principle feasible--by substitution of capital and man's know-how for energy use.

If one wants to follow the concept of substitutability one must admit that the development and introduction of new technical systems that use energy more efficiently has always been a very lengthy process. Take the progress in prime movers, for instance; it has taken decades to significantly improve the efficiency in real world systems (Figure 7). Because of the time requirement, we must therefore expect our infrastructures to remain qualitatively the same in the foreseeable future.

Assuming the present patterns to persist, what then is the related energy demand?

W. Sassin (1979) has in this context examined in some detail settlement patterns and related energy densities, arriving at some surprising results. As Table 1 shows, the difference in energy consumption between India and the F.R.G. results primarily from the lifestyles in rural areas. In urban areas, the per-capita energy consumption differs only by a factor of 2.5, and is even higher in India than in the F.R.G if compared in terms of energy consumed per $m^2$ of built up area. Independently of physical, climatic, and social conditions, conurbations appear to require worldwide an energy density of 10 $W/m^2$, and rural areas one of 1 $W/m^2$. Considering the spread of urbanization (Figure 8) particularly in the less developed countries, a drastic increase in energy demand must be expected. One can imagine an extreme case for 2050 of 8 billion people living in large conurbations that take up 10% of the continent's surface and consuming 80 Twyr/yr of energy--ten times as much as today.

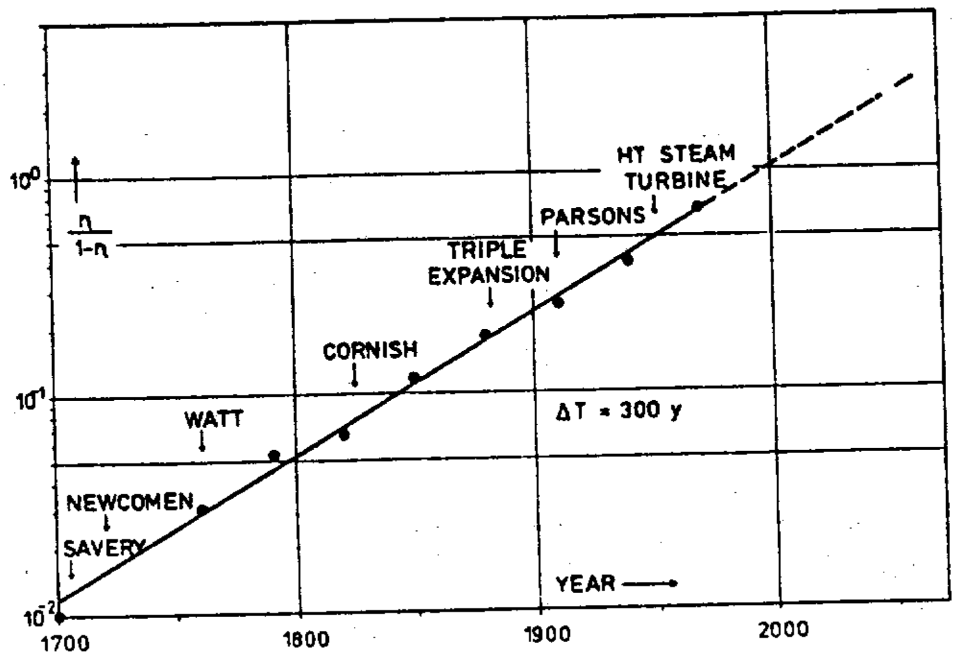



FIGURE 7 Efficiency of prime movers.

TABLE 1 Energy consumption densities in developing and developed countries.

| | Federal Republic of Germany | India |
|---|---|---|
| Population Density (cap/km$^2$) | | |
| Average | 245 | 168 |
| Urban[a] | 1,500[c] | 6,000[d] |
| Rural[b] | 150 | 135 |
| Specific Consumption (kWyr/yr, cap) | | |
| Average | 5 | 0.6 |
| Urban[a] | ≈5 | 2 |
| Rural[b] | ≈5 | 0.3 |
| Energy Consumption Density (W/m$^2$) | | |
| Average | 1.2 | 0.10 |
| Urban[a] | 7.5 | 12 |
| Rural[b] | 0.75 | 0.04 |

[a]Conurbations.

[b]Including farms and small towns.

[c]45% of total population.

[d]Represents 9% of total population.

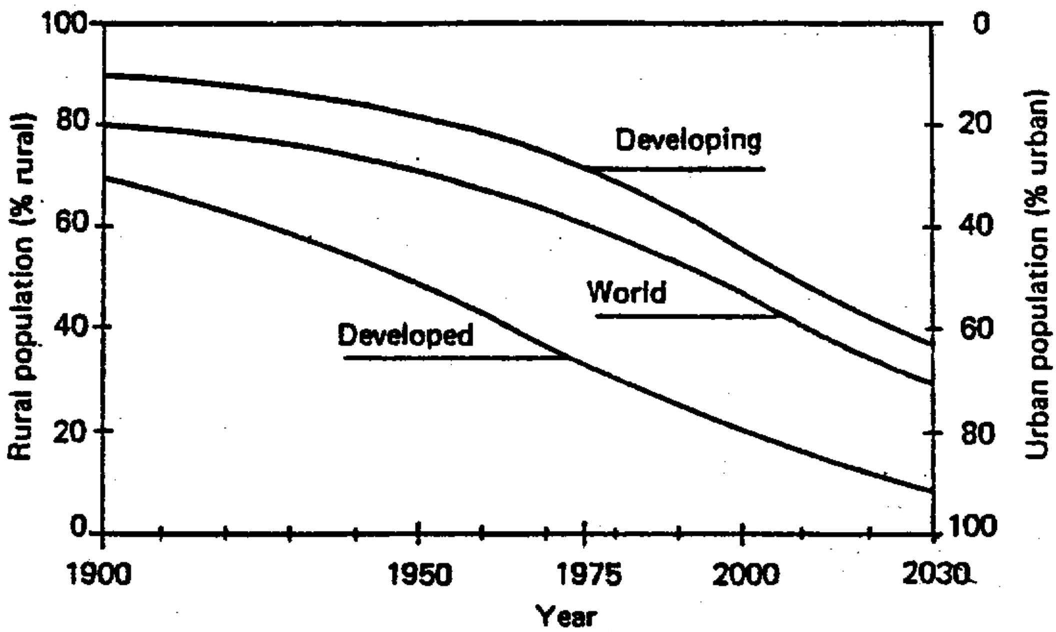



FIGURE 8 Estimated rural/urban population, 2030. SOURCE: Based on papers submitted to the UN Population Conference, Bucharest, 1974.

These broad outlines demonstrate the variety of possible options on energy demand.

However, without a clear indication of how energy demand might sensibly develop over the next decades it is impossible to tackle the energy problem. Indeed, resources, technologies, etc., must be measured against energy demand to judge their potentials meaningfully.

Therefore much effort has gone into our study of energy demand. In view of the complexity of the problem, we did not strive for precise predictions but aimed at estimating a bandwidth of reasonable developments that could be matched by adequate supply.

This task was complex. With no ready-made approach available, we started out to explore the methodologies available, in search of a method appropriate for treating the long-term energy problem.

## Approaches Explored

Various approaches to energy demand were examined and their scope and limitations identified, in the hope that this research would provide us with new insight into the many facets of energy demand.

The study's global orientation required the chosen method to be applicable to all the existing economic systems. First, an attempt was made to develop an econometric method suitable for studying market as well as planned economies.

The steps undertaken were: an analysis of individual Eastern and Western countries, a cross-section analysis of countries with the same type of economy, and an international analysis of countries with planned and market economies.

As a main result, this activity led to a better understanding of the present relationships between energy demand, price mechanisms, and general income. In particular, the study of elasticities was emphasized (e.g. Table 2).

Difficulties were above all encountered in the international analysis. For one, the econometric approach is data-intensive and adequate data are scarce. For another thing, the time element is difficult to grasp with econometric models, offering only a static view of economic and technological structures; and the related energy demand projections are necessarily a short time horizon, definitely less than 10-15 years.

The second approach used was *energy analysis* (Charpentier 1976). This was done to understand, from an engineering point of view, the changing of energy contents and requirements in goods, processes, and services. A typical result is illustrated in Table 3.

TABLE 2 Individual countries, long-run elasticities.

| Sectors | Factors | Elasticities | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | F | F.R.G. | I | NL | U.K. | U.S.A. | Comp. |
| Aggregate | Income | 1.17 (.09) | 1.15 (.13) | 1.25 (.13) | .48 (.34) | .67 (.09) | .32 (.10) | .84 (.11) |
| | Price | .10 (.26) | .70 (.32) | -1.30 (.21) | -1.20 (.25) | -.26 (.25) | -1.73 (.36) | -0.66 (.26) |
| Domestic | Income | 2.34 (.52) | 1.55 (.28) | .49 (.29) | .00 (.63) | 1.10 (.32) | .27 (.08) | .44 (.17) |
| | Price | .22 (.34) | -.68 (.35) | -1.40 (.25) | -1.30 (.33) | -.30 (.45) | -1.75 (.21) | -1.14 (.29) |
| Transportation | Income | 1.32) (.08) | 1.19 (.11) | 1.65 (.11) | 1.52 (.20) | 2.11 (.06) | 1.01 (.15) | 1.68 (.10) |
| | Price | -.15 (.13) | -.87 (.18) | -.60 (.40) | -.37 (.40) | -.15 (.21) | .13 (.47) | -.36 (.22) |
| Industry (except energy) | Income | .57 (.16) | 1.24 (.17) | 1.15 (.19) | 1.72 (.70) | .06 (.15) | .99 (.13) | .78 (.17) |
| | Price | -.38 (.16) | 1.03 (.25) | -.96 (.22) | .02 (.48) | -.73 (.31) | -.35 (.23) | -.30 (.23) |
| Energy | Income | .32 (.19) | -.13 (.27) | .25 (.30) | -.01 (.89) | -.94 (.17) | .36 (.07) | .18 (.14) |
| | Price | -.30 (.12) | .89 (.50) | -1.19 (.35) | -.52 (.49) | 1.28 (.73) | -.71 (.44) | -.33 (.25) |

NOTES: Comp. = composite estimate of coefficients. Upper figures = estimated coefficients. Lower figures in parenthesis = standard errors. Underlined figures = elastic coefficients (absolute value > unity).

TABLE 3 Total energy consumed per $ final output in French industry, 1971 (kWh(th); $ = 4.5 F).

| Sector | Total Energy Consumed per $ Output |
|---|---|
| Food industry | 2.20 |
| Building industry | 16.07 |
| Glass industry | 16.03 |
| Steel industry | 34.85 |
| Non-steel industry | 33.16 |
| First metal process | 11.44 |
| Electrical and mechanical industry | 6.01 |
| Chemical industry | 11.41 |
| Textiles industry | 2.92 |
| Paper industry | 5.62 |
| Miscellaneous | 4.93 |

This method provided us with insights into the relationship between lifestyles and energy consumption. It also helped us to formalize assumptions on technological progress and to introduce, to a certain extent, the concept of change into lifestyle scenarios.

Third, we attempted to quantify the relationship between energy consumption and economic development other than by simply interlinking aggregate GNP and energy consumption. To this end, *factor analysis* was used. The goal of this method is to sum up and reduce a given data set by extraction of factors that represent linear combinations of the original variables. In this way, groups of countries with similar structures can be identified and various development patterns can be studied.

These preliminary studies led us to adopt a scenario approach for our energy demand projections. A model, based on macroeconomic assumptions and lifestyle scenarios, was to be developed in order to compute the end-use energy demands in several economic sectors. The procedure was purposely held transparent; using clearly specific assumptions the method should enable us to iterate the modeling until a set of consistent and clearly understood energy demand data was obtained.

## Modeling Approaches

The modeling technique desirable for IIASA's global approach was to account for a great diversity of economic units. Several roads were explored, warranting a maximum chance of success.

For *developing* regions two models were considered. SIMA (*Si*mulation of *Ma*croeconomic Scenarios for Energy Demand) (Parikh and Parikh 1979), was adapted by J. and K. Parikh. It is an econometric model developed for India that distinguishes between the agricultural and nonagricultural sectors driving the energy sector. The model simulates economic growth paths for various policy scenarios, such as increasing foreign aid, improving efficiencies in capital utilization, varying rates of growth in the agricultural and nonagricultural sectors, and increasing public investment through higher taxes. For each policy, the energy requirements are computed by the model--with specific consideration of the needs for noncommercial energy--and the related capital and foreign exchange requirements are determined.

SIMA has been very useful as a prototype model for studying the demand of the developing world. Employing it with alternative economic scenarios has fostered our understanding of their special conditions and energy needs.

The other model on energy demand in less developed countries (LDCs) was SIMCRED developed by J. Parikh (1978). Future energy demand is projected with a simulation procedure, the parameters of which were estimated by a cross-country regression analysis of noncommercial and commercial energy consumption and of electricity consumption in connection with such factors as urban/rural population, agricultural/nonagricultural GDP, etc. (see Figure 9). For a simulation, urban and rural populations as well as GNP growth rates are specified exogenously. The model outputs are

- per-capita commercial energy demand;
- the ratio of commercial energy to noncommercial energy;

and

- electricity consumption.

SIMCRED served to produce benchmark figures in our early modeling stages.

MUSE (*M*odeling *U*seful *E*nergy) played a similar role. It was conceived by J.M. Beaujean and T. Müller to evaluate the useful and final energy demands in *developed* regions on the basis of lifestyle indicators, industrial activities, agricultural production, income, and energy prices. This model was purposely kept simple and transparent, and sophisticated techniques were shelved in favor of quick but comprehensive and easily understandable results. It basically consists of a set of energy accounting equations with coefficients obtained by regression analysis. As inputs, it uses lifestyle parameters (rooms per household, hot water demand, etc.), technical parameters (insulation coefficients, energy intensity of transportation, etc.), and economic indicators (GNP, transportation requirements, etc.). The outputs are data on useful and final energy demand per sector and per fuel. A later development was MUSEDEV, a version specifically oriented towards the study of LDCs.

All these efforts provided us with a background necessary for choosing an approach to energy demand which

- would be precise enough for the computerization of demand projections that were sufficiently detailed to serve as inputs to our strategies studies (see Chapter 5);
- but at the same time would not be too data intensive, so that all the regions under study could be treated.

B. Chateau and B. Lapillonne of the Institut Juridique et Economique de l'Enérgie of the University of Grenoble, France, had developed a general approach for assessing the long-term evolution of energy demand. This approach is based on the following steps:

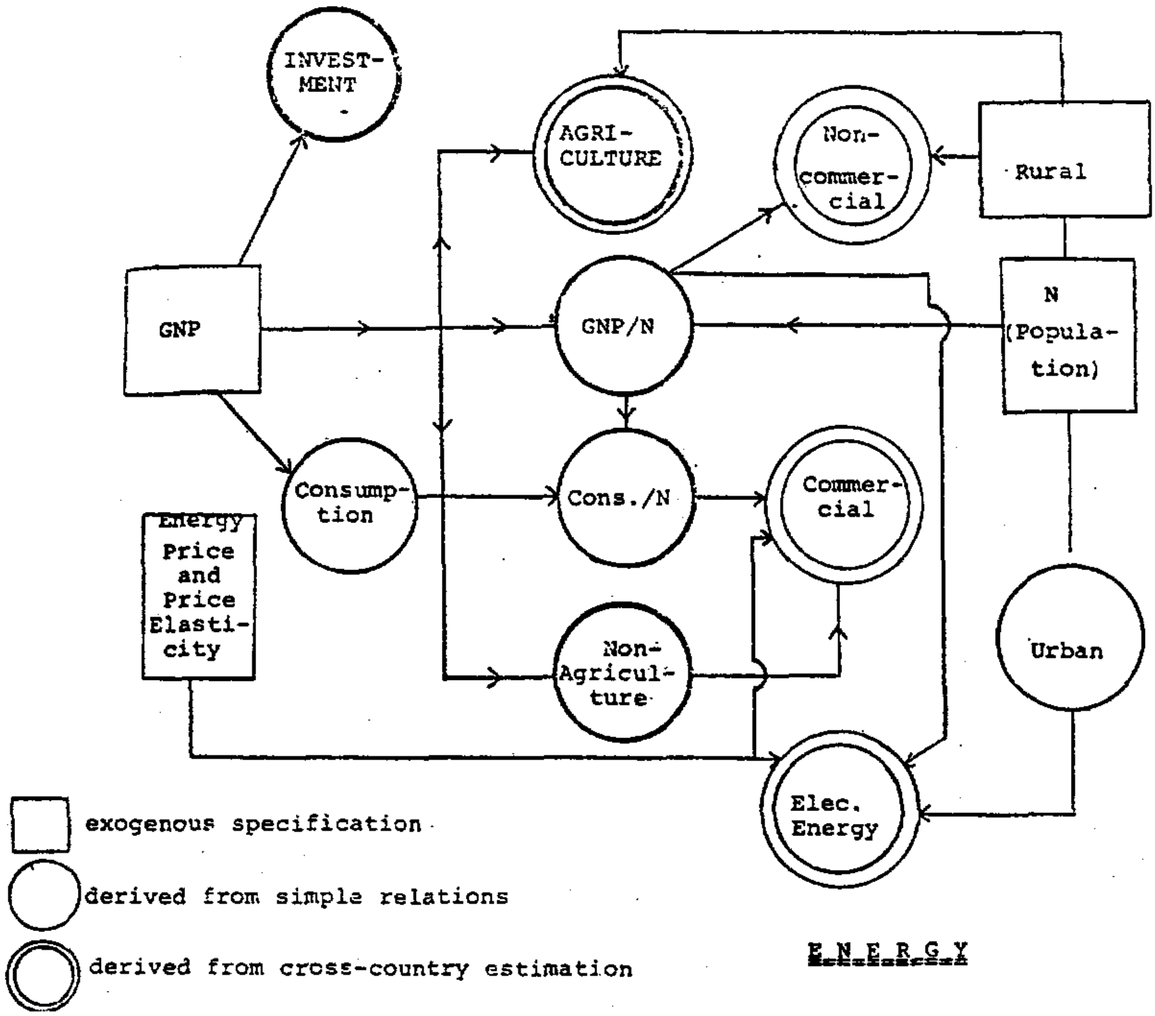



FIGURE 9 Schematic diagram of the energy demand model (SIMCRED), J. Parikh (1978).

1 Disaggregation of the total energy demand into a multitude of end-use categories or sectoral demands;
2 Analysis of the main determinants governing the long-term evolution of energy demand for each end-use category;
3 Organization of those factors in a structure which permits consideration of intersectoral demand dependencies; and
4 Use of a simulation model based on this structure, whose determinants are in part endogenous to the model and in part exogenously treated as scenario variables.

This methodology leads to a very detailed and precise analysis of energy demand but is extremely data-intensive. Therefore, in cooperation with the energy/environment study group of Professor W. Foell at IIASA and the University of Wisconsin, U.S., this method was adapted to our requirements by B. Lapillonne and M. Müller. The model developed was called MEDEE-2 (*M*odèle d'*E*volution de la *D*emande d'*E*nérgie ) (Lapillonne 1978).

In designing this model we pursued several objectives. First, it was to reflect structural changes affecting long-term energy demand, such as the evolution of social needs (e.g. growth

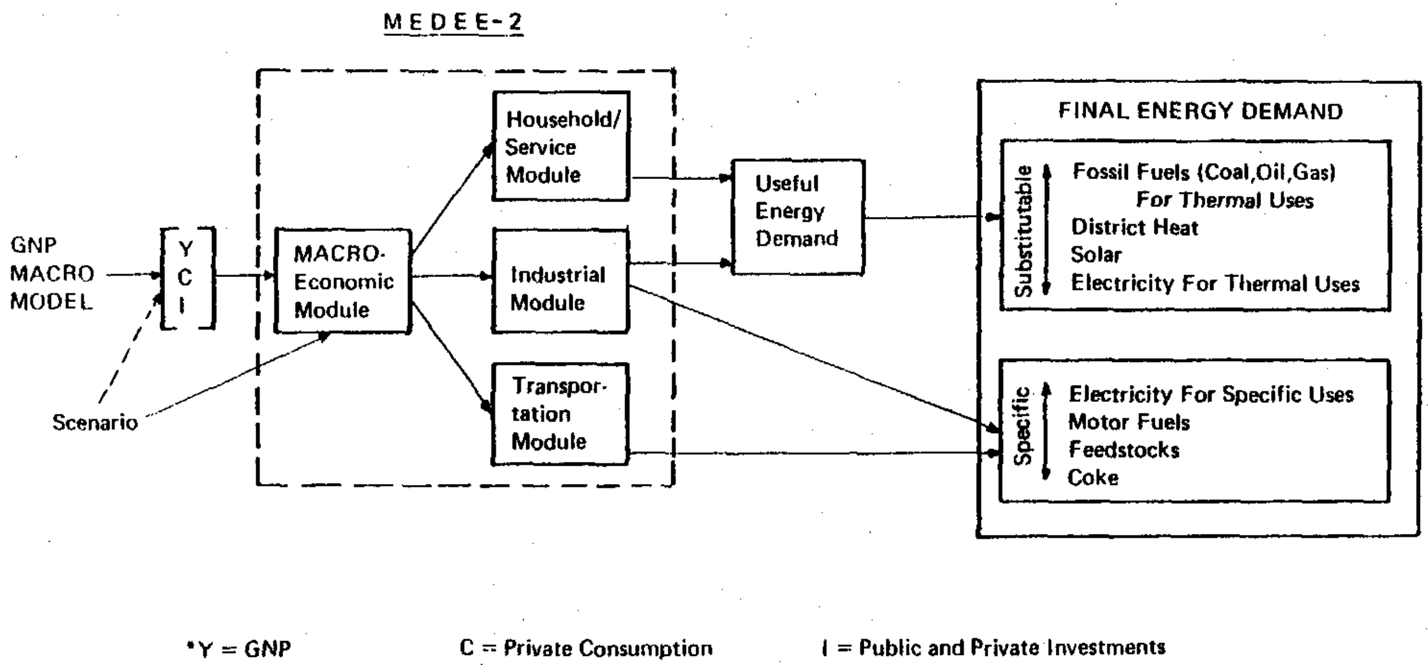



FIGURE 10 General structure, input, and output of MEDEE.

and saturation), government policies, energy prices, and technology. Second, the model was to be applicable to different economic systems. Finally, the model output should include information about the potential market for each secondary energy source, so that an optimal mix of energy supply technologies could be determined.

Figure 10 sketches the model structure. On the basis of a scenario projection of GDP and GDP expenditure, a simple macroeconomic module determines the contribution to GDP of various economic sectors.* Six major sectors are considered:

- agriculture
- construction
- mining
- manufacturing:
  - basic materials
  - machinery and equipment
  - nondurables
  - miscellaneous
- energy
- services

Besides these macroeconomic assumptions, the scenario also specifies elements that cannot be extrapolated from the past, but which characterize the long-term evolution of economic, social, and technological structures.

Three demand modules calculate the energy demand for the transportation (freight/passenger), industrial (agriculture, construction, mining, manufacturing) and household/service sectors. The energy demand of the "productive" sectors is directly or indirectly related to the GDP contribution of these sectors; the energy demand of the "consumptive" sectors is related to physical indicators. For substitutable uses (essentially thermal uses), the basic energy demand is calculated in terms of useful energy; additional assumptions concerning the penetration of various energy sources in their potential markets and their end-use efficiencies are required to determine the final energy demand. For nonsubstitutable uses, the energy demand is directly calculated in terms of final energy. Table 4 summarizes the sectoral energy end-use categories distinguished in MEDEE-2.

MEDEE-2 is a flexible instrument allowing the explicit incorporation of assumptions on long-term future aspects of lifestyles and societies of the various world regions. It has helped us transcribe qualitative "visions" of energy needs into quantitative values of energy demand. MEDEE-2 is therefore a tool for calculating rather than for forecasting the evolution of energy demand conceived in a scenario.

## The Two Scenarios: Basic Features

The Energy Systems Program has been aware of the pitfalls involved in the interpretation of results from a methodologically sophisticated procedure. Therefore, it has complemented its demand studies by attempts at gauging the order of magnitude of global energy demand through simple "back of the envelope" estimation.

*This macroeconomic module can also be skipped and the GDP shares of these sectors directly specified as a scenario.

TABLE 4 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 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 | | | Household |
| urban: car (MF, EL) | Agriculture | Motor fuel use (F) | Space heating (U): pre-/post-75 dwellings |
| urban: mass transit (MF, EL) | Construction | Specific[a] electricity uses (F) | Space heating (U): multifamily/single family |
| intercity: car (MF) | Mining | | Space heating (U): central heating/other |
| intercity: plane (MF) | Manufacturing | Thermal uses (U) | Water heating (U) |
| intercity: bus (MF) | Basic materials | Steam generation | Cooking (U) |
| intercity: train (CL, MF, EL) | Machinery and equipment | Furnace/direct heat | Cooling (U) |
| | | Space and water heating | Electrical appliances (F) |
| Freight Transportation | Food textiles, and other | Coke for iron-ore reduction | |
| long distance: truck (MF) | Energy[b] | Use of energy products as feedstocks (F) | Service |
| long distance: train (CL, MF, EL) | | | Thermal uses (U): pre-/post-75 buildings |
| long distance: barge (MF) | | | Cooling (U) |
| long distance: pipeline (MF) | | | 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 in relation to 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 also use electricity or gas.

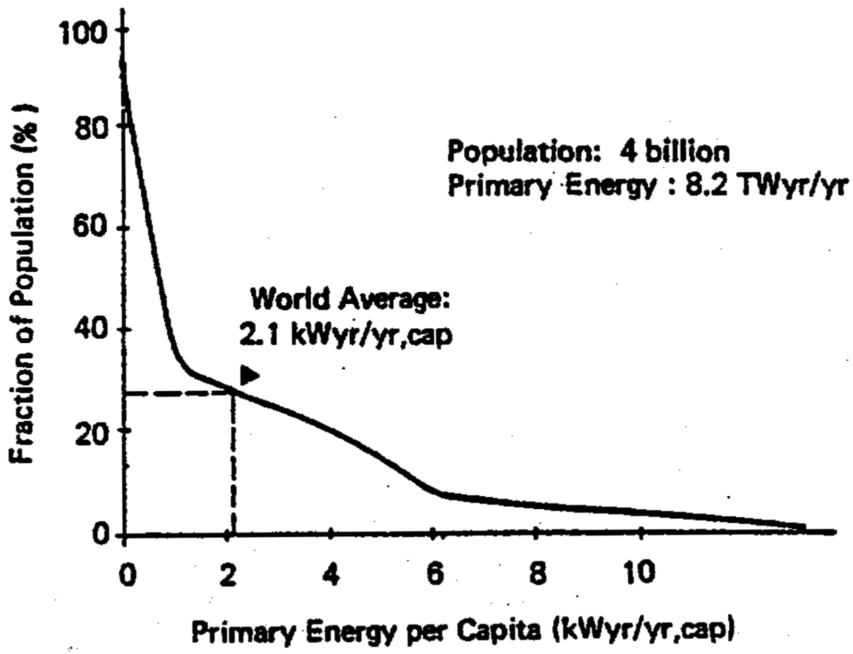



FIGURE 11 Per capita commercial primary energy consumption, world, 1975. Values show fraction of population whose primary commercial energy consumption is smaller than the corresponding value on the horizontal axis.

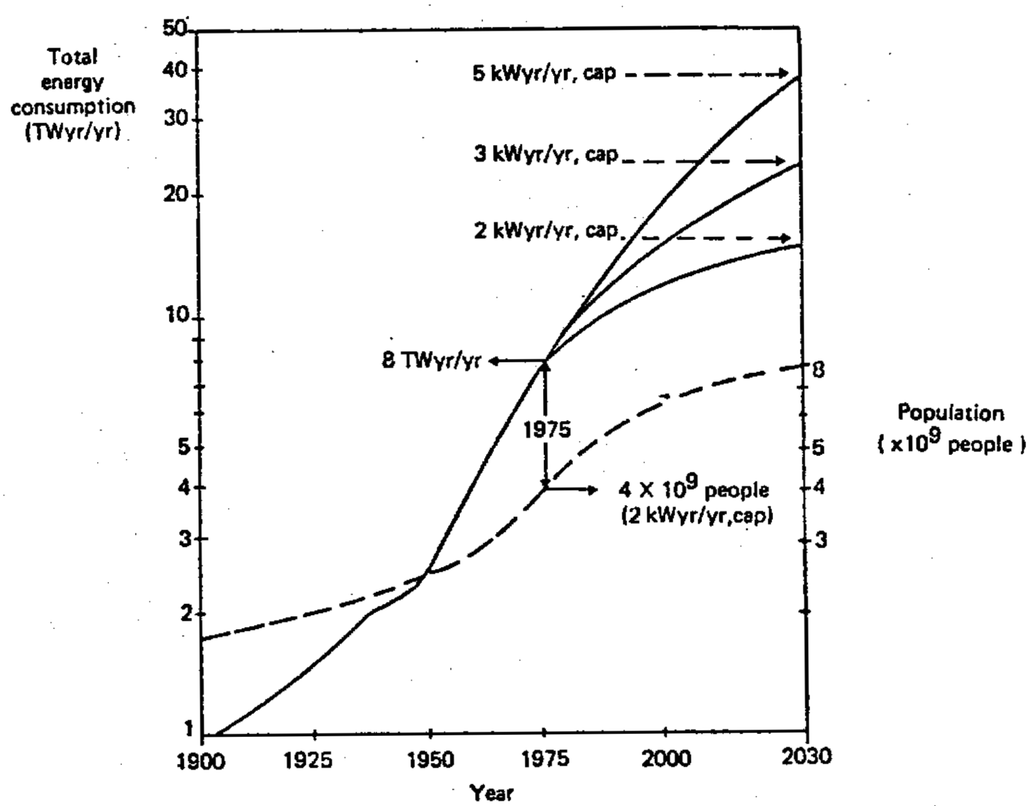


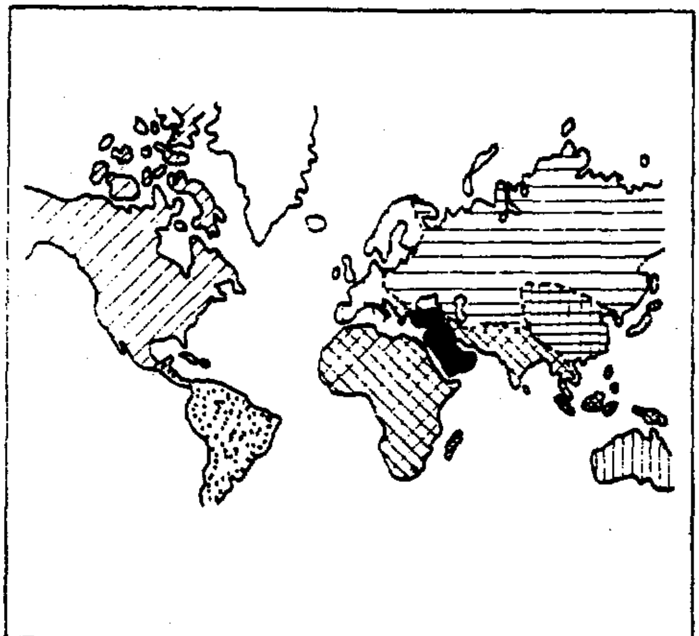

FIGURE 12 Total energy consumption, 1975-2030: three possibilities. The solid lines indicate energy consumption; the dashed line indicates world population.

A particularly illustrative example is an estimate by Häfele and Sassin (1976), pointing to the diversity of present-day energy consumption (see Figure 11). Only in three countries is the per-capita consumption higher than 7 kWyr/yr (kWyears/year = kW). In contrast, the vast majority of the world's population--about 72%--consume less than the world average (2 kW/cap), namely 1.2 kW/cap.

It is obvious that this inequality cannot persist and that the energy consumption patterns must come closer; this is a foremost goal of any long-term future energy strategy. Along these lines Figure 12 illustrates what it would mean in terms of overall energy demand (1) if the average per-capita consumption remains the same; (2) if it increases slightly to 3 kW/cap; and (3) if it increases to roughly the present European level of 5 kW/cap. Assuming an eventual stabilization of the world population at 12.5 billion would thus result in a level of energy demand three to eight times today's value. This very rough estimate clearly signals the size of the problem ahead of us.

A more detailed energy demand estimate was completed by Häfele and Sassin (1977). Economic growth rates for the seven world regions (as depicted in the Introduction) were determined judgmentally: 2.4%/yr for developed market economy countries, 4.8%/yr for centrally planned countries, and 5.6%/yr for LDCs, with successful conservation measures assumed for the developed regions.

These demand considerations led to a 35 TWyr/yr world energy reference demand scenario for the year 2030 (Figure 13). This value was, by no means, to be considered as a prediction. It merely represented a quantitative estimate resulting from a qualitative judgmental process geared towards a compromise between



| Region | Pop. $10^6$ | kW/cap | TW |
|---|---|---|---|
| I | 310 | 16.5 | 5.0 |
| II | 460 | 11.6 | 5.3 |
| III | 780 | 10.5 | 8.2 |
| IV | 720 | 3.3 | 2.4 |
| V | 3700 | 1.4 | 5.2 |
| VI | 300 | 4.8 | 1.4 |
| VII | 1800 | 4.6 | 8.3 |
| | | | ~ 35 |

POPULATION: $8 \cdot 10^9$, ENERGY: 35 TW OR 4.4 kW/CAP

FIGURE 13 Reference demand scenario, world, 2030.

the feasible and the desirable. However, this estimate was highly useful to us when we initiated the formalized modeling procedure, serving as a "mental model" or benchmark for the interpretation of the detailed and intricate results obtained.

The foregoing helped prepare the background for the development of two scenarios for each world region, delimiting a bandwidth for what could be considered reasonable paths of development. Neither of the scenarios was meant to serve as maximum or minimum prediction, however; reality might bring forth even lower values than those obtained in the "Low" case or even higher values than those of the "High" case. Our aim was merely to conceive two consistent, possible sets of assumptions about the future that would smoothly fit with the past and describe a future evolution devoid of major disruptions. At the same time, the range described by the scenarios was to be wide enough in order to account for the inevitable uncertainties.

The scenarios described below are in fact not sheer "best judgment" estimates. Several of our initial assumptions had to be revised in the course of a lengthy learning process of iterative model runs, consistency checks, reappraisal by discussion with leading experts, etc. Thus the initially exogenously defined inputs were modeled to become well tested and understood results.

The scenarios are driven by two basic development variables: population and gross domestic product (GDP). Both variables are assumed to have decreasing growth rates. It is further assumed that there will be no major changes in the sociopolitical environment or in lifestyles except for changes that accompany economic development in the LDCs. Energy prices are assumed to increase ushering in strong conservation measures.

With the project's focus on the energy issue, upper and lower bounds of poplation projections are not explicitly given. The projections, which resulted from a study by N. Keyfitz of Harvard University, U.S.A. (Keyfitz 1977), tend to be more at the conservative end. A bare replacement of fertility in developing regions is assumed to be achieved by 2015. Population growth rates gradually decrease from currently 2%/yr to less than 1%/yr by 2030. The growth rates in the LDCs are three times higher than those in the developed countries. (The population data thus obtained are summarized in Table 5.) Also note the increase in nonworking population, urbanization, and family size (Table 6).

For the assessment of economic activities, GDP was chosen as indicator. Throughout the study, 1975 U.S. dollars and 1975 official exchange rates and prices were used.* For centrally planned economies World Bank estimates were employed (World Bank 1977). GDP, defined as the starting point, was measured country by country and then aggregated for each region.

We were aware that using GDP as indicator of economic activities has certain disadvantages. For one, national GDP estimates are difficult to use meaningfully for comparison of greatly differing economic structures; and for another thing, aggregate GDP is not an adequate measure of welfare. Overall, however, GDP is useful for broad comparisons, which makes it a well suited yardstick for our study which aims at comprehensive understanding rather than at exacting detail.

Our initial GDP projections were based on studies conducted by the Workshop on Alternative Energy Strategies (1977) and the

TABLE 5 Population projections by region.

| Region | Population ($10^6$) Base Year 1975 | Projection 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) | 1,422 | 2,528 | 3,550 |
| VI (ME/NAf) | 133 | 247 | 353 |
| VII (C/CPA) | 912 | 1,330 | 1,714 |
| World | 3,946 | 6,080 | 7,976 |

NOTES: 1975 data are mid-year estimates from United Nations *Monthly Bulletin of Statistics*, January 1978.
The same population projection is made for both High and Low scenarios.
SOURCE: Keyfitz (1977).

World Energy Conference (1978). In the course of our work we were brought to revising these estimates downward in order to reach an easier demand/supply balance. The growth rates obtained are given in Table 7. Increasing scarceness of resources and decreasing population growth rates result in decreasing GDP growth rates.

By assumption, LDCs will continue to depend on trade with the developed regions functioning as a major stimulant to economic growth in the developing world. Therefore the LDC's growth potential will be limited by levels one or two percentage points higher than the growth in the developed regions. At the same time, the economic structures will develop differently. Whereas the industry share of the developed world will decrease (e.g., from 32% to 20% in the High case for North America) it will increase in the developing world (e.g., from 36% to 47% in the High case for Latin America). The service sector will gain importance in the developed regions and have a constant share in the developing regions.

In summary, both scenarios can be considered as "moderate departures from observed trend cases." Compared to historical developments or politically set objectives of development, such as are described by the New Economic Order (Leontief 1977), they are low, perhaps even discouragingly low: in the High scenario, growth rates in the developed regions drop by 50%; only Latin America and the Middle East with North Africa reach GDP/cap figures on the order of values obtained for the OECD countries in 1975. Proponents of a nongrowth society, however, may consider our assumptions to be too high: they would expect the impact of scarcities and of economic maturation to be greater than is reflected in our projections.

*Unless explicitly noted otherwise.

TABLE 6 Demographic assumptions.

| Region | 1975 | | | 2000 | | | 2030 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Persons Per Househ. | Popul. in Large Cities[a] (%) | Econom. Active Popul.[b] (%) | Persons Per Househ. | Popul. in Large Cities[a] (%) | Econom. Active Popul.[b] (%) | Persons Per Househ. | Popul. in Large Cities[a] (%) | Econom. Active Popul.[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 (1976); United Nations (1974); FAO (1977); Paxton (1976); CMEA (1976); U.S. Department of Commerce (1976); Statistics Canada (1975); Keyfitz (1977).

TABLE 7 Historical and projected growth rates of GDP, by region, High and Low scenarios (%/yr).

A. High Scenario

| Region | Historical 1950-1960 | Historical 1960-1975 | Scenario Projection 1975-1985 | Scenario Projection 1985-2000 | Scenario Projection 2000-2015 | Scenario Projection 2015-2030 |
|---|---|---|---|---|---|---|
| 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

| Region | Historical 1950-1960 | Historical 1960-1975 | Scenario Projection 1975-1985 | Scenario Projection 1985-2000 | Scenario Projection 2000-2015 | Scenario Projection 2015-2030 |
|---|---|---|---|---|---|---|
| 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 which exclude centrally-planned economies.

NOTE: Historical and projected values of GDP in constant (1975) U.S. dollars are given in Chant (1980).

THE LONG-TERM ENERGY DEMAND:
ASSUMPTIONS, RESULTS, OBSERVATIONS

GDP and population are important driving variables for long-term energy demand. But in order to capture other factors such as economic structure, lifestyle, and technological characteristics, MEDEE-2 was used to assess the energy demand. Unfortunately, disaggregated sectoral data are scarce in particular for developing regions, and there is no widely accepted method for projecting the evolution of various socioeconomic activities and related technological parameters over a period of several decades. Therefore, our assumptions had to be guided by past trends, interregional and intercountry comparisons, estimated relationships reflecting the interdependence between various economic and social activities, and estimated prospects of future technological developments--with most parameters influenced directly by the aggregated GDP projections.

Table 8 records the *assumptions* made concerning the GDP shares of the three basic sectors agriculture, industry, and services.** Developing regions were assumed to show the largest changes, reflected mainly in a shift from agriculture to industry. In the developed regions the industrial sector supposedly decreases, with the economic activity shifting increasingly to the services sector.

In a further step, then, projections of the evolution of certain socioeconomic activities (transportation system planning, equipment of dwellings, etc.) and of changes in lifestyles were introduced.

In 1975, considering both the developed and developing regions together, the *transport sector* accounted for 24% of the total final energy consumption. On the average, the developing regions (30-41%) had a higher share than the developed ones (19-30%). The future of the transport sector in developed nations will be influenced by changes in the public attitude vis-à-vis energy availability, higher energy prices, government regulations, saturation of car ownership , and growing urban congestion. Thus we foresee a relatively lower growth in personal travel and a moderate increase in the use of public transportation in urban areas. At the same time greater economies in gasoline consumption will be achieved. In contrast, in the developing regions personal travel is far from saturation, and freight transport will increase strongly along with relatively high economic growth. Regarding the mode of transport, developed regions will move more towards plane travel and, except for North America, towards car travel. Developing regions* will significantly shift towards cars, and less noticeably towards trains. The large share of bus travel in those regions will decrease substantially. Load factors are assumed to remain practically constant in the developled market economies. In the developed countries with planned economies

*Although the developing regions proper include Regions IV, V, VI and VII, Region VII generally required special treatment. Thus, as is used here, the phrase "developing regions" should be taken to mean Regions IV, V, and VI. When Region VI is also separated out from the others, explicit reference will be made in the text.

** For more details see Khan and Hölzl (1980).

TABLE 8 GDP sectoral shares assumptions (% of GDP).

| | 1975 | | | High Scenario 2030 | | | Low Scenario 2030 | | |
|---|---|---|---|---|---|---|---|---|---|
| Region | Agricul. | Industry[a] | Service | Agricul. | Industry[a] | Service | Agricul. | 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.

load factors are expected to decrease by a factor of 2. Similarly, in LDCs where overcrowding of buses and trains is more or less standard practice today, a substantial drop in the load factors is assumed.

Figure 14 summarizes the results of the MEDEE-2 runs for this set of assumptions. The differences between regions are striking. North America experiences the smallest relative increase; the other developed market economies increase their mobility steadily up to the North American level. The developed planned economies also experience a marked relative increase but the share of the personal travel remains relatively low, due to considerable rail and urban mass transit. The biggest increase can be observed in the developing regions where energy use for transport (in the High scenario) grows by factors greater than 10.

Households and the service sector consume both fuels and electricity for heating, lighting, cooling, cooking, etc.; the service sector needs additional electricity for special equipment, such as computers, office machines, etc. In 1975, these *energy uses in buildings* represented a 23-31% share of final energy demand in the developed regions and 11-14% in the developing regions.

Housing construction in the scenarios is tied to population growth and the average number of persons per household (for values see Table 9). In the developed market economies, the share of centrally heated dwellings would reach 90% (1975: 45%). Air conditioning would be available in 30-40% of the households (1975: 12%). In the developing regions the number of residental dwellings would reach 1130 million by 2030 (360 million in 1975). However, due to climatic conditions only 25% would need space heat.

Service sector floor area is projected to increase substantially in all regions. Developed market economies would use by 2030 1.7 to 2.1 times, developed planned economies 3.2 to 4.4 and developing regions 6 to 7.5 more floor area than in 1975.

Some aggressive assumptions with respect to conservation and the introduction of new technologies have been made, particularly with regard to space heat. Pre-1975 housing stock in the developed regions is supposed to reduce heat losses by 20-30% through 2030 through retrofitting of improved insulation. Post-1975 dwellings would have an average heat loss of only 50% of those in 1975. Soft solar energy, heat pumps, district heat as well as substantial efficiency improvements in the use of all fuels (10-25% for fossil, for instance) will contribute to reducing the consumption of the space heat sector.

In contrast, electricity use for electric appliances will continue to grow. Whereas saturation and improved efficiencies might flatten the present growth curve in developed nations, developing regions must be expected to reach levels 3-17 times higher than today--mainly because the present level of use is so low.

Table 9 for the household sector and Table 10 for the service sector summarize the model projections obtained from those assumptions.

*Industrial energy use* covers a major portion of the world energy consumption today and our scenarios do not envisage this situation to change significantly.

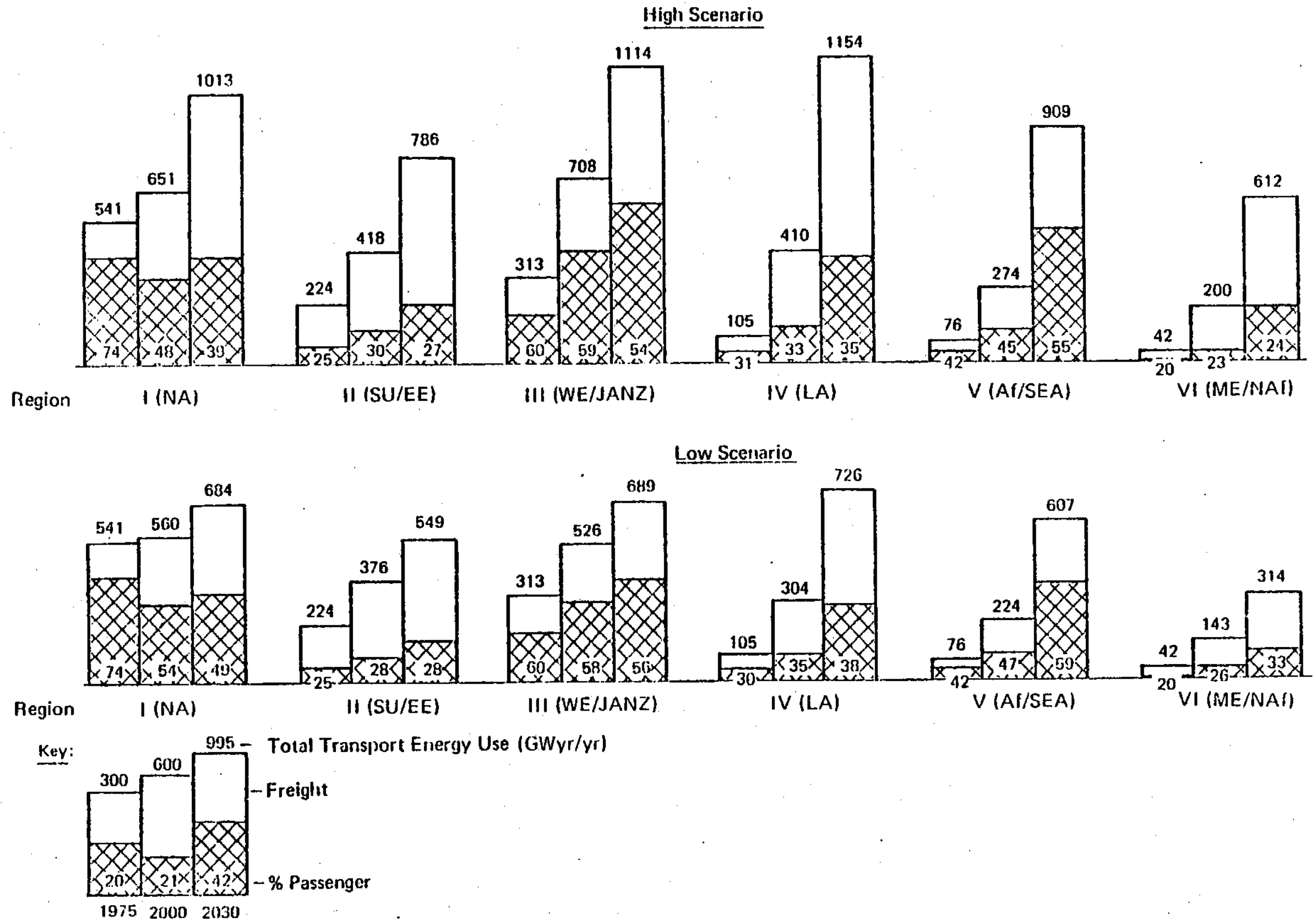



FIGURE 14 Transportation final energy-use projections.

TABLE 9 Projected useful energy requirements in households ($10^3$ kWh per dwelling per year).

| Region | 1975 Cooking | 1975 Space & Water Heating | 1975 Air Condi-tioning | 1975 Misc. Elec. Appl. | High Scenario 2030 Cooking | High Scenario 2030 Space & Water Heating | High Scenario 2030 Air Condi-tioning | High Scenario 2030 Misc. Elec. Appl. | Low Scenario 2030 Cooking | Low Scenario 2030 Space & Water Heating | Low Scenario 2030 Air Condi. tioning | Low Scenario 2030 Misc. Elec. Appl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 10 Useful energy projections for service sector.

| Region | 1975 Service Sector Working Area ($10^9 m^2$) | 1975 kWh/m² Space & Water Heating | 1975 kWh/m² Air Condi-tioning | 1975 kWh/m² Misc. Elec. Appl. | High Scenario 2030 Service Sector Working Area ($10^9 m^2$) | High Scenario 2030 kWh/m² Space & Water Heating | High Scenario 2030 kWh/m² Air Condi-tioning | High Scenario 2030 kWh/m² Misc. Elec. Appl. | Low Scenario 2030 Service Sector Working Area ($10^9 m^2$) | Low Scenario 2030 kWh/m² Space & Water Heating | Low Scenario 2030 kWh/m² Air Condi-tioning | Low Scenario 2030 kWh/m² Misc. Elec. Appl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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.

TABLE 11 Assumed distribution of manufacturing activities, High scenario.

| Region | 1975 | | | | 2000 | | | | 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 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 (% of total GDP).

[b] Manufacturing of basic materials (% of total manufacturing value added).

[c] Manufacturing of machinery and equipment (% of total manufacturing value added).

[d] Manufacturing of (non-durable) consumer goods (% of total manufacturing value added).

NOTE: In Regions I, II, and III, basic materials also include mining of non-energy products but exclude manufacturing of petroleum and coal products.

SOURCES: United Nations (1977b); United Nations (1977a) United Nations (1977c).

TABLE 12 Energy consumption in manufacturing.

| Region | Base Year 1975 | High Scenario 2000 | High Scenario 2030 | Low Scenario 2000 | Low Scenario 2030 |
|---|---|---|---|---|---|
| I (NA) | | | | | |
| Manufacturing energy use[a] (GWyr/yr) | 700 | 1,189 | 1,701 | 984 | 1,186 |
| *% 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 | 1,350 | 2,369 | 1,216 | 1,623 |
| *% 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 | 1,385 | 2,011 | 1,052 | 1,298 |
| *% 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 | 1,102 | 293 | 628 |
| *% 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 | 1,615 | 395 | 774 |
| *% 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 |
| *% 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]% of final energy is manufacturing energy as a percent of commercial final energy.

[c]Electricity is electricity used in the manufacturing sector.

TABLE 13 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 |

In our specific context, "industry" denotes four sectors: agriculture, mining, construction, and manufacturing. Energy use for each of those sectors is projected as a product of their value added and the energy use per-capita unit of value added--their energy intensity which is determined for specific uses of motor fuels and electricity as well as thermal uses, for which energy can be provided by various energy forms. The first two coefficients are given in terms of final energy, the last in terms of useful energy. To obtain an overall final energy intensiveness then, an average end-use efficiency for fossil fuels relative to electricity is defined, and various factors capturing differences in economic structures as well as reflecting technological patterns are taken into consideration.

*Manufacturing* keeps its predominant role: in 1975 it accounted for 90 to 97% of the industrial energy consumption in all regions except the Middle East and North Africa where, due to the dominance of hydrocarbons production, manufacturing's share reached only 62%. In our scenarios, taking into account the assumed structural economic changes (Table 11), manufacturing's share in industrial energy consumption varies between 76 and 90% in all regions.

In our projections of energy demand for manufacturing, summarized in Table 12, we incorporated substantial conservation measures. The introduction of new technologies, better practices, increased use of cogeneration, and efficiency improvements should result in an energy intensity reduced relative to 1975 by 35-55% in different world regions (the use of coke in the steel industry and feedstocks are excluded) (Table 13). The developed regions show a greater reduction than the developing regions, where, except for Latin America, structural change tends to increase the energy intensity.

*Agricultural activities* are projected to increase by a factor of 2.2 to 2.5 in developed countries and by a factor of 3.7 to 4.5 in developing nations. This growth is expected to be joined by a ten-fold increase of the energy intensity of agriculture in the developing countries.

The surface of arable land in the developing regions cannot be much expanded and thus an improvement in production depends largely on a growing use of fertilizers*, irrigation and mechanization. Final energy use in agriculture is therefore estimated to increase by a factor of 45 to 37 in the High and Low cases respectively. Its share of the total industrial energy amounts to 3 to 5% (1975: 1 to 4%) except for South and East Asia and most of Africa where it reaches 10% for the High and 15% for the Low case.

## What Forms of Energy Are Required?

It is important to note that various activities require not only energy but a very specific form of energy for which is impossible or at least difficult to substitute (e.g., electricity for stationary motive power, or motor fuels for transportation). Therefore, energy demand is not only a question of how much but of how much *of what?*

*The energy needed for the production of fertilizers is counted in the basic materials manufacturing sector.

In general, *electricity* is demand-driven in our analysis. "Essential electric" uses such as aluminum production, lighting, motive power in industry, and computers will grow at a rate comparable to the related sectoral activities. Electricity will at the same time moderately enter the heat market. In particular in the developing regions it could supply in 2030 7% of the heat (and cooling) requirements (today 1%). With regard to industrial heat, between 4-10% would be supplied by electricity. Finally, in the transport sector electric use is expected to increase in all regions due to increasing electrification of railways and mass transit systems and a certain shift to electric cars for urban travel. In developed countries with the exception of North America electricity could cover thus 4-9% of the transport needs. In North America and the developing regions 1-2% could be reached.

Globally seen, electricity growth rates are assumed to drop in most regions to one half of the present values mainly due to saturation reached in many developed countries. However, electricity growth would--worldwide--still be a factor of 1.4 higher than overall energy growth, leading to a required capacity of 6320 and 9845 GW(e) in 2030 (1975: 1600 GW(e)).

*Liquid fuels* in both scenarios will have to be used primarily for transport and feedstocks--in some regions almost exclusively. Nonessential uses will be increasingly covered by other fuels. This shift is assumed to be induced by the rising prices of crude oil (placed at 21 U.S. dollars (1975)/bbl and 19 U.S. dollars (1975)/bbl for the marker crude in 1990 for the High and Low scenarios respectively), but accomplished judgmentally in our analysis.

However, the demand for liquids still continues to grow: 1.6-2.4% worldwide, 1975-2030, reaching in 2030 in terms of final energy 6.69 TWyr/yr in the Low and 10.36 TWyr/yr in the High scenarios. Essential uses determine respectively 88 and 92% of this demand.

*Soft solar technologies*, that is small-scale uses, might contribute some significant percentages. In the Western developed regions we assumed that through aggressive policies 50% (30% in other developed areas) of all post-1975 single-family centrally heated homes and low-rise service sector buildings will be equipped with solar systems requiring backup for 30-50% of the time (see also the section on solar in Chapter 3). Thus, in North America, for instance, 14% of the residential space heating and 28% of water heating could be of solar origin (6-7% for water and space heating in the service sector). In North America and the other developed market economies 3% of the industry's process heat demand and 10% of its space heat demand might be provided by solar in 2030.

Penetration of solar space and water heating in developing countries is assumed to be later and slower than in developed regions. Moreover, heating demand in developing regions is low due to climatic conditions. Still, some 14% of the heat demand in the household/service sectors of those regions might be covered by solar. In the industry sector 4% of the heat demand might be provided by solar (30% of low temperature steam/hot water demand and 10% of the higher temperature steam demand with 20% back-up by fossil fuels).

The remainder of the energy requirements which are not supplied by electricity, district heat, combined cycle, liquid fuels

TABLE 14 Assumed penetrations of renewable sources of energy, regions IV (LA) and V (Af/SEA).

| Demand Sector | Nature of Demand | Projected Penetration of Renewables[a] (% 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.

[b]Towns are urban agglomerations with less than 100,000 inhabitants.

[c]Villages include all rural households.

SOURCE: Khan (1980).

or solar systems are assumed to be provided by interchangeable fossil fuels comprising coal, oil, gas, biogas, charcoal/wood, animal wastes, etc. In 1975 48% of the final energy was met by those substitutable fossil fuels in the developed regions and 45% in the developing regions. In our scenarios their share would be reduced to 27-29% by 2030.

*In North America* coal is abundant and its relative price low. Therefore we assumed that substitutable fossil sources would meet 25 to 30% of the industry's energy requirements by 2030. Gas increasingly replaces liquid fuels: it is more abundant than oil and prices, therefore, rise more slowly.

The centrally planned developed countries dramatically shift away from oil as a heat source. Gas, and to some extent combined cycle and district heat systems, provide the major share of the heat requirements in both industry and household/commercial sectors. Coal might shift towards an increased use for electricity or combined heat and power production.

The remaining developed world is less endowed with resources. Coal is relatively plentiful and therefore direct coal use in industry is projected to grow slowly (20% of the substitutable demand in 2030 in the High scenario compared to 12% in 1975). Offshore finds and good supply availability of gas will increase its role and contribute to reduce the share of oil for substitutable uses from 59% in 1975 to 23-26% in 2030.

Because of economic considerations, Latin America, Africa, and South and East Asia are assumed to pursue aggressive policies to save fossil fuels by making an extensive use of renewable sources. Commercial charcoal/wood, agricultural wastes and biogas may make interesting contributions (Table 14).

Latin America, in view of its substantial hydrocarbon resources,will keep its high share of oil use in the substitutable fossil market with wood contributing most of the remainder. Africa and South and East Asia, in contrast, have significant coal and to a lesser extent gas resources. Coal, wood, and gas therefore can be expected to provide the bulk of the industrial and urban substitutable needs, whereas biogas could play an important role in meeting the commercial requirements of rural households.

## IMPLICATIONS AND CONCLUSIONS

In a final step all these detailed sectoral projections were aggregated into two regional and global demand scenarios reaching 35.7 TWyr/yr of primary energy in the High case and 22.4 TWyr/yr in the Low case (or 22.83 and 14.57 TWyr/yr of final energy). The values for the individual regions and the respective growth rates are summarized in Tables 15 and 16. (What types of energy are needed is shown in Figure 15).

In terms of per capita consumption some improvement is made. As illustrated in Table 17, the developing regions close somewhat the existing gap between them and the developed regions: today's factor of 44 (!) between the poorest and richest region is reduced to a factor of 13 in the High scenario and to 25 in the Low scenario. According to current North-South comparisons, the Low scenario appears to be a much less stable case than the High scenario: some dangerously low consumption values in some developing regions still persist.

TABLE 15 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.
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 non-rounded data and then rounded to one decimal place; these rates may therefore appear to not apply exactly in part A of the table.

TABLE 16 Summary of scenario energy projections: primary energy.

A. **Primary Energy for 1950 and 1975 and Projections to 2030 (TWyr/yr)**

| Region | Historical 1950 | Historical 1975 | High Scenario 2000 | High Scenario 2030 | Low Scenario 2000 | Low Scenario 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)**

| Region | Historical 1950 1975 | High Scenario 1975-2000 | High Scenario 2000-2030 | Low Scenario 1975-2000 | Low Scenario 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.

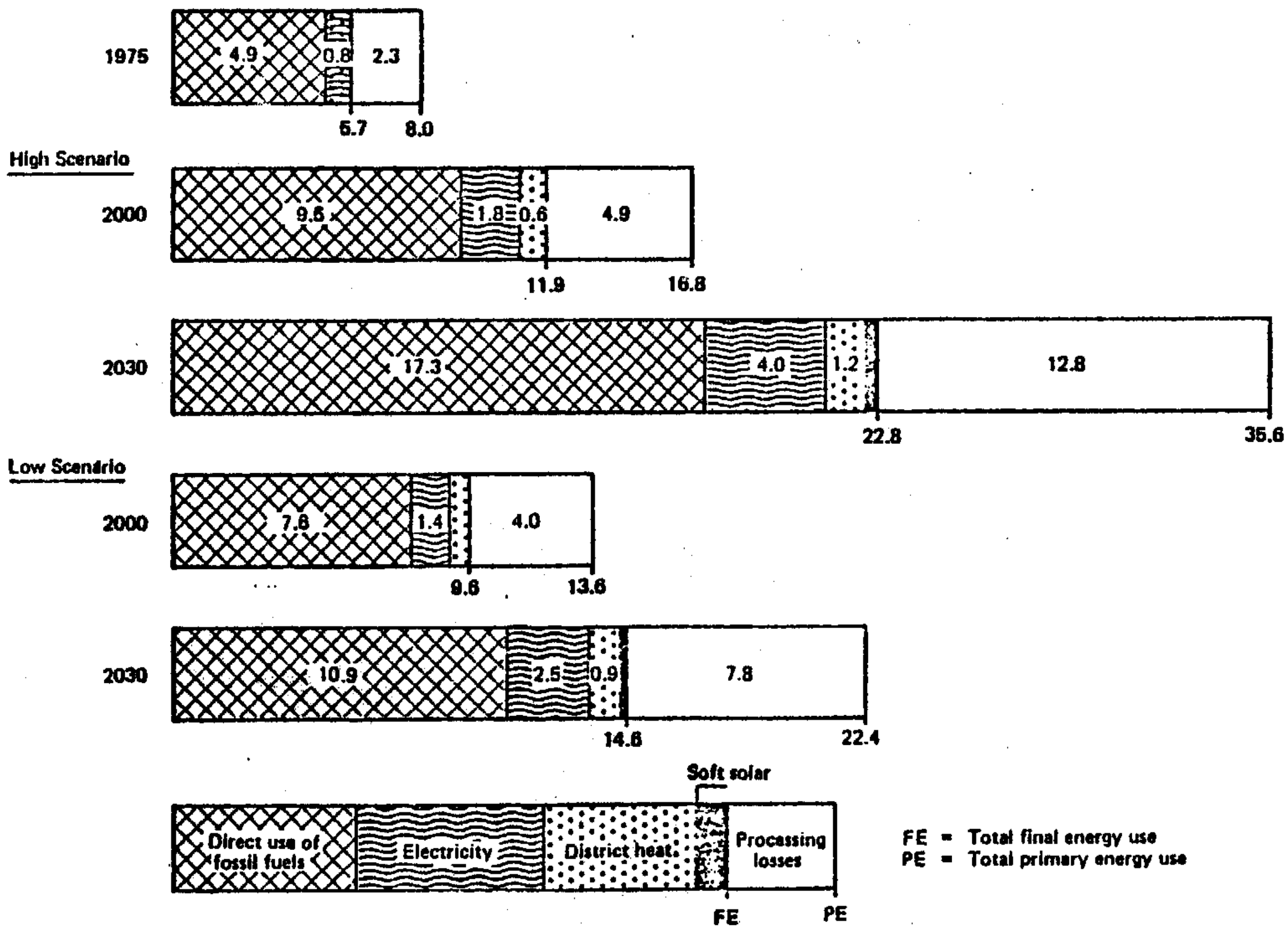



FIGURE 15 Global energy demand projections, 1975-2030. FE = total final energy use; PE = total primary energy use; units: TWyr/yr.

TABLE 17 Per capita final (commercial) energy consumption, two scenarios 1975 to 2030 (kWyr/yr,cap).

| Region | | Base Year 1975 | High Scenario | | Low Scenario | |
|---|---|---|---|---|---|---|
| | | | 2000 | 2030 | 2000 | 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 VII 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.**

According to the high conservation projections, energy intensity will be reduced in all developed regions; but less so in Western Europe, Israel, Japan, Oceania, and South Africa (Region VII) whose infrastructure is less energy intensive on account of local resource scarceness than those in the remaining developed world. Developing regions, in contrast, can be expected to increase the energy intensity of their economies slightly, in view of the projected structural economic changes, i.e., a stronger emphasis on industries and an increased energy intensity of agriculture.

This trend is very much reflected in the development of energy densities, an indicator characterizing man-made environments. Given such materially defined environments the social and institutional problems are largely dependent on how many people have to arrange themselves within such an environment and share the projected infrastructure. The material factor of 10 which masks the differences in average energy densities between developing and developed regions in 1975 is reduced to 2. The situation is reversed in rural areas. There the energy density increased by a factor of 10 (0.01 to 0.12 $W/m^2$) in developing regions and decrease slightly in developed regions (0.08 to 0.05 $W/m^2$). Taking all changes together, one can expect worldwide growth of energy consumption to be less strongly coupled to economic growth than today (Table 18).

This is in line with the scenario projections of price increases of a factor of 2.4 to 3. The impact on the economies will be very significant, as is shown in Table 19, and particularly so in developing regions. There, the share of GDP of payments for energy might triple. Thus, issues related to the prospects of world trade and the balance of payments will increasingly dominate the international energy scene.

*With the exception of the centrally planned economies of Asia; there, energy densities are comparable to those of developed regions, due to an average population density which is five times higher than the world average.

TABLE 18 Final energy-GDP elasticities, $\varepsilon_f$, 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 the equation below using five-yearly data (see Chant, 1980). Values for the projection period *result* from the scenario data.

Elasticity $\varepsilon$ is defined by the following relationship:

$$\frac{E(t_2)}{E(t_1)} = \left\{\frac{GDP(t_2)}{GDP(t_1)}\right\}^{\varepsilon} ,$$

where $t_1$ and $t_2$ are two points in time, 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, $\varepsilon_p$, or to final energy, $\varepsilon_f$. Numerical differences between $\varepsilon_p$ and $\varepsilon_f$ can be due to changing energy conversion efficiencies or fuel mixes.

TABLE 19 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.

# 3 ENERGY OPTIONS AND RESOURCES: THEIR SYSTEMS IMPLICATIONS

## THE SETTING

In the previous chapter, the future requirements for energy were identified. We concluded that it is prudent to assume an increase in primary energy demand by a factor of roughly 3-5, over the next half century or so. This presupposes that the industrialized nations already now initiate serious efforts to reduce the energy intensity of their economies and infrastructures.

Obviously, these larger global energy requirements presuppose a very substantial effort on the supply side. There seem to be several ways and opportunities to meet this demand; yet, as the analysis will show, *all* options will have to be relied upon in concert.

In this paper, a clear distinction is made between technologies relying on sources of energy that, in principle, are renewable, such as hydropower, wind, tidal energy, etc., and technologies based on resources that represent a one-time endowment to mankind, accumulated over very long time periods, such as fossil resources or uranium.

Many feel that the energy supply system of the future should rely extensively, if not exclusively, on renewable sources (see, e.g. Lovins 1977). For, at first glance renewables appear to be clean, easy to handle, and flexible. It will be shown that a truly large-scale exploitation of renewables would have severe implications and, due to the very characteristics of these sources, would greatly limit their potential. Nonrenewable technologies, on the other hand, do not divert part of the flow of a natural cycle but involve exploitation of energy deposits that are stored by nature.

While nature has, in principle, provided us with very large amounts of energy resources, it is crucial to assess whether and under what constraints they are made accessible. A methodology

(WELMM) developed in the past years permits assessment of the systems implications of resource extraction, focusing explicitly on its impacts on other resources. WELMM is a useful means for comparing energy technologies from a resources point of view.

Only a few of the renewable and nonrenewable technologies are capable of providing truly large amounts of energy over extended periods. Table 20 summarizes five such options. Two of them, dry geothermal energy and fusion energy, are still not mastered technologically, and their economics are little if at all understood. Even if a geothermal technology were available at acceptable cost, the harvesting of the earth's gradient, involving considerable heat exchange arrangements deep underground, would entail severe ecological disturbances and mechanical impacts on the ground, such as are known from deep mining operations. It is the least known option among the five.

The potential technology and impacts of nuclear fusion, on the other hand, are much better understood, but demonstration of its commercial feasibility is generally not expected before 2010-2020.

While fusion and dry geothermal may be important in the long run, no important contribution to the energy supply can be expected from them over the next 50 years or so. Three main supply technologies in particular will then have to be available to support most of the world's energy needs: a sophisticated fossil technology making use of fossil resources in a manner qualitatively different from that of today; nuclear breeding; and, to a lesser extent, solar energy in various forms. Theoretically, each of them is by itself capable of meeting the world's energy demand; the other technologies known to us cannot do so.

TABLE 20 Options for "unlimited energy supply".

| Options | Resource (TWyr) | Technological Maturity | Side effects |
|---|---|---|---|
| Fossil | $\sim 3 \times 10^3$ | Mature at present scale; to be developed for large scale coal | Unfavorable working conditions; land requirements; $CO_2$ waste and other pollution |
| Fission (breeder) | $3 \times 10^5$ | Sufficient for power plants; not yet sufficient for large-scale fuel cycle | Storage of fission products; emission of radionuclides |
| Solar | $\infty$ | To be developed for large scale | Land and material requirements; climatic disturbance? storage and transportation |
| Fusion (D-T) | $3 \times 10^5$ | To be developed | Storage of activated material; emission of radionuclides |
| Geothermal | $\sim 10^4$ (???) | To be developed | Storage of waste? emission of pollutants? earthquakes? |

## THE POTENTIAL OF RENEWABLE SOURCES

### Renewables in the Past--and in the Future?

The use of renewable energy sources is nothing new. Indeed, for thousands of years and until very recently, man has exclusively relied on renewables for his energy supply. Wood, farm wastes, wind power and water mills were well suited to support societies that were largely characterized by low population densities and an extensive mode of agricultural cultivation.

The basic limitations on the use of renewable sources became apparant with the coming of the great classical civilizations. Building civilization centers like ancient Rome led to demand densities impossible to meet by energy derived from local wood. Going further afield was difficult logistically, in particular with respect to expensive transportation. A solution was found in the utilization of charcoal, "invented" many times, which represents *the* prototype of energy conversion technology. Its drawbacks were increasing deforestation effects.

A similar crisis occurred in Europe in the late 18th and the early 19th centuries. Improved agricultural techniques provided enough food to support a rapidly growing population that, enticed by early industrialization, increasingly lived in urban agglomerations. The change in infrastructure led to higher demand densities, and wood and the other traditional forms of energy were no longer sufficient. Coal and railway transport helped solve the crisis in Europe, but foreshadowed economic interdependence, the trend towards specialization, and the increasing energy intensiveness of our modern system.

Even today, several countries as well as world regions with a fast population growth (India, Africa, and even Latin America) undergo a comparable experience. For a great number of the world's population, the real energy crisis of today is not a shortage in oil supply but in firewood.

It would be wrong to view these developments as demonstrating a lack of compatibility between modern energy-intensive societies and diffuse renewable energy sources. Renewables will and should increasingly continue to provide a significant, and a possibly even substantial, share of our energy supply: their specific characteristics make them an excellent emergency supply system in times of crisis, which could add to making the growing interdependence more palatable and acceptable.

But the main problems in using renewables still remain. Their low densities require big investments in land and in energy harvesting equipment. The amounts to be supplied are typically limited by the natural cycles they are derived from, for the harvesting of power must under no circumstances destroy the system concerned. Furthermore, there is the question of cost. One would expect renewables to be in at least the same economic ballpark as other forms of energy supply. Political, ecological, and other considerations might permit somewhat higher costs but only within sensible limits.

Energy Flows

As mentioned, renewables are sources of energy that is diverted from natural power flows in the earth's atmosphere and hydrosphere, the bedrock of the earth surface, and the biosphere. The sources feed these systems (Hubbert 1971), as is indicated in Figure 16, by sunlight, planetary motion, and geothermal energy.

*Sunlight* arriving at the upper layers of the atmosphere is the dominating inflow, providing 178,000 TWyr/yr; its extraterrestrial density amounts to 1.35 $kW/m^2$, measured in perpendicular direction to the sun. The respective values on the earth differ widely: yearly averages in central Sahara areas may be 250 $W/m^2$ with up to 4000 hours of sunshine per year; densities in central Europe average about 100 $W/m^2$ with 1500 hours per year of direct insolation.

Thirty percent of the sunlight is reflected back into space. Of the remaining 70%, 83,000 TWyr/yr is in the form of sensible heat of air and water, and 41,000 TWyr/yr as latent heat from evaporation, essentially that which is released upon condensation. The absorbed solar heat finally leaves the earth in the form of infrared radiation.

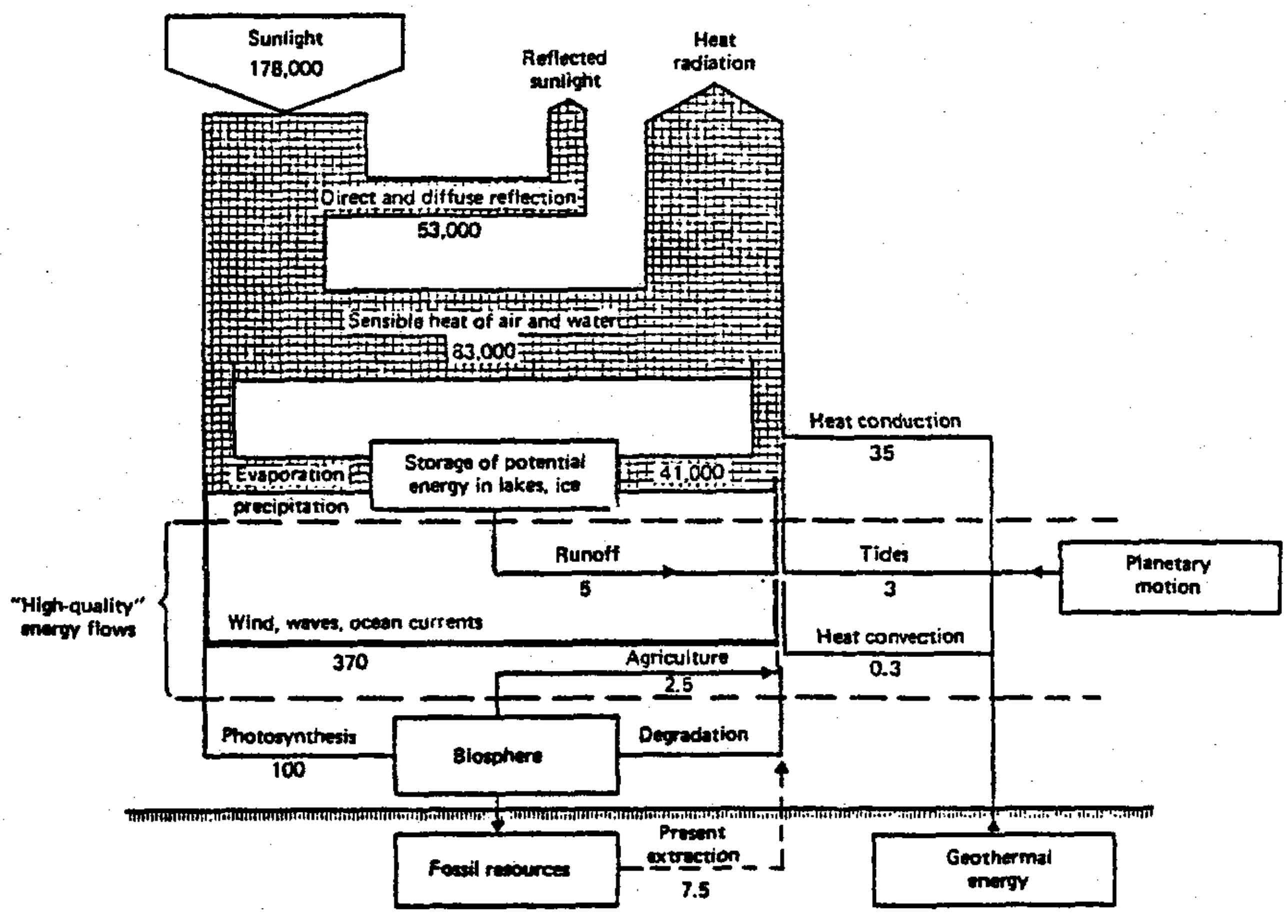



FIGURE 16 Energy flows through the environment (power levels in TWyr/yr). In many of the numerical presentations extra significant figures beyond what is significantly valid are listed. This is done to make arithmetic identities valid.

Sunlight powers several secondary systems, in particular the climate system and the biosphere. Wind, waves, and the kinetic energy of ocean currents dissipate roughly 370 TWyr/yr, and the continental runoff, via friction heat is some 5 TWyr/yr. Biomatter converts some 100 TWyr/yr (agriculture draws 2.5 TWyr/yr from that system).

*Geothermal energy* provides 35 TWyr/yr via heat conduction to the atmosphere. Only 1% of this amount comes by way of volcanoes or active geothermal fields.

Finally, 3 TWyr/yr of kinetic energy are dissipated in the tidal movements caused by *planetary motion*. The energy from these sources that is within man's reach is 25,000 TWyr/yr in the form of sunlight, some 3000 TWyr/yr in the form of heat stored in the oceans, as well as some 150 TWyr/yr in the form of wind at accessible heights above the continents, biomatter, continental run-off, and wet geothermal sources.

These figures seem high. Harvesting these energies might, however, interfere with some sensitive couplings between the natural energy flows. Therefore, any significant amount of mechanical energy obtained from ocean currents might seriously impact on the climate blocking the much larger regular heat transfer of the ocean. Instead, the ratio of the kinetic energy harvested (0.2 TWyr/yr) and the heat transported is 1:10,000.

The case of wind power is less dramatic. With a kinetic energy potential of 350 TWyr/yr, the respective ratio is on the order of 1:25.

It is interesting to compare the changes in physical power flows due to present agricultural practices. A yield of 2.5 TWyr/yr of useful products is contrasted by changes in the albedo and evaporation rates on the order of 25-100 TWyr/yr. It can be estimated that a diversion of about 10 TWyr/yr would heavily affect all the ecological systems of the globe unless it is balanced by an artificial stimulation of biomass growth--of the same magnitude and in selected locations.

## The Technical Potential

The optimal source of energy would be characterized by a high power density, continuous availability, and easy convertability into all forms of useful energy required by the consumer. Renewable sources display many different characteristics in these respects as is shown in Table 21.

Group I denotes *direct* insolation and its uses. This source, which will be discussed in more depth at the end of this section, has a very substantial, and for practical purposes, "unlimited" potential of 25,000 TWyr/yr reaching the surface of the earth.

Group II is a summary of the *indirect* power flows induced by solar radiation. Solar radiation is converted into *biomass* at a rate of 100 TWyr/yr. Approximately 30% of this energy is transformed into wood. Cultivated land provides 10 TWyr/yr of biomass (0.4 TWyr/yr is food; the remainder goes into uses such as fiber production and animal food). Should we be prepared to cultivate all of the continents and islands at the maximum intensity possible, given the need to prevent unacceptable soil degradation, then some 25 TWyr/yr could be obtained. If one deducts the amount of biomass needed to feed a population twice that of today, as well as the amounts serving other nonfuel

TABLE 21 Characteristics of main groups of renewable energy technologies.

| DIVERTED ENERGY FLOW | Thermo-dynamic Quality | Natural Trans-formation into Acceptable Power Densities | Storable and Transportable Natural Energy Carrier | CONVERSION TECHNOLOGY | Auxiliary Technology | Accessibility |
|---|---|---|---|---|---|---|
| Direct solar radiation (Group I) | High | No (but rela-tive simple concentrations possible) | No (but areas exist with high availability) | *Photovoltaic*<br>*STEC*<br>*Solar chemical*<br>*Heat collection* | Electrical grid additional generating capacity<br>Pipeline network<br>Back-up supply<br>Storage | Widespread<br>In sunny regions, preferably deserts<br>Widespread |
| Indirect solar use (Group II) | High | Good<br>↑<br>Poor | Poor<br>↓<br>Good | *Waves*<br>*Wind*<br>*Hydroelectricity*<br>*Biomass (wood, farmwaste)* | Elec. chem. fuel conversion<br>Elec. grid and/or add. generation<br>Elec. grid<br>None | Mostly along coastal areas with adverse climate<br>Widespread |
| Indirect Solar use (Group III) | Low | Good<br>↓<br>Poor | No | *OTEC*<br>*Water*, *Soil*, *Air* } *Heat pumps* | Elec. chem. fuel conversion<br>Increasing demand for high quality feed power backup | Along warm tropical ocean currents<br>Widespread |
| Geothermal (wet) (Group IV) | Medium | Yes | Very limited | *Power plant*<br>*District heat* | Elec. grid<br>District heating, grid | Along geological folding lines |
| Tides (Group V) | High | Yes | Very limited | *Power plants* | Elec. grid | Along a few coast-lines |

purposes (including reconditioning of the soil), some 6 TWyr/yr of biomass might be available for fuel purposes, after conversion into high-grade energy forms equivalent to high-quality coal or refined oil products.

5 TWyr/yr mechanical energy are available in the form of *hydropower*. However, approximately 2 TWyr/yr of this potential is inaccessible, due to ecological reasons (preservation of ecological systems of rivers, minimum speed of water flow, etc.) or physical reasons (finite size of technical devices; dispersed supply at heads, etc.) even in advanced programs such as the Tennessee Valley Authority Project. Thus, including glacier power, some 3 TWyr/yr could perhaps be technologically accessible.

*Wind* has a substantial physical potential. However, a large share is inaccessible as it occurs in areas (high mountains, polar regions) or heights where harvesting would be practically impossible. If one ignores the smaller contributions in the continents interiors, but assumes that *all* wind power entering on the coasts at heights up to 200 m could be captured, one obtains an estimate of 3 TWyr/yr.

A contribution of energy from *ocean currents* or *wave power* is not expected. The kinetic energy of currents is 0.2 TWyr/yr and any significant harvesting would severely impact the climatological system. With regard to wave power, no technology is yet foreseen that could efficiently convert energy both of waves 3 m in height and waves 30 m in height; the latter are typical of almost all coasts with a significant wave power potential.

Other than Group II, Group III does not refer to power flows but to temperature differences between natural heat reservoirs maintained by solar radiation.

The heat stored in *water*, *soil*, and *air* can be made accessible through heat pumps. Operation of heat pumps requires external supplies of "high-quality" mechanical energy. In the lights of overall efficiency considerations, heat pumps may above all be viewed as devices that conserve energy: a small amount of high-quality energy such as electricity is used in order to process energy produced by other sources at a relatively lower efficiency.

The *ocean thermal energy conversion* scheme (OTEC) makes use of the temperature difference between the surface layers of the oceans and the deep sea. With the systems suggested in the recent literature (ASA 1975c) 0.25 watts per $m^2$ of tropical ocean surface could be obtained, which corresponds to a technical potential of 22 TWyr/yr. However, harvesting this amount would lead to a transfer of 720 TWyr/yr of latent atmospheric heat into the system of ocean currents transporting 3000 TWyr/yr from the tropical regions to the polar regions. Within a few decades the temperature gradients in the oceans would obviously be changed. Exploiting the natural heat flows between the upper layers of the oceans and the deep sea would reduce the OTEC potential to merely 1 TWyr/yr (Wick and Schmitt 1977). Only such modes of OTEC could strictly be considered as *renewable* technologies.

Our estimates consider the 1 TWyr/yr potential. The heat source tapped by OTEC is of a very low quality only, and would therefore require an extremely large-scale deployment of facilities, making even an electricity generation of 1 TWyr/yr a gigantic undertaking. In view of the substantial technological problems and of the possibly significant side-effects, which are only poorly understood, we have assumed that it would be prudent to consider this value to remain an upper limit for the next 30 years.

The same dichotomy, between a large heat storage and a comparatively small flow, characterizes *geothermal energy* (Group IV). The case of dry geothermal energy, that is, heat stored in the earth crust, requires a technology not yet conceived. Our estimate of wet geothermal sources is based on two studies made in the U.S.A. (Geothermal Resource Group 1979; Armstead 1978). From those statistics we have inferred a potential of 2 TWyr/yr for the world.

Group V considers the energy provided by planetary motion. 3 TWyr/yr is dissipated in the form of tidal energy. But only a very small percentage of this energy can be collected in practice. Only in very few locations are the tidal levels high enough, and suitable basins for intermediate storage constitute a further constraint. An overall potential of not more than 0.04 TWyr/yr within 50 years seems realizable.

Table 22 adds up the technical potentials of renewable sources to an impressive 15 TWyr/yr, which is twice the world's energy consumption in 1975. Note that the foregoing considerations of renewable sources merely concentrated on physical aspects, leaving aside the economics and uses of renewables.

Indeed, the applicability of renewable sources varies greatly, depending on the infrastructure in which they are to be embedded. Thus, in less developed societies, standards of "continuous" availability and "easy" convertability can be of little importance if the alternative is mostly nonavailability or nonapplicability. Economic considerations will seldom constrain the use of noncommercial

TABLE 22 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 | |

fuels since, in the near term, alternatives will not be accessible to these countries lacking a wide transmission infrastructure. Such considerations are characteristic of a *user*-oriented approach, according to which the collection and disposal of energy should be adjusted to the user's needs and purposes (Table 23).

A. Khan (1980) has estimated the potential contribution of renewable energy in the world's developing regions (excepting China). Under the inclusion of urban users, he arrives at a renewables' share in 2030 of 0.7-1.1 TWyr/yr of final energy; the assumed total final energy demand is 4.41-7.45 TWyr/yr for a population of 4.7 billion. Scaled up proportionally to include China, the estimated use of renewables in developing regions is expected to be at most 1.35 TWyr/yr, in terms of what seems socially and practically achievable. By far the largest share of 1.15 TWyr/yr comes from biomass (firewood, straw, biogas, dung, etc.), mainly in the form of charcoal. User-collected electricity from wind and hydropower could reach 0.1 TWyr/yr. Direct solar energy, supplied locally, is less important (0.01 TWyr/yr of heat) than might be expected: the demand for comfort heating is low, and solar cooling has failed to gain acceptance in spite of repeated attempts at introducing it in these regions.

TABLE 23 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.

Highly industrialized regions, in contrast, are characterized by a very high degree of urbanization and a dense infrastructure. Continuous availability and easy convertability are important. However, a tightly knit network between sources and a great variety of options available ease these requirements: grids provide relatively simple backup systems and help to embed intermittent sources of supply. But they also make alternatives accessible, and therefore economics rapidly become a constraining factor. High demand densities due to extensive urbanization require a substantial effort of commercial collection and concentration of energy, reducing sharply the potential for a user-oriented approach. As Figure 17 indicates, the densities of most renewable options are significantly below those of present urban demand.

This is borne out by a recent case study, sponsored by the U.S. Department of Energy (1978) on the ways in which California could be brought to use a maximum of distributed energy forms. It was concluded that under California's very favorable conditions and with a very unusual conservation effort (final energy demand in 2025 does not exceed today's value), induced by a fourfold energy price increase, California could become nearly energy self-sufficient by 2025 by basing its supply almost exclusively on renewable sources.

Most of this energy produced, however, requires centralized processing and commercial distribution. Direct solar energy only is applied in a user-oriented mode; and, whenever this is possible, direct solar is also used for cogeneration of electricity.

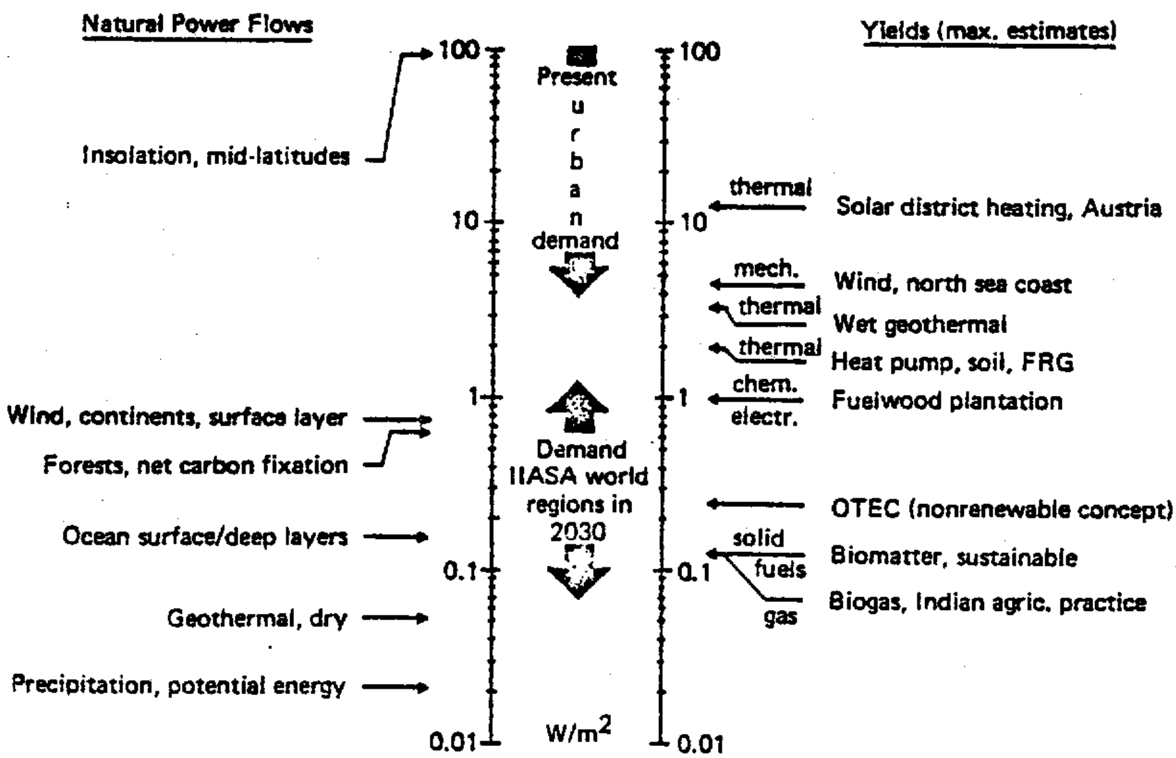



FIGURE 17 Energy supply densities.

Assuming 1/3 of that electricity to be consumed by the producer, California would need 0.052 TWyr/yr of solar heat and 0.002 TWyr/yr of electricity that would be obtained in ways other than by the regular electricity grid.

From those figures we have inferred for the industrialized regions by 2030 a maximum consumption of 2.2 TWyr/yr of direct solar heat and 0.08 TWyr/yr of electricity in a user-oriented mode.

To these contributions for both developed and developing regions, another source must be added. If most of the wood scrap generated by the lumber and paper industry should be used for energy purposes, this industry could become more or less energy self-sufficient. Assuming a growing efficiency in energy use in that industry to match increasing per-capita demands, we estimated that 0.8 TWyr/yr could be provided. This value, however, corresponds to a harvest of perhaps 2.4 TWyr/yr of energy equivalent in the form of nonfuel use of wood, which certainly is close to the maximum limits of a possible annual forest harvest.

In summary, the worldwide potential for a user-oriented consumption of renewable energy is up to some 4-5 TWyr/yr (Table 23). We do not believe that this figure can be exceeded, but there are many possibilities, and perhaps also certain probabilities, for shortfalls to arise. Note that with the price of photoelectric cells approaching a roughly commercial level the use of direct solar energy might be significantly higher.

*Costs* of renewable sources vary greatly, and are characterized by grave uncertainties. If used on a large scale beyond a locally practical level, these sources require storage, backup, transportation and distribution. Moreover, they are generally land-intensive and lead to noneconomic costs to be compensated by, for example, royalties payments. On the other hand, fuel costs are nil, and only operation and maintenance costs add to the capital cost of the basic installations. At the same time, considerations of balance of payments might provide an incentive, and noneconomic factors, such as safety of supply, etc. offer a commercially judgable bonus by lessening, for instance, the economic burden of introducing and maintaining an emergency storage system.

Table 24 gives some estimates of the investment costs relative to the yearly energy output, which may serve as a yardstick for comparing electricity generating technologies. The examples chosen are considered typical cases. No storage and transmission costs were included. Most renewable options appear quite competitive.

In Table 25 two different costing standards are applied to technologies that provide material energy carriers for local consumption, depending on whether investment or operating charges are dominant. Firewood, biogas and wet geothermal compare favorably with the retail price of light fuel oil. Heat pumps are competitive where cheap electricity and groundwater is available. The cost of solar panels would have to be reduced significantly.

All the figures given are very rough estimates under generally favorable conditions to be used for reference purposes only. Present literature contains a wide range of values, both higher and lower than the ones used here. However, considering that we can expect highly favorable economic conditions in some regions

TABLE 24 Electricity from renewable sources: examples of capital costs and contribution to electrical costs.

| Technology | Plant Capacity | Investment Costs (1975$/MW(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 | 4,000 | 2.0 | Mature, |
| Low head | 250 MW(e) | 1,400 | 4,000 | 3.4 | deployed |
| Tidal Power | 1.6 GW(e) | 400 | 2,000 | 1.95 | Under design, experience with large pilot plants |
| Wind | 6 kW(e) | 1,600 | 2,500 | 6.4 | Some commercial experience, projects, studies under way |
| | 3 MW(e) | 450 | 2,500 | 1.8 | |
| OTEC | 100 MW(e) | 650 | 6,500 | 1.0 | Studies |
| *For comparison* | | | | | |
| Direct solar[c] | 100 MW(e) | 3,000 | 6,000 | 5 | |
| Oil-fired (including oil well and transport) | 300 MW(e) | 650 | 4,000 | 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% *fixed capital charge.*

[c]Heliostats at 2 × U.S. Department of Energy cost targets; includes 9 to 12 hours of energy storage; southwestern United States.

SOURCES: Based on data from ASA (1975b, 1975c, 1975d).

TABLE 25 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 to 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) | 6,000 | Geyser fields, Iceland; cost of delivered hot water as fuel equivalent |
| Hot dry rocks, geothermal anomalies | 400 extraction (+)1,000 (distribution) | 28 (CCI) | 2,500 | Feasibility study |
| Heat pumps: electric schemes | 2,100 (high estimate)<br>800 (low estimate) | 42 (CCI)<br>16 (CCI) | 1,700 | One third of heat supplied by electricity if water is available as a heat source |
| Solar panels: residential heating | 7,500[b] | 150 (CCI) | 1,700 | 50% fossil fuel backup |
| *For comparison* | | | | |
| Light fuel oil | 100-200 | 20 (FC) | Negligible storage costs | Retail price (1976) |
| | | 70 (FC) | 1,700 | Cost of delivered hot water from district heating system, as fuel equivalent |

[a]The cost levels refer approximately to those layouts which were chosen to estimate the technical potentials in Table 22. 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 and d).*

and forbidding ones in others, the economic factors will lead to a bandwidth of possible uses of a specific technology that is very close to neither a maximum use nor to no use at all.

W. Sassin and B. Spinrad (Energy Systems Program Group of IIASA 1981) have attempted, in a judgmental way, and assuming generally favorable conditions, to synthesize these considerations into estimates of the renewables potential practically realizable within the next 50 years. The actual values are summarized in Table 26 and compared to the technical potential.

The technical potential of *biomass* was estimated to be 6 TWyr/yr. Subtracting the user-oriented contributions, 4.05 TWyr/yr remains for commercial processes.

We can expect that the 0.8 TWyr/yr gathered and used by the lumber and paper industry will be fully consumed. In contrast, we judge that only slightly more than 3/4 of the user-oriented potential of wood in the developing nations will be realized due to the mismatch between supply and demand distribution: most of the demand is generated in South East Asia, whereas the largest resources are found in Africa.

The commercial exploitation of biomass is constrained by competitive land use and economics. The priority of energy production from biomass in a world of 8 billion people will be second priority--and food production first--so that probably not more than 50% of the crops anticipated will be available. The high transportation costs of charcoal indicate the necessity to produce a liquid--whose conversion is less efficient however (30% instead of 50%). Against this background, possible commercial use of biomass will not exceed 3.1 TWyr/yr, resulting in a practically realizable potential of slightly less than 5 TWyr/yr of secondary energy.

*Urban waste* is a residual form of biomass that can be used for organic and inorganic purposes. Some 0.3 TWyr/yr might become available from this source.

The technical potential of hydropower is estimated to be reduced to 50% in practice, because of competitive uses (irrigation, preservation of ecological values, navigation) as well as technical and social restrictions. With the economics assumed to be favorable, some 1.5 TWyr/yr should be realizable.

Economic and aesthetic considerations as well as land use are the factors constraining the use of *wind power*. Furthermore, this intermittent energy source must be integrated into a system with a major storage capacity and a sufficient thermal baseload. Thus, even if dispersed uses of wind for water pumping and very small-scale electricity uses are included, it would not be reasonable to expect more than 1 TWyr/yr to be realized.

Arbitrarily, the realizable potential of wet *geothermal energy* is estimated to be half the technical potential. The mismatch between resources and users as well as ecological constraints (pollution) are considered to be the most restraining factors. One half of the estimated 1.0 TWyr/yr is expected to be used as low-temperature heat, while the other half is assumed to be used for generating electricity at a 20% conversion efficiency.

*Local solar energy* is mostly constrained by its low economics. Out of a 2.2 TWyr/yr potential, only slightly more than 40% (approximately 0.9 TWyr/yr) would be realized, all of which is used in the form of low-temperature heat.

TABLE 26 Comparison of technical and realizable potential.

| Source | Technical Potential (TWyr/yr) | Realizable Potential (TWyr/yr) | Constraint | 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% 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<br>0.005 | 0 | Computational | Amount available insignificant compared with uncertainties of other estimates. |
| Total | $\doteq$15 | $\doteq$ 9.6 | | |

[a]Not included in Table 22. For general discussion see this chapter's section on the Solar Option.

For physical and technical reasons, *waves*, *tides* and *ocean currents* cannot be expected to provide any globally significant amounts of energy. OTEC technology and economy are still little understood so that an assumed 0.5 TWyr/yr seems and ample potential.

## Conclusion

Renewable energy sources could altogether contribute perhaps up to 9.6 TWyr/yr to the world's energy supply in the form of secondary energy. In terms of primary energy, this is the equivalent of 14-15 TWyr/yr of fossil fuel or 15 TWyr/yr of nuclear power, for example; a comparable mix of secondary energy is illustrated in Table 27.

However, this energy does not come from a simple source. Several technologies, very different in scope and character, will have to be developed and deployed, which requires a host of additional efforts of R&D, commercialization, and marketing.

This enterprise would mean an all out effort, on the borderline of what seems feasible. In Table 28 we compare our results with the California study (U.S. Department of Energy 1978) mentioned above and with a study made by Revelle (1979). In California's sophisticated and extremely favorable context, an output energy density of 0.3 $W/m^2$ is achieved, traded off against the use of virtually all the useable land (100% commercial forests and agricultural land plus 50% of noncommercial woods, brush, and grass land). Revelle's study relies on a less sophisticated technology: its result is a density of 0.09 $W/m^2$, which is also contingent on an almost total commitment of land use. Thus the value of 1 $W/m^2$ yield density for the world that characterizes our study demands an enormous land use as well as substantial technological advancements. A big step towards a world cultivated like a garden would be taken if existing equilibria were supplemented or replaced by new equilibria that have to be controlled or be controllable by man.

Moreover, renewable sources harvested at 0.1 $W/m^2$ could sustain a population with 100 persons/$km^2$ consuming 1 kWyr/yr each. But enhanced urbanization and much higher consumption densities must be expected. The idea to conceive systems that predominantly or even exclusively rely on renewables misses the point.

TABLE 27 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 |
| (Unprocessed primary fuel) | 3.0 |
| Total | ≐9.6 |

TABLE 28 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) | $38.6 \times 10^6$ | $3{,}250 \times 10^6$[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 commerical forests and agricultural land plus 50% of non-commercial 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.

Introducing renewable sources on the scale contemplated here necessitates development of new infrastructures. From a market penetration point of view, most renewable technologies--not considering perhaps biomass, which only must retain its present share--will therefore encounter severe problems. Institutional factors, on the other hand, might tend to slow down the introduction of such technologies. Land use allocation, the extraterritorial location of OTEC, possible continental impacts of large-scale wind use and ecological and climatological constraints presuppose a new set of both national and international instruments involving perhaps even global-sociopolitical action.

In summary, renewables are an important supplement to the world's energy supply of tomorrow. They must be treated seriously, and sensible opportunities for their employment must be grasped even if they can only meet a limited fraction of the energy needs. But it would in any case be unrealistic to consider their large-scale use as "soft". The ecological, economic, and sociopolitical factors of the deployment of renewables make their use an undertaking at least as difficult as the introduction of nuclear energy into a system so far based on the exploitation of fossil fuels.

## THE FOSSIL OPTION: HYDROCARBONS

### Estimates of the World's Conventional Oil Resources

Oil is the main energy source today meeting slightly less than half of the present total demand of 8TW yr/yr. Large amounts of oil will also be needed in the future, which means that the problem of oil supplies will remain at the forefront of the more general energy problem. Obtaining an assessment of the oil actually available has been a major focus of the Energy System Program, therefore.

About 25 estimates of ultimate world oil reserves have been compiled over the last 35 years, some of which were made by the same person or refer to each other; altogether, there might be some 12 independent estimates. It is interesting to note a general upward tendency in these estimates, which dropped in the first half of the 1970s, and converged in 1975-76 around Moody's estimate of 277 billion tons of oil.

Under a research project sponsored by the World Energy Conference and led by P. Desprairies (1977) a Delphi study was conducted on the basis of replies to a questionnaire returned by some 30 world experts. Figure 18 compares the Delphi results to other estimates. Under the assumption that by 2000 production cost should not exceed US$ 20 (1976) per barrel, 90% of the experts thought that more than 225 billion tons of oil should still be available. 25% of the experts put the figure above 225 billion tons. P. Desprairies in his 1977 analysis, points to a figure of 300 billion tons of ultimately recoverable oil reserves. This presupposes an increase in the recovery rate from 25% to 40%. By way of "educated guesses", 36% of this oil may be estimated to be produced at less than US$5/barrel, 26% in the range of US$5-US$12 per barrel, and 38% at more than US$12.

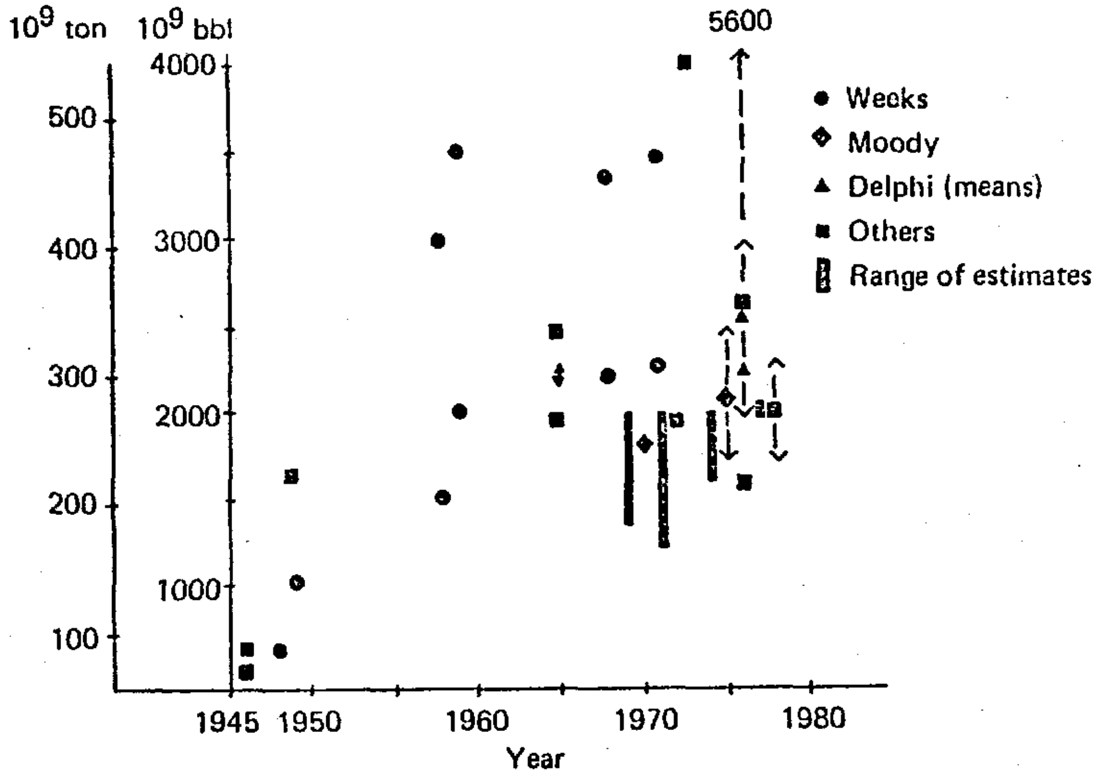



FIGURE 18 Evolution of ultimate world oil resource estimates.

Regional characteristics of these resources vary strongly even within the North American Continent, the most densely explored area in the world. Still average values can be derived. They are outlined in Table 29 and compared to estimates of the proven reserves (Desprairies 1977; International Petroleum Encyclopedia 1978; Grossling 1976) in the seven IIASA world regions. Drilling density, total number of wells, and prospective sites point to a severe exploration gap, and it might be that the estimates for Latin America, South East Asia and Africa are somewhat low.

One can argue that 300 billion tons of ultimately recoverable resources is both a low figure and a high figure. The discovery rates might well be conceived to decline quickly because all the easily accessible fields are already known. The postulated increase in the recovery rate might not materialize. Furthermore, institutional constraints might prevent exploration or development of new fields.

But there might also be a lucky strike. New technologies might permit a more thorough exploitation of existing fields, making fields and resources accessible that so far were impossible to exploit.

In the face of these enormous uncertainties, it does not appear prudent to devise any strategy for the future that relies on oil in a measure similar to that of present oil supply availability. On the other hand, oil will -- at a certain price -- continue to be a most important element of the supply system.

TABLE 29 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 $km^2$) | Total Number of Wells[c] (end of 1975) | Drilling Density (total wells/1000 $km^2$)[c] |
|---|---|---|---|---|---|
| I (NA) | 28,000 | 4,857 | 12,928 | >2,575,000 | 202.75 |
| II (SU/EE) | 46,730 | 10,670 | 9,797 | 542,325 | 55.36 |
| III (WE/JANZ) | 16,020 | 4,021 | 11,030 | 34,737 | 3.15 |
| IV (LA) | 23,000 | 5,521 | 12,444 | 103,359 | 8.31 |
| V (Af/SEA) | 21,150 | 6,176 | 17,729 | 28,281 | 1.60 |
| VI (ME/NAf) | 109,100 | 54,363 | 8,212 | 12,501 | 1.52 |
| VII (C/CPA) | 12,730 | 2,736 | 2,831 | 8,500 | 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).

Unconventional Oil Resources

Many studies point closely to unconventional oil resources, such as shales or sands, etc., as being probably by far bigger than conventional resources. They were extensively reviewed at IIASA, on the occasion of the Second IIASA Resources Conference in 1976 on 'The Future Supply of Nature-made Oil and Gas', jointly organized with the United Nations Institute for Training and Research (UNITAR) (Meyer 1977). Most of the results of that conference have, with minor modifications, been adopted by the World Energy Conference study.

The most noticeable feature of exploitation of unconventional oil resources is that it resembles more closely the exploitation of coal than of oil. Since straightforward drilling is usually not possible, in order to gain access to the energy source, large amounts of overburden will have to be moved or processed.

Furthermore, their distribution is very uneven. 90% of the world's sands and heavy crudes can be found in three countries: Canada, Venezuela, and the USSR. Approximately 300 billion tons of heavy oil and tar sands are contained in four giant fields. The Orinoco belt in Venezuela (100 billion tons); Athabasca (86 billion tons) and Cold Lake (23 billion tons) in Canada; and Olenck (86 billion tons) in the USSR. Another 27 billion tons is contained in 8 large fields in Canada, the USA, and in Madagascar. With present surface mining technologies 5-10% is recoverable. An additional 30-50% might be recovered by other techniques.

More than 420 billion tons of shale resources have been identified, two thirds of which lie in the USA. Here, too, under present conditions, 5%-10% seems recoverable.

Production costs for recovery are given from 12-15 US$/barrel (Orinoco), 12-20 US$/barrel (Athabasca), up to 20-25 US$/barrel for the Colorado oil shale (1978 U.S. dollars). Costs might be lowered through government sponsored R and D programs.

Against this background, estimates of ultimately recoverable oil resources have been provided by M. Grenon for the supply part of our scenarios (see Chapter 5). These estimates, grouped according to cost categories, are summarised in Table 30.

Gas Resources

The rapid growth of natural gas consumption is a still recent phenomenon. It started in the USA only after World War II, and in Europe during the 1960s with the discovery of the Italian, French, and Dutch fields. Until now less than 8% of the gas resources have been used up - largely in existing production plans. The volume of reserves is constantly expanding by new discoveries. New deep drilling techniques enhance gas findings, and there is no slackening in the rate at which new giant or supergiant deposits are recovered. There is strong consensus that during the next decades gas consumption and production, even in the face of storage and transportation problems, will continue to expand.

Estimates of ultimately recoverable gas resources are scarce. The values selected for our purposes are those prepared

TABLE 30 Summary of estimates of ultimately recoverable oil resources.

| | TWyr | | | $10^9$ toe | | |
|---|---|---|---|---|---|---|
| Cost Category[a] | 1 | 2 | 3 | 1 | 2 | 3 |
| Region I (NA) | 23 | 26 | 125 | 16.2 | 18.3 | 88.2 |
| Region II (SU/EE) | 37 | 45 | 69 | 26.8 | 31.8 | 49.4 |
| Region III (WE/JANZ) | 17 | 3 | 21 | 12.0 | 2.1 | 14.8 |
| Region IV (LA) | 19 | 81 | 110 | 13.4 | 57.1 | 77.6 |
| Region V (Af/SEA) | 25 | 5 | 33 | 17.6 | 3.5 | 23.3 |
| Region VI (ME/NAf) | 132 | 27 | n.e. | 93.1 | 19.0 | n.e. |
| Region VII (C/CPA) | 11 | 13 | 15 | 7.8 | 9.9 | 10.6 |
| World | 264 | 200 | 373 | 187.0 | 141.7 | 263.9 |

n.e.: no estimate made

[a]1: 12$/boe
2: 12-20$/boe
3: 20-25$/boe
(in constant 1975$)

by the US Institute of Gas Technology (Parent and Linden 1977), which have also been adopted by the WEC: 280,000 billion $m^3$ remain to be produced after 1975. Table 31 gives a tentative distribution according to the IIASA world regions. WEC experts have estimated that by 2000 75% of these resources should be recoverable at a cost of less than US$(1974) 14/boe, and the remainder at less than US$ 20/boe.

The IIASA/UNITAR Conference attempted to assess unconventional gas resources (gas in geopressure zones, in tight formation, methane from coal fields, etc.). The conference agreed that the volume of unconventional gas resources is remarkable, but it concluded that a worldwide estimate cannot be made at present. Unconventional resources might be one or two orders of magnitude higher than conventional ones.

For the purpose of the modeling effort, these considerations were synthesized into estimates per cost categories of the ultimately recoverable resources (Table 32).

## Potential Future Oil Production

Given an estimate of the ultimately recoverable oil resources, it would be interesting to know how much of this oil could be recovered and fed into the energy supply system within the study period considered.

Future oil production will have to rely on future additions to reserves, which could come from extensions of existing fields, discovery of new fields, or enhanced recovery and exploitation of unconventional resources, such as deep offshore, tar sands, or shale.

TABLE 31 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) | 7,763 | 43,500 |
| II (SU/EE) | 22,654 | 59,000 |
| III (WE/JANZ) | 5,061 | 14,500 |
| IV (LA) | 2,695 | 15,000 |
| V (Af/SEA) | 3,560 | 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 (1978).

[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.

TABLE 32 Summary of estimates of ultimately recoverable gas resources.

| Cost Categories[a] | TWyr | | | $10^{12}$ $m^3$ | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| Region I (NA) | 34 | 40 | 29 | 28.90 | 34.00 | 24.65 |
| Region II (SU/EE) | 66 | 51 | 31 | 52.70 | 40.80 | 24.65 |
| Region III (WE/JANZ) | 19 | 5 | 14 | 16.15 | 4.25 | 11.90 |
| Region IV (LA) | 17 | 12 | 14 | 14.45 | 10.20 | 11.90 |
| Region V (Af/SEA) | 16 | 10 | 14 | 13.60 | 8.50 | 11.90 |
| Region VI (ME/NAf) | 108 | 10 | 14 | 91.80 | 8.50 | 11.90 |
| Region VII (C/CPA) | 7 | 13 | 14 | 5.95 | 10.20 | 11.90 |
| World | 267 | 141 | 130 | 233.55 | 116.45 | 108.80 |

[a]1: 12\$/boe
2: 12-20\$/boe
3: 20-25\$/boe
(in constant 1975\$)

We do not expect giant new oil fields to be discovered. However, a correlation is known to exist between conventional oil finding rates, the size of exploratory drilling, and cumulative discoveries. For several regions the correlations have been analyzed qualitatively. The result thus obtained served as a basis for extrapolating conceivable additions of conventional reserves in the study period. Since little is known about such future additions we assumed similar correlations to exist but that, due to improved exploratory methods and economic incentives, unconventional resources would, in the aggregate, be discovered more rapidly than conventional resources. Figure 19 illustrates the results for conventional oil in several regions.

The introduction of enhanced (tertiary) recovery techniques could substantially increase reserves. Yet many techniques are not yet mastered on a large scale and might be also strongly constrained by physical factors, such as rock porosity, oil viscosity, etc. Note that enhanced recovery data exist only for the USA. We have assumed similar results to be obtained also in other regions, postulating however, that only conventional fields would be exploited in this way and that enhanced recovery increases reserves of conventional oil in place to 2030 by a factor of 1.25.

Oil shales production is not expected to be constrained in terms of reserves, but by market penetration dynamics and environmental impacts in terms of large-scale exploitation. Since the situation is similar to that of coal liquifaction, the same maximum buildup rates have been assumed.

The maximum potential oil production rates for the various regions were estimated under the following assumptions:

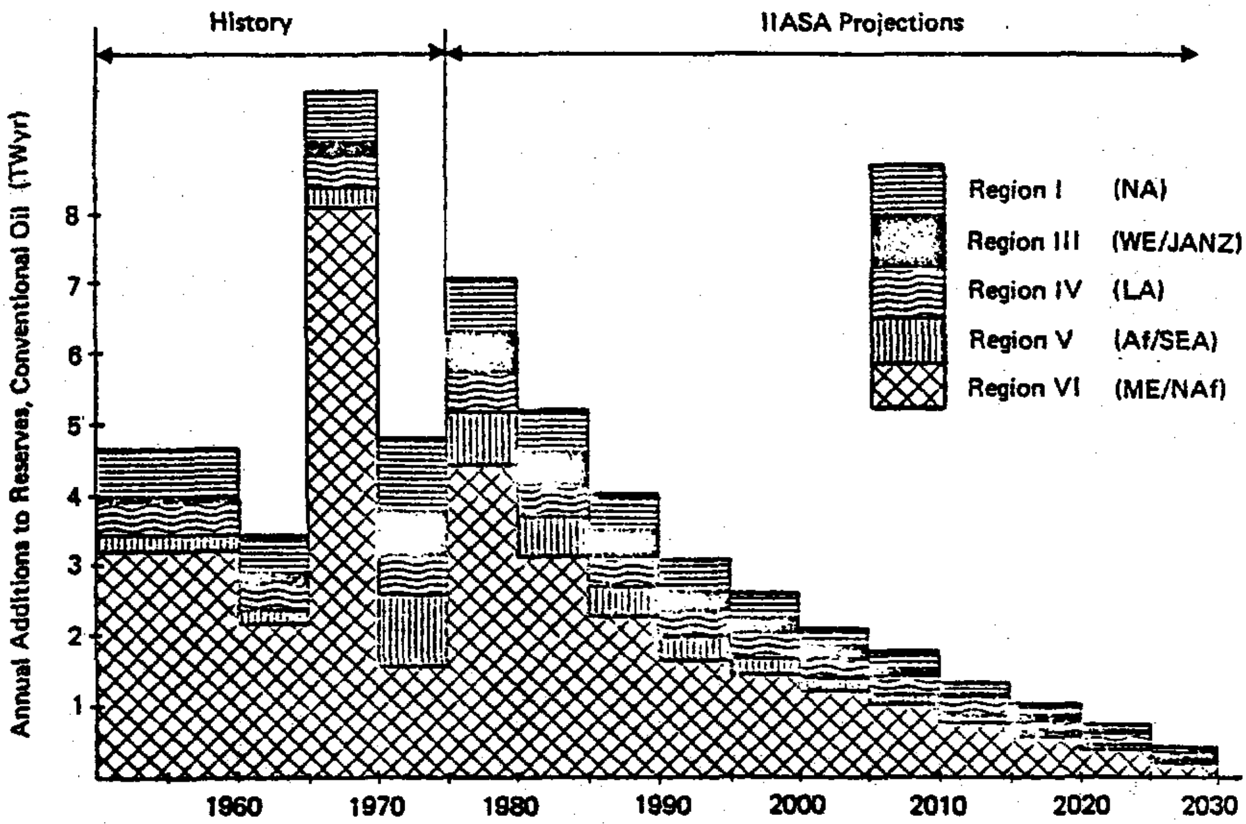



FIGURE 19 Annual gross additions to reserves of conventional oil, world except centrally-planned economies, 1975–2030.

- The limiting ratio of reserves to production is 15:1 (worldwide average) for unconventional, deep offshore, and polar region oil; 7.5:1 for enhanced recovery methods; and 25:1 for (conventional) heavy crude recovery.
- Production rates, after reaching peak levels, decline exponentially.
- Peak production for enhanced recovery is obtained after 5 years.
- Oil production plants for tar sands, shales, and heavy crudes (advanced methods) operate at constant levels over their assumed 30-year lifetimes.
- Buildup of shale or tar sand processing feasibility requires 5 years. In developed regions, once a capacity of 6 GWyr/yr is reached, this capacity might be doubled in 5 years hence.

In North America (Region I) presently known reserves will be exhausted by 2000. High, but gradually declining, additions to reserves could increase oil production by 430 GWyr/yr (2.4 billion barrels) in 2000. By 2030, conventional oil production would have declined to 120 GW, however(Figure 20a). Enhanced recovery would reach its maximum contribution of 730 GW (3.8 billion barrels/year) in 2005. The major new source would be Canadian tar sands (strip mined and in-situ conversion) which might contribute about 1 TWyr/yr by 2030. Due to restricted water availability and waste handling, oil shales will only contribute a small fraction.

North Sea oil will bring Region III oil production to a peak by 1985-90, which will decline thereafter. New discoveries in Oceania or Turkey might delay the decline somewhat, but by 2000 total conventional oil production will not be more than 340 GWyr/yr (1.8 billion barrels/year). By 2030 it will have declined to 30-50 GWyr/yr. Enhanced recovery will peak around 2010-2015 at 160-170 GWyr/yr, and deep offshore might contribute 180 to 200 GWyr/yr by 2030 (Figure 20b). Oil shales will not be able to contribute significantly.

Latin America's conventional oil production will be of the order of 430-450 GWyr/yr by 1990-1995, and decline to 160 GWyr/yr by 2030. Heavy crudes, however, might contribute very significantly if buildup constraints on drilling equipment, steam generation, and upgrading capacity are overcome. The development assumed appears modest in relation to the resource base but still leads to a production of 3 TWyr/yr in 2030 (Figure 21a)

Past development of oil production (Figure 21b) in Region V has been rapid. We assume high additions to reserves till the end of the century. Peak production of conventional oil would be around 1995-2000 at 480 to 500 GWyr/yr. Enhanced recovery and unconventional oil might bring 2030 production up to 750 GWyr/yr.

Together, Regions I, III, IV and V might thus produce 3.2 to 3.3 TWyr/yr by 2000, and 6.3 to 6.5 TWyr/yr by 2030. Those figures are very high: they denote a *maximum potential*, much in the sense of the technical potential of renewables, under optimum technical and economic conditions; actual production rates will be much lower (see Chapter 5).

As for Region VI, we have to distinguish between countries with high and low reserve-to-production ratios. The latter are

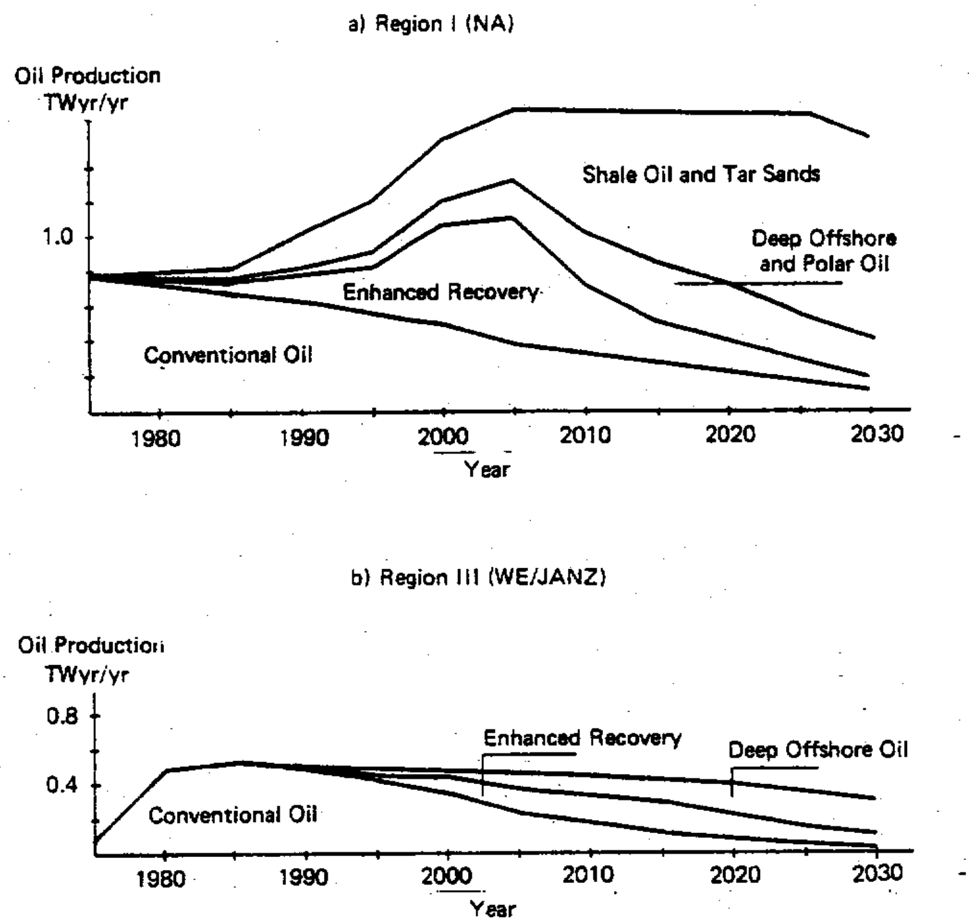
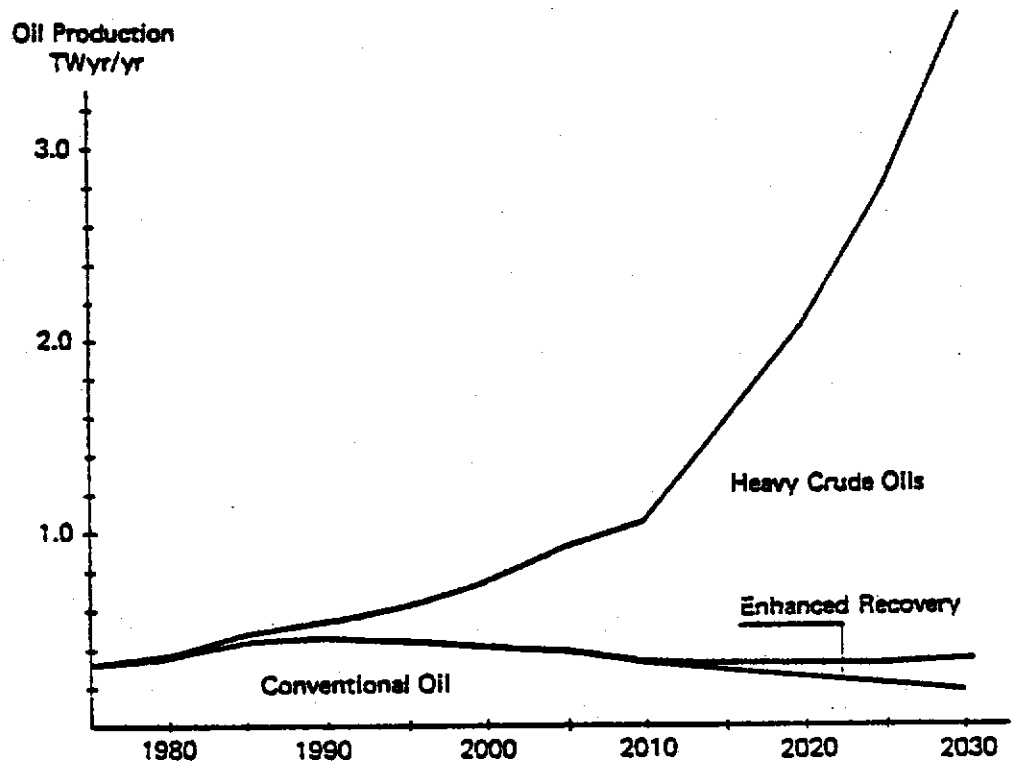



FIGURE 20 Maximum potential production profiles by type of oil in Regions I and III.

(a) Region IV (LA)




(b) Region V (Af/SEA)

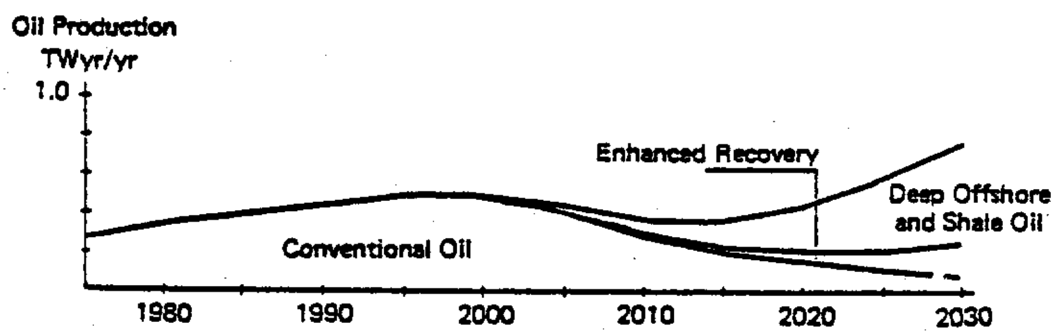



FIGURE 21 Maximum potential production profiles by type of oil in Regions IV and V.

already now producing up to capacity limits; these, as a rule, are densely populated countries with urgent development needs. In contrast, most of the former countries have a low capacity for absorbing financial income.

Saudi-Arabia, Kuwait and the United Arab Emirates, owning approximately one half of the world's conventional reserves, could in principle increase their production substantially. But, with no other resources available to them and being hard-pressed to absorb an income much above their requirements without severe socioeconomic disturbances, these countries consider limitations on oil production a necessity, in order to stretch their vital resources until they can be supplemented by alternative sources of income.

Finally, a physical doubling of production in the Arab Peninsula is doubtful. In Saudi-Arabia, the OPEC member most highly endowed, production can not, at short notice, be increased by more than a couple of million barrels per day.

In view of these considerations, we have imposed an artificial ceiling on oil production in Region VI of 33.6 mbd.

## THE FOSSIL OPTION: COAL

### Coal Between Wood and Oil

Coal development is closely linked to the origins of Western industrialized societies. As an energy source, coal has been known for almost 2000 years. Its role as main energy supplier began when energy consumption densities rapidly outstripped the local supplies of renewable energy sources, particularly wood, which until then had met the largest portion of the demand.

This transition was due to two factors. The early *industrial revolution* led to higher labor requirements, fostering rapid population growth in urban centers and centralization of economic structures. Among the energy sources available, only coal was a sufficiently concentrated form of energy to match this centralized demand. The necessary bulk transport of coal from the mines to the consuming centers was made possible by the new *railways*. The "new" fuel boosted the growth of the railway systems, raising the demand for steel and leading to a still greater need for coal.

Figure 22 illustrates that it took coal only some 80 years to replace wood as the main source of energy; providing less than 30% of the world's energy in 1850, it held 70% of the energy market by 1930.

Figure 22 also shows that coal was not able to hold its ground for long. Oil penetrated the market already before 1900 and together with natural gas initiated the decline of coal from about 1920 onward. Coal was pushed out of its predominant position as quickly as it had captured it.

This rather dramatic retreat was founded on the more sophisticated urban lifestyles of the growing cities, requiring energy in forms other than solid coal. Gas lighting, for instance, which was used for the first time already in 1825, initiated the buildup of urban pipeline networks supplied by towngas derived

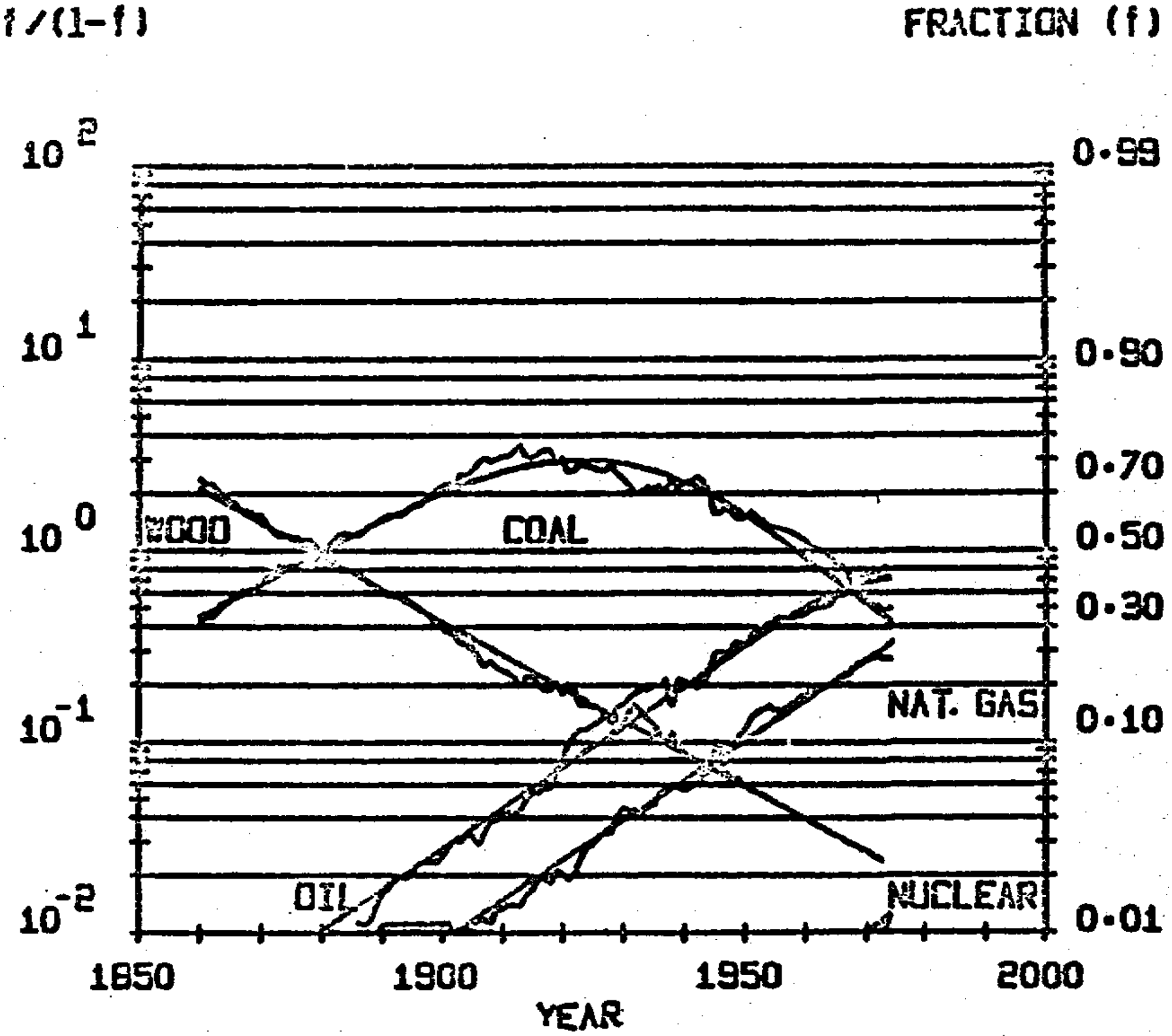



FIGURE 22 Global primary energy substitution. Logarithmic plot of the transformation F/(1-F) where F is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.

from coal. In the second half of the 19th century, electricity began to displace gas as a source of illumination, and gas was increasingly used for heat. Coal, on the other hand, quickly overtook hydropower as a main source of electricity.

Oil and gas met well with this trend towards more convenient and flexible energy services. Natural gas was an easy feed to existing grids; and oil was much easier to store and transport than coal. Oil, at the same time, and especially after World War II in Western Europe, smothered social economic constraints limiting coal production at the time. Finally, oil-fueled ships, as well as automobiles and airplanes made oil the indispensible fuel in the transportation sector.

In summary, oil and natural gas have allowed the extension and enhancement of an industrial infrastructure that was originally fueled by coal. The lower price of oil, though helpful, was less influential than these development patterns themselves, which led to specialization, a greater mobility, a high urban population density, etc. And there are no signs that the trend toward increasing sophistication will abate. On the contrary.

## Coal Resources

This development has led to the rather paradoxical situation of our present reliance on scarce hydrocarbons although the coal, i.e., carbon, resources are relatively more abundant. Compared to an estimate of 840 TWyr of ultimately recoverable oil resources, there are some 600 TWyr of known coal reserves that are accessible with present technologies--amounting to about 6% of the estimated total coal resources (10,000 TWyr) or 20% of the identified coal resources (3000 TWyr).

These figures show that, at present consumption rates, coal will be available for several centuries to come. They even seem to indicate optimistically that coal would, for a lengthy period, be able to meet the global fossil energy requirements. But several constraints might dim this view.

Coal resources, like oil resources, are very unevenly distributed. The regional and national coal resources estimates show that about 85% of the resources are located in three countries: the USSR, the USA, and China (see Table 33). This concentration creates an obvious transportation and trade problem, but also makes coal a subject of sensitive strategic considerations. Only in a stable world of political détente, with all the parties accepting the necessity for globally responsible action, can we hope that substantial amounts of coal will become available on a truly worldwide scale.

The second constraint is resource economics. No future energy system can use a source regardless of its price. Even today, there is no global reference price for coal. Factors such as quality, demand for certain types of coal, the general energy price development, etc. strongly influence the market

TABLE 33 Geological Coal Resources: worldwide and in Western Europe.

| Geological Coal Resources | $10^9$ tce | Percent of World Total |
|---|---|---|
| World | 10,126 | 100 |
| USSR | 4,860 | 48 |
| USA | 2,570 | 25.4 |
| China | 1,438 | 14.2 |
| Western Europe | 420 | 4.1 |
| FRG | 247 | 2.4 |
| UK | 164 | 1.6 |
| Others | 9 | 0.1 |

SOURCE: Based on World Energy Conference data (1978).

value of coal. A very rough figure of orientation for a relatively cheap coal might be $20/ton at the minemouth.

A. Astakhov (1980) studying the prospects of exploiting the world's major coal basins has estimated "ultimate economically recoverable resources." This category includes all resources that, in accordance with foreseeable technological improvements and labor cost trends, could become available at costs below $(1975)40/tce at the minemouth if, irrespective of the local demand, all the accessible resources were to be exploited. To some extent, the estimated volume of some 3200-3700 tce (see Table 34) corresponds to the "technical potential" of renewable sources. Under optimistic assumptions (excluding, for instance, environmental constraints, exotic basins, as well as deposits with a recoverability of less than 0.2% of the stated geological resources), some 2400 TWyr of coal might be made available at the minemouth at an average cost of $(1975)17.5/tce. Coal, other than oil, is not a cheap material to transport, and its distribution over the globe is unfavorable. Should it still become a global option it would have to be carried over long distances. The price difference between $20-30/tce at the minemouth in the Rocky Mountains and of about $50/tce after delivery to the U.S. East coast illustrates the magnitude of the problem. Introduction of long-distance electrical transmission or slurry pipelines, though difficult (large capital investments, transmission losses, environmental impacts, etc.), could help to solve the transport problem.

Against this background, as in the case of hydrocarbons, regional coal resources figures for the study period considered were estimated for two cost categories, ≤$(1975)25/tce and $(1975)25-50/tce, respectively, at the minemouth. Uncertainties made us choose rather conservative assumptions such as considering only 10% of the resources in the USSR, USA, and China. The results are summarized in Table 35.

TABLE 34 Prospective economically recoverable coal resources (TWyr).

| | |
|---|---|
| Long-term global prospects at cost levels ≤$(1975)40/tce | 3200 ÷ 3700 |
| Out of which in major basins | |
| USA | |
| Northern Rocky Mountains | 450 |
| Illinois | 130 |
| USSR | |
| Lenskij | 450? |
| Tunguskij | 300? |
| China | 800 |
| Australia | 185 |
| India | 45 |
| Total | 2360 |
| Non-exotic larger coal basins total at a weighted cost average of $(1975)17.5/tce | 2400 |

TABLE 35 Recoverable coal resources.

| Resource Unit Cost Category[a] | TWyr | | $10^9$tce | |
|---|---|---|---|---|
| | 1 | 2 | 1 | 2 |
| Region I (NA) | 174 | 232 | 188 | 250 |
| Region II (SU/EE) | 136 | 448 | 149 | 489 |
| Region III (WE/JANZ) | 93 | 151 | 100 | 163 |
| Region IV (LA) | 10 | 11 | 11 | 12 |
| Region V (Af/SEA) | 55 | 52 | 59 | 56 |
| Region VI (ME/NAf) | <1 | 1 | 0 | 1 |
| Region VII (C/CPA) | 92 | 124 | 99 | 134 |
| World | 560 | 1019 | 606 | 1105 |

[a] 1: <US$(1975) 25/tce.
2: US$(1975) 25-50/tce.

NOTE: Only a part of the ultimate resources (~15%) 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.

SOURCES: Ashley et al. (1976), Grenon (1977), and Penner and Icerman (1975).

## Conditions and Constraints for a Coal Revival

With the growing need for replacing hydrocarbons as the major energy supplier and in view of coal's very significant potential, it would seem appropriate to use more of the latter. But coal has been shown to be losing ground, and in order to reverse this trend it would have to meet certain requirements.

For one, it would have to be compatible with modern energy supply systems that are geared toward flexible and convenient secondary and final energy forms.

Success or failure of secondary energy form depends on

- its technical suitability for the consumer;
- its effective conversion, transportation, and distribution; and
- the concentration of side effects on the supply side rather than at the consumer's end.

These filters--the first two having been most prominent in the past, and the third most likely to be constraining in the future--have been pushing infrastructural development to the use of liquid fuels and grids. Figure 23 is an illustration of the secondary energy market in the FRG over the past 25 years. There is a dramatic transition from solids to liquids for heating purposes, accompanied by a slower but distinct penetration of the market by grid-supplied energy, saturating the liquids market share even before the 1973/74 oil crisis. Again, these trends are fundamentally related to infrastructure rather than to price structures or short-term availability.

Even with a further extension of grids, an irreducible demand for liquids remains. Transportation is the prime example;

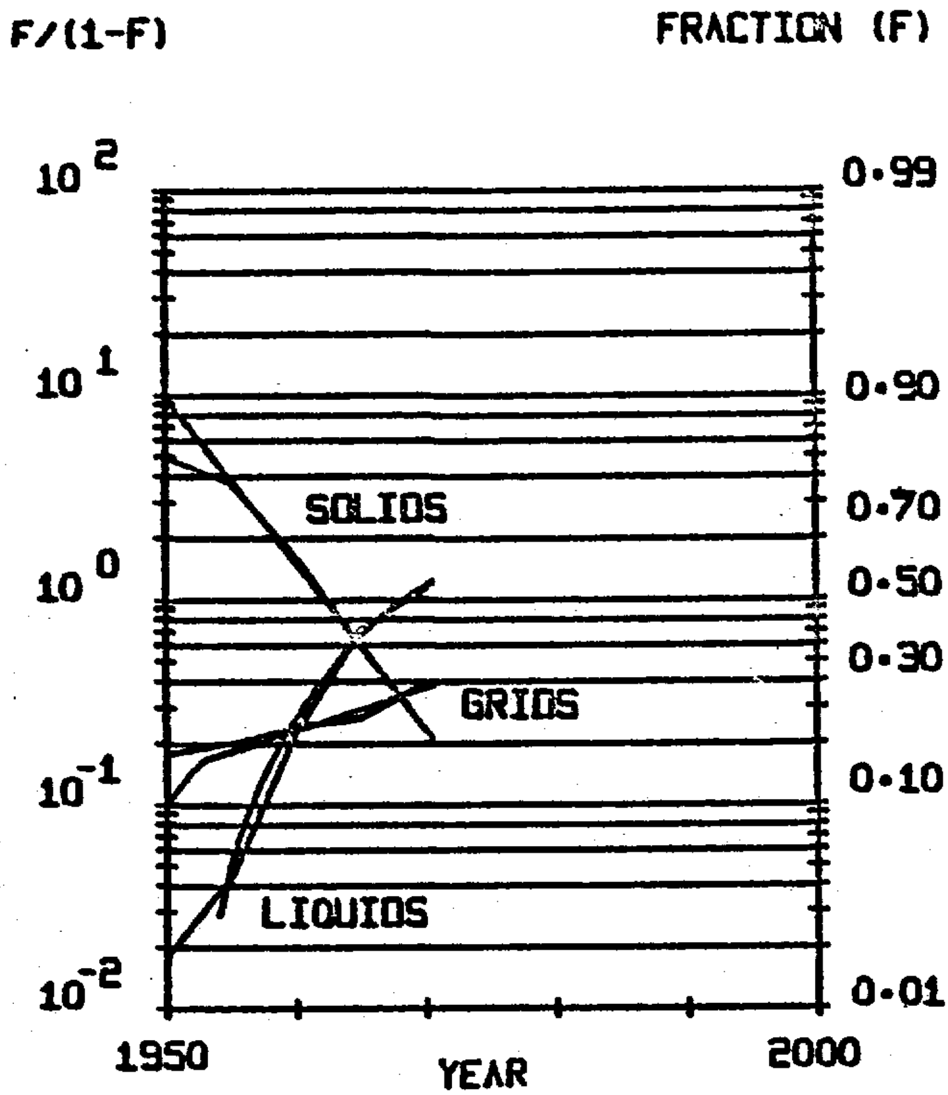



FIGURE 23 Secondary energy supply, FRG, 1950-1970. Logarithmic plot of the transformation F/(1-F) where F is the fractional market share. Smooth lines are model estimates of historical data; straight lines show the logistic model substitution paths; model estimates follow historical data and are therefore not easily distinguishable in the graph.

it accounts for about 20% of the total final energy requirements in advanced societies. Decentralized uses in rural areas or in smaller agglomerations enhance the liquid demand in industrial regions. In less developed regions, with inadequate infrastructures, the availability of energy-dense and easily transportable and storable liquid carriers is even more important. Fifty percent of the present final energy needs requires liquids. Confining liquid almost exlusively to essential uses in the future, still some 7-10 TWyr/yr of liquid secondary energy will be required.

Possible alternatives to carbonaceous synthetic energy carriers might be hydrogen or, in principle ammonia, and $SO_2$. Early hopes for a fast introduction of hydrogen have faltered;

and the technological, economic and safety features of a pure hydrogen system are still to be mastered. Nevertheless, we will see that hydrogen could play an important, if not dominant, role within the study period considered. This is not so for synthetic fuels that rely on substances other than carbon or hydrogen.

Synthetic liquids derived from coal are in fact intermediaries between nature-made petroleum and gas and a pure hydrogen society. In synthetic hydrocarbon fuels the carbon atom acts as a kind of lost storage material for the hydrogen atoms it carries. Thus coal liquefaction appears the best solution for providing the required fuel supplies, at least for the coming century, bridging the time until a pure hydrogen technology would be well in hand.

While coal liquefaction or gasification may be the best solution, the use of carbonaceous fuels obtained is not without problems. Foremost is the impact on climatic conditions of large releases of $CO_2$ to the atmosphere. This issue has been studied in some depth under the UNEP/IIASA contract on "A Systems Study of Energy and Climate", FP-0700-75-02 (717) (Williams and Krömer, 1978). The results suggest that $CO_2$ might indeed severely constrain the use of fossil fuels. But they also indicate that if the fossil carbon context is handled prudently, releases might be held low enough so as to prevent climatic changes from rising too rapidly for mankind to adjust to. A liquid hydrocarbon consumption of 10 TWyr/yr might thus still be acceptable. Yet the overall goal must be to save the carbon for specific purposes.

This requirement coincides with other environmental considerations. Mining operation hazards, particulate emissions, emission of sulfur and nitrogen oxides, etc.--they all support a prudent use of the carbon atom.

Therefore, in order to recapture a major energy market share and thus substantially contribute to the world's energy supply, coal as an energy source must be adjusted so that:

- it becomes a flexible, easily transportable and storable energy carrier;
- the potential hazards of its large-scale use can be minimized (in particular $CO_2$);
- the large but nonetheless exhaustible recoverable resources can be properly managed; and
- the transition may be easier to a future noncarbon system that most probably is based on hydrogen.

A promising candidate for such a fuel is methanol. It can be synthesized from coal and other residual fossil fuels as is outlined in Figure 24. Coal is first gasified by partial combustion with oxygen and then combined with hydrogen to form methanol. The excess hydrogen needed may be provided via a shift reaction with gasified coal and steam, or through thermolytic or electrolytic water splitting using solar or nuclear heat or electricity as the primary energy, as will be described in the following subsection. In the latter case, no $CO_2$ is released during the entire process; coal is not only a source of energy but also functions as chemical carrier for hydrogen. Figure 25 illustrates this; the energy content of the methanol obtained is twice that of the coal input, which is the most economical way of using coal for production of a synthetic hydrocarbon.

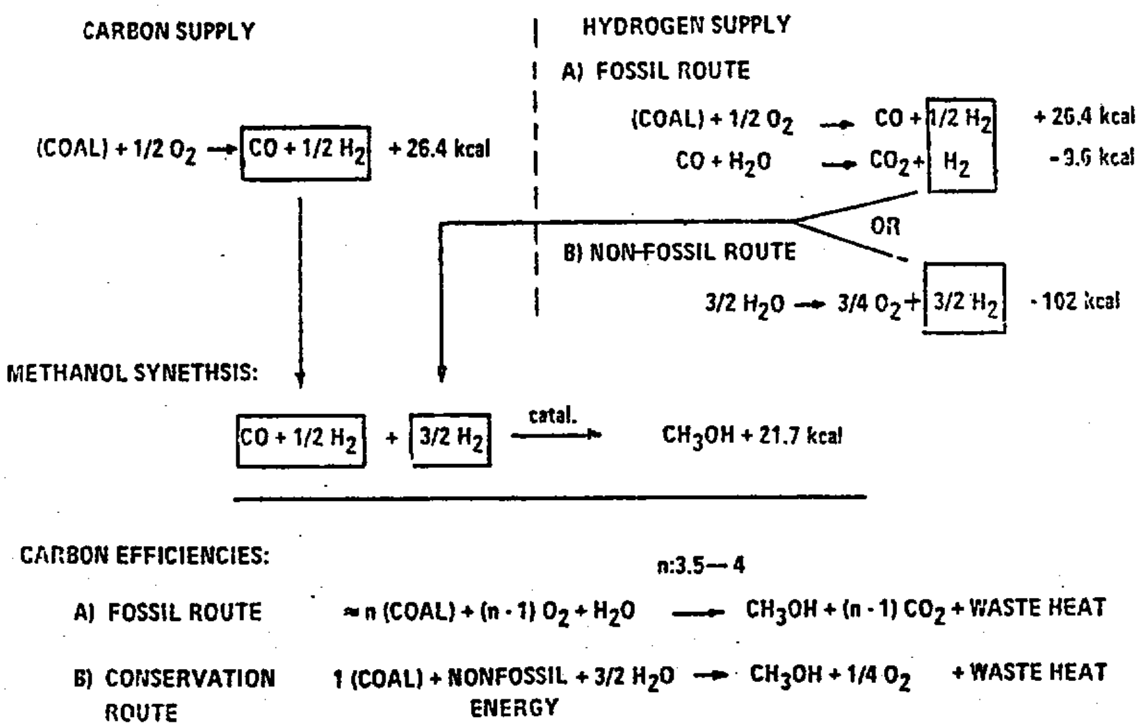



FIGURE 24 Methanol production routes.

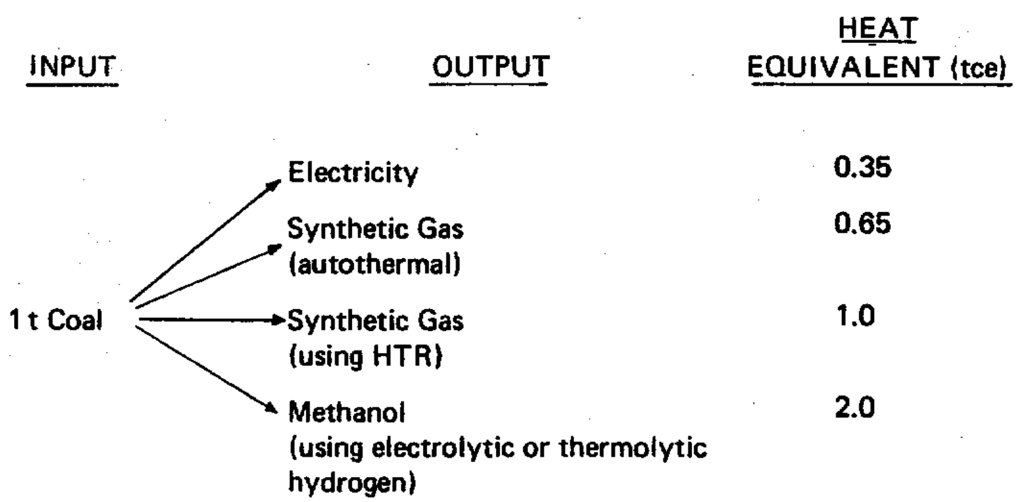



FIGURE 25 Efficient use of carbon atoms.

Methanol is a liquid that could be incorporated into our system of consumption without major technological changes since, technologically speaking and with respect to use, transport, and storage, it does not differ much from gasoline. But its density is half that of gasoline, and its large-scale use would require additional infrastructural investments--but these are still lower than those that would be needed for direct use of solid coal. On the other hand, as an alcohol it has clear environmental advantages over present fuels: air pollution is much less, spillage into water has less dramatic impacts, etc.

## Coal's Potential Contribution

So far the analysis has shown that a revival of coal will not be easy though most probably necessary. Any coal strategy would probably have to rely extensively on a coal liquefaction scheme because of structural (e.g., transport, demand for liquids, etc.) and environmental reasons (e.g., minimizing $CO_2$ releases, concentration of detrimental effects, etc.).

The most difficult step in the chain from mining to using a liquid synthetic fuel is to convert the solid coal into a raw gas suitable for further conversion. Two basic requirements must be fulfilled:

1 This conversion should work for all types of coal, ranging from anthracite to the lowest-quality lignites; and
2 It must be appropriate for commercialization on a terawatt scale around the turn of the century.

Only few processes are known today to produce a gas suitable for further synthesis. Most of them, however, are carefully designed for an optimal utilization of a narrow choice of coals. The reference gasification technology discussed here is the molten iron process (MIP) investigated by Klöckner Humboldt, FRG, and other companies. It has been chosen to serve as a basis for quantitative estimates and not to support prediction of a certain technological development.

The molten iron process is conceived to use an iron-steel converter. Pure oxygen and carbon, together with minerals capable of forming a particular type of slag, are fed into the bottom of the converter. The carbon is dissolved and oxidized in a liquid iron bath and leaves the converter as CO. Impurities such as sulfur are taken up by the slag forming on top of the bath. A tandem concept (illustrated in Figure 26) would allow impurities to be separated while achieving a high carbon utilization factor. The discontinuous transformation process requires two separate gas and slag handling systems but only one iron loop.

Technologically, the molten iron process is derived from the widely used LD steel technology, which may be indicative of the technological feasibility of the MIP and its potential for large-scale coal conversion. With the main components already operating on the scale that will be required, one can attempt to obtain prospective cost estimates. A technoeconomic study (Mietzner and Schwerdtfeger, 1980) based on the performance

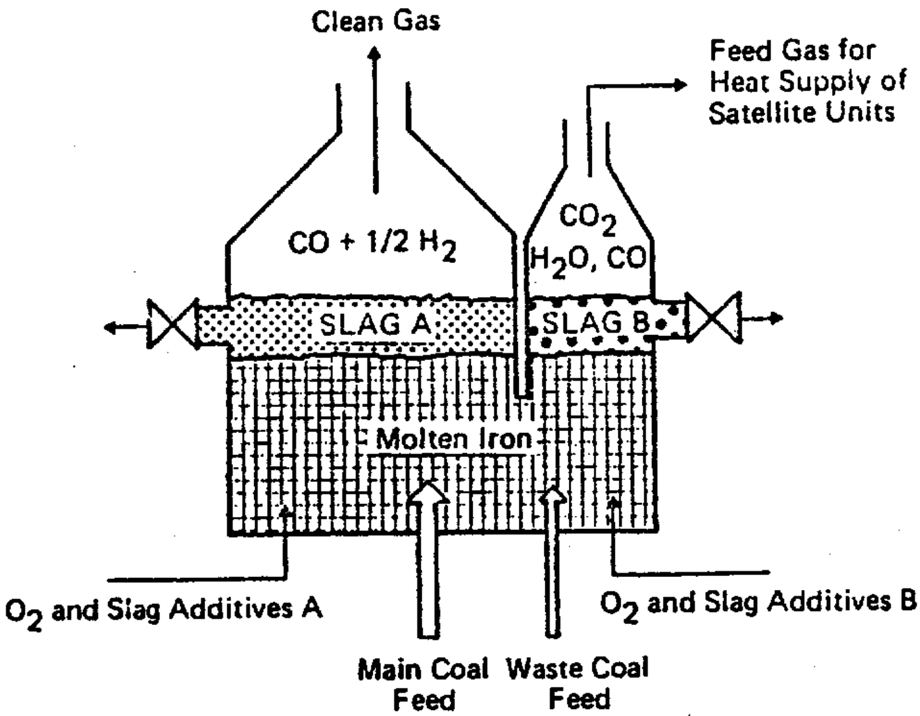



FIGURE 26 The Linz-Donawitz (LD) process modified for coal gasification for synthetic liquid fuels production: TANDEM scheme. A and B distinguish between two different slag additives. SOURCE: Based on Mietzner and Schwerdtfeger (1980).

data of steel converters points to a prospective investment cost level of US$ 100 per continuous kW of coal input for unit sizes in the GW range.

However, the change from present uses of coal (e.g., as heat or electricity source) to substitutions for natural hydrocarbons will not occur overnight. The bulk coal supply up to 2000 would still go to the traditional uses. After 2000, however, coal would increasingly have to substitute for natural liquid hydrocarbons.

Figure 27 depicts two alternative strategies. Curve (a) is based on a projection of present growth rates in coal industry until 2020. It implies GW methanol production to set in by the beginning of the 1990s and substituting nonfossil hydrogen for hydrogen from coal to start by 2010. Thus with a share of 12% of the geological coal resources, a liquid hydrogen production of 10 TWyr/yr could be sustained for more than a century.

This is contrasted by curve (b), a high fossil energy strategy supplying 15-17 TWyr/yr of liquids over a long time which accounts for delays in the introduction of nonfossil energy sources. With a total resource requirement of 24% of the geological resources, strategy (b) probably touches upon the limits of nonexotic recoverable resources. Any higher production than the latter would severely cut the investment capability of societies to adapt nuclear and solar energy to future settlement and lifestyle patterns and thereby shift coal use from investment to consumption.

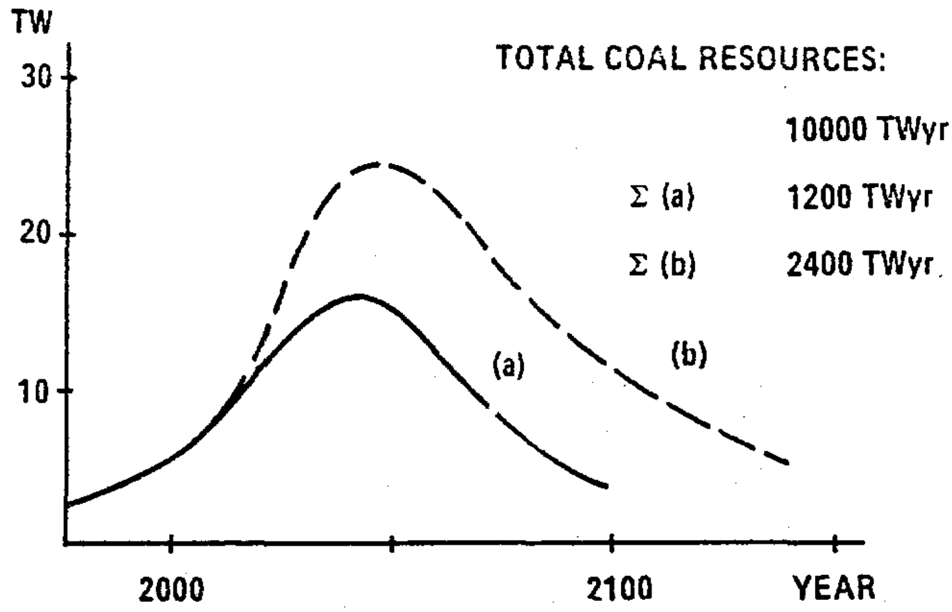



FIGURE 27 Resource requirements for alternative "maximum" coal strategies.

Over time, curve (a) will most probably not exceed environmentally "prudent" $CO_2$ release levels. Curve (b) might well go beyond acceptable levels, and therefore, is a "maximum" coal strategy by definition.

In both cases, coal would have to commence its new and nontraditional role as a liquid in an autothermal conversion scheme, in order to compete with the natural liquid hydrocarbons. Then, for the more expensive fossil hydrogen economy to develop, the prices of oil and gas would have to be still higher. It is crucial therefore, to build up a system that is flexible enough to involve nonfossil hydrogen at a later date. Methanol production qualifies well since, as we have seen, it permits decoupling front end gasification of the coal from its synthesis into a liquid.

However, as we have noted the transition to nonfossil hydrogen is much slower in the maximum coal strategy curve (b). Here, coal use is maximized by keeping the short-term economic costs low, and the emphasis is on coal as a primary energy source. If one estimates the investment cost of an MIP-based autothermal scheme by target figures of US$ 400-800 per continuous kW of methanol, and if one assumes a conversion efficiency of 0.65, adding a bonus of 10$/bbl of crude for refining costs and losses, a coal at a minemouth cost of US$ 25-70 per tce could be transformed into a liquid at a bbl cost of US$(1975)12.5-30. In spite of the recent dramatic changes in the world oil market this indicates that, at the beginning, coal liquefaction will have to rely on the cheapest coal available and perhaps on some form of subsidy.

What concrete medium-term measures would be necessary to efficiently enhance the uses of coal has been studied in a joint task force with institutions in the FRG and the UK, analyzing possible coal strategies for those two countries (Sassin, Hoffmann, and Sadnicki, 1977). The two countries were chosen because both, as major producers, are experiencing a stagnation or even decline

| New coal technologies coming in instead of: | Penetration of New Technologies. Year | Level of coal use (1% of market) | Time to penetrate from 1% to 50% of market (yr) | Characteristics of New Technologies | Final Energy Forms in the year 2000 to be served by New Technologies |
|---|---|---|---|---|---|
| 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 28 New coal technologies, their penetration characteristics, and applications in the FRG as projected for the year 2000.

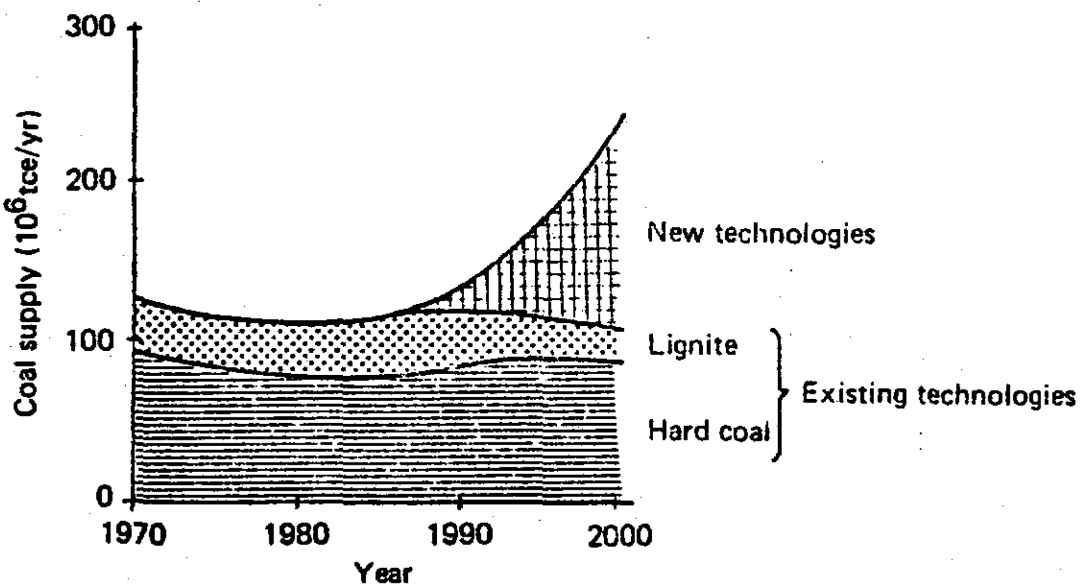



FIGURE 29 Uses of coal by existing and new technologies, FRG, 1970-2000.

of their coal industry. Thus, any strategy leading to a revival of their coal sectors would certainly presuppose conditions at least as favorable as those now prevailing in Poland or the USSR, for instance. Besides coal technologies that are soon to mature technologically and which would offer a competitive secondary energy form for broad existing submarkets, several pathways towards new patterns of coal use were determined (see Figure 28). Assuming availability of mechanisms based on energies derived from coal at the same time these energies become competitive, one could identify unexpectedly high potentials for coal use. Figure 29 summarizes the results for the FRG. For the UK a similar pattern would arise 10-15 years later due to North Sea oil exploitation.

Both investigations reveal that this potential of coal will not be realizable under normal market conditions, notably since newly introduced technologies take a long time to affect consumption rates and since large investments would be required at a time of stagnation in the coal industries.

These findings were extensively discussed and compared to other national case studies at the 1977 International Coal Conference in Moscow, organized by IIASA together with the Moscow All-Union Institute for Systems Studies (1977). Their main conclusion was that the technologies under development mostly concentrate on electricity, pipeline gas, or district heat and do not prepare for liquid coal. This observation confirms that a fundamental mismatch exists between planning tendencies toward expanding the traditional uses and the ever greater long-term necessity to enhance coal use for liquid purposes.

## Summary Evaluation of Coal

Coal resources are very large. In principle, coal could conceivably become the top primary energy source in the next century. Half of the geological coal resources would theoretically suffice to meet even the requirements of the High scenario until the end of the 21st century. This potential, which basically compares to the technical potential of renewables, does not account for fundamental constraints. In terms of a realizable potential, a maximum primary coal strategy would be capable of sustaining a peak supply of 20-25 TWyr/yr around 2050, provided the institutional and structural constraints can be overcome.

The question remains whether such a strategy is desirable. The situation of coal among the various energy options is a peculiar one. Its actual "potential" does not lie in its primary use but in its suitability as a chemical carrier for solar- and nuclear-produced hydrogen. This role of coal would strengthen the introduction of nonfossil technologies, smoothen the transition towards a secondary energy system relying exclusively on hydrogen. Using coal in this way would mean to invest into an energy future that is not constrained by fossil resources and resource-dependent technologies.

By way of such a strategy of investive coal use, autothermal coal conversion would have to be introduced first in order to revise the present downward trend of coal within the given economic constraints and then, gradually, as the prices of alternative liquid or gaseous energy carriers increase, hydrogen from nonfossil resources would become a substitute for hydrogen from coal. The sooner this transition takes place the better one of man's few truly large natural resource assets could be managed and be preserved.

## THE NUCLEAR OPTION

### The Scope of the Investigations

Nuclear energy is one of the most promising technologies. That it can contribute a large share of the future energy requirements is undisputed. Still it is one of the most hotly debated issues of today. Though its scientific basis is well known and understood, most nonscientists view it as a mysterious and extremely complicated and new technology--even after some 20 years of practical experience.

Its real potential can only be appreciated if it is considered in the appropriate framework. Today, the need for a transition away from resource-limited technologies to energy options sustainable in the long term is not yet really felt, and the consequences of having to balance global demand and supply on a level of 20, 30, 50 or more TWyr/yr is not yet understood. It is this long-term global background, however, against which nuclear energy must be judged: the pressing reasons for beginning the nuclear adventure now root in the requirements of the next century.

To use nuclear energy in such a large-scale fashion requires that it be released from the constraints imposed by the electricity market. Therefore, a major thrust of our investigation has been directed towards the study of nonelectric applications. Already in 1975, on the occasion of the European Nuclear Conference on Nuclear Energy Maturity in Paris, W. Häfele and W. Sassin (1975) pointed in this direction. Their paper concluded that nuclear energy was originally considered a means of technological innovation, *the* spearhead of modern technology in the 1950s. Its typically large units and high power density made it an ideal candidate for electricity generation. If nuclear energy was to contribute to the future energy supply, its use would have to shift toward the production of process heat and liquid energy carriers. The paper identified hydrogen produced by thermochemical or electrolytical water splitting as the most probable long-term, future use of nuclear energy at the time the asymptotic stage of the nuclear system would be reached. It concluded that an all-nuclear supply would be possible in principle, and described the main features of a related strategy.

The second line of using nuclear energy on a large scale is the deployment of a nuclear fuel cycle. In the fall of 1975 R. Avenhaus, W. Häfele, and B.E. McGrath (1975) published a study evaluating the order of magnitude of hazards and risks involved in the large throughputs of a conceived asymptotic nuclear system. The analysis included mass flows of nuclear material, normal operational radioactive releases, the problem of waste storage as well as potential hazards from blackmail or sabotage, including the construction of a nuclear device. The paper concludes with several decision-oriented assessments.

Fission breeding is one long-term nuclear technology, fusion is the other one. Our third large effort in the nuclear field was a comparison of the fission and fusion breeder technologies (Häfele et al. 1977). The format of a task force was chosen, comprising experts of the University of Berkeley, the University of Wisconsin, and Lawrence Livermore Laboratory in the USA, Gesellschaft für Kernforschung, Karlsruhe, FRG, the Institute of High Temperature and the Academy of Sciences, Moscow, USSR, as well as Energy Systems Program members. The two year effort led to several substantial conclusions: neither technology is limited in resources. The insensitivity of the cost of electricity from fission breeders with respect to fuel cost allow the use of even very dilute sources of uranium. The limiting fuel in the case of deuterium-tritium (D-T) fusion (deuterium-deuterium fusion is much less understood) is lithium. The smallest estimates of low cost resources point to a potential of some 2500 TWyr/yr. The two technologies greatly differ in terms of maturity. Fission breeding, which is available in a prototype form after having passed the thresholds of scientific and technological feasibility, should become commercial by 1990. Fusion power, in contrast, still has to pass the threshold of scientific feasibility. Magnetic confinement technologies are estimated to attain scientific break-even by the early 1980s. Some advocates of laser technologies believe that this might also happen with laser, which is more controversial and uncertain however. Technological feasibility of fusion will probably not come before 2000, and commercialization is unlikely to be achieved in time for fusion to contribute even 10% of the world's electricity demands by 2030.

The characteristics of the two technologies were compared by way of the TOKAMAK and liquid metal fast breeder (the German/Belgian/Dutch SN300 design) reactor reference systems. From an economic point of view, both fusion and fission breeders require a heavy R&D effort and high capital investments for commercial reactors and supporting facilities to continue. Technologically and physically, they have much in common: complex large-scale engineering, large units, materials damage and activation by neutrons, the need to contain and manage large radioactive inventories, and, for many present designs, the use of liquid metal for heat transfer. Construction and operation of both therefore require a very high degree of meticulousness and vigilance.

The environmental aspects or problems are very similar, but fusion if prudently developed might be quantitatively superior to fission. Specifically, the damage potential of its radioactive inventory of fusion would be lower as would be its radioactivity decay-heat; the amounts of readioactive waste from fusion would have shorter decay-times, require a smaller volume of dangerous shipments and offer less opportunity for fuel diversion for weapon purposes. However, the widespread use of fusion would result in a proliferation of weapon know-how.

In summary, a careful development of fusion breeding would make this option appear more advantageous than fission breeding. It is inconceivable, however, that it would influence the energy supply within the period of consideration.

The Potential of Nuclear Power by 2030

By the end of 1977 the total installed nuclear capacity was on the order of 0.12 TW(e)yr/yr (Nuclear News 1978). This value is expected to be close to 0.4 TW(e)yr/yr by 1982 when all plants presently under construction will operate. The front end step of the fuel cycle (uranium mining, processing into yellow cake, conversion into $UF_6$, enrichment, conversion into $UO_2$, and fuel fabrication) are commercially well in hand. The tail end (intermediate fuel element storage, reprocessing, intermediate waste disposal, waste solidification, and fuel waste disposal) are technologically mastered but not all its uses are mature commercially. The status and the near-term development of the fuel cycle industry are described in Table 36.

Against the background of existing and foreseeable achievements we have attempted to estimate the maximum possible contributions of nuclear power in our study period.

Disregarding the early introductions of nuclear power in nuclear weapon states where civilian uses profited from the military infrastructure, the beginning of commercial nuclear power can be placed in the year 1966 when nonweapon states made their first commitments. Little can be done, on the other hand, to add significantly to the total potential expected by 1982. Within this "historic" period the highest observed introduction rate was 37 GW(e) per year (1980).

Possible introduction rates of nuclear power in the USA were analyzed in a study sponsored by the Atomic Industrial Forum (1973). It concluded that a vigorous nuclear program started in 1973 and carried on without public opposition, would have led to a capacity of 500 GW(e) by 1980. For the OECD countries this indicates that a significant potential for acceleration should be exploitable the more so in the other parts of the world unhampered by opposition to nuclear power. In our best judgment we have estimated that a program started in 1985 could result in introduction rates of 150 GW(e)/yr around the year 2000. This figure is high but not inconsistent with an estimated introduction rate of 37 GW(e) in 1980. Assuming the contribution of nuclear energy to double or even triple between 1982 and 2000, and assuming further a 4% annual growth in the rate of introduction after 2000, a capacity of about 8-10 TW(e) would be provided by 2030.

A second, different approach yields a similar result. Using a logistic curve to describe the introduction of a new technology into the primary energy market and assuming that nuclear growth rates would be similar to those of other energy technologies, we estimated that by 2030 nuclear energy would have captured 40% of the market. A more theoretical approach developed by V. Peterka (1977) employing cost and price ratios to predict market penetration rates has led to the same figures.

Forty percent of the primary energy demand corresponds to roughly 14 TWyr/yr. Assuming a thermal efficiency of 0.4 and a load factor of 0.7, this is equivalent to 8 TW(e) of installed capacity.

Aiming for a rough upper guess and in view of the existing uncertainties, we, therefore, consider a capacity of 10 TW(e) to be the *maximum reliable global potential* of nuclear energy by 2030--

TABLE 36 World[a] nuclear fuel cycle capacities and number of facilities[b] (operable, under construction or on order)

A. Front End

| Year | Uranium Mining and Milling # | Uranium Mining and Milling $10^3$ t/yr | Uranium[c] Conversion # | Uranium[c] Conversion $10^3$ t/yr | Uranium[d] Enrichment # | Uranium[d] Enrichment $10^6$ SWU/yr | Fabrication Uranium Metal and Oxide # | Fabrication Uranium Metal and Oxide $10^3$ t/yr | Fabrication, Mixed and Plutonium Oxide # | Fabrication, Mixed and Plutonium Oxide t/yr |
|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 63 | 35 | 14 | 50 | 17 | 19 | 30 | 12 | 14 | 119 |
| 1980 | | 70 | | 62 | | 34 | | 18 | | |
| 1985 | | 97 | | 62 | | 71 | | 20 | | |
| 1990 | | 115 | | 62 | | 91 | | na | | |

B. Tail End

| Year | Uranium Metal Reprocessing # | Uranium Metal Reprocessing $10^3$ t/yr | Uranium Oxide Reprocessing # | Uranium Oxide Reprocessing $10^3$ t/yr | Reprocessing # | Reprocessing t/yr |
|---|---|---|---|---|---|---|
| 1977 | 5 | 4 | 9 | 2.7 | 2 | 0.8 |
| 1980 | | | | 2.7 | | |
| 1985 | | | | 5.4 | | |
| 1990 | | | | 12.2 | | |

[a]Excluding the centrally-planned economies.

[b]Pilot and laboratory facilities are included.

[c]Different conversion stages added in terms of capacities per year.

[d]Different enrichment processes added in terms of SWU per year.

SOURCES: Nuclear Engineering International (1976); Häusserman, H. et al. (1977); OECD-NEA/IAEA (1977); Fuji, H. (1978).

a power which will not be used for electricity generation only but also for the generation of other secondary energies.

## Uranium Resources

The size of uranium resources is a heavily discussed topic. There have been several attempts to assess the economically exploitable resources. Table 37 summarizes values determined by a joint OECD-NEA/IAEA study (1977), estimating the world's uranium resources at less than US$ 130/kg to be approximately 4.3 million tons.

For our purposes, using the breeder technology, resource costs do not really matter and the value of interest would be ultimately recoverable resources. But this value is unknown.

Present knowledge of the geological features of uranium deposits seem to indicate that much more uranium than the cited 4.3 million tons might be available. In particular, exploration has not been very even. Table 38 illustrates the interrelationship between drilling, reserves and finding rates for various countries. Most remarkably it turns out that the USA, the country with the highest reserves, has shown a very low finding rate. A.M. Perry (1979) and other authors conclude from this that the USA is not particularly well endowed with uranium resources.

Thus it might not be unreasonable to take the USA as a sample on which to base a very rough order of magnitude estimate of the world's uranium resources to be accessible in a not too distant future. In the United States, uranium at a cost of less than US$130/kg is available at an average of 0.2 tons per $km^2$. Using Perry's method, we therefore estimated world resources by assuming a density of 0.18 tons per $km^2$ for all other regions of the world; accordingly we concluded a potential availability of about 27 million tons of uranium (Table 39).

Other similar studies have confirmed this order of magnitude. A Soviety study (Alexandrov and Ponomarev-Stepnoy 1974; Belostotsky 1977), using an old IAEA/OEDC data, estimated resources at 17.5 million tons. The findings of Brian J. Skinner (1976), based on a comparison of geological occurrence for geochemically scarce metals, point up to 27 million tons of recoverable resources.

TABLE 37 Estimated world[a] resources of uranium ($10^6$ tons of uranium).

| | Reasonably Assured Resources | Estimated Additonal Resources | Sum |
|---|---|---|---|
| <$80/kg | 1.65 | 1.51 | 3.16 |
| $80-130/kg | 0.54 | 0.59 | 1.13 |
| Total (<$130/kg) | 2.19 | 2.10 | 4.29 |

[a]Excluding Eastern Europe, the Soviet Union and China.
SOURCE: OECD-NEA/IAEA (1977).

TABLE 38 Uranium Findings and Finding Rates

| | Drill Holes ($10^3$ m) | Findings[a] ($10^3$ tons) | Finding Rates (kg/m) |
|---|---|---|---|
| Australia | ≐1,100 | 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 | 5,151 | 123 | 24 |
| United States | 82,500 | 1,918 | 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).

TABLE 39 Adjusted Uranium Resource Estimates

| IIASA World Regions | Area ($10^6$ km$^2$) | 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 E. Europe) | 23.5 | | 4.23 |
| III (W. Europe, Japan, Australia, N. Zealand, S. Africa, Israel) | 15.5 | 1.26 | 2.79 |
| IV (Latin America) | 20.6 | 0.08 | 3.71 |
| V (Africa except N. Africa and S. Africa, South and Southeast Asia) | 33.6 | 0.33 | 6.05 |
| VI (Middle East and N. Africa) | 9.8 | 0.08 | 1.76 |
| VII (China and Centrally Planned Asian Economies) | 11.5 | | 2.07 |
| I-VII | 136 | 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 (Soviet Union and E. Europe) and VII (China and Centrally planned Asian Europe).
[b]Including the speculative resources given in OECD-NEA/IAEA (1977).

Therefore, it seems a reasonable assumption to expect altogether some 15-30 million tons of uranium potentially available at global exploration rates similar to that of the USA.

A remark about thorium should be added. Thorium, which is not a fissile material, would be used for conversion into U-233. The presently known resources are in an order of 0.8 million tons. Geologically, however, thorium is four times as abundant in the lithosphere as uranium, and we can expect that enough thorium should be available to support a long-term fission economy.

One should note that the mining of 15-30 million tons of uranium would be an undertaking qualitatively much less efficient than today's uranium mines exploiting the richest deposits at around 2000 ppm. Exploitation of deposits of 50-100 ppm would eventually require a mining operation comparable to the effort of coal mining (Table 40) with respect to material handling, labor intensity and land requirements. Uranium would, so to speak, become a kind of yellow coal.

## Reactor Strategies

Fifteen to thirty million tons of uranium used in a light water reactor (LWR) strategy without reprocessing is not a very significant amount of energy. As illustrated in Figure 30, a level of 10 TW(e)yr/yr could not be sustained for much longer after 2020; 20 million tons of uranium would be equivalent to approximately 240 TWyr--a relatively low figure compared to a demand of 22-36 TWyr/yr.

Several technologies exist that could improve the situation. Some advanced designs such as of the high temperature reactor (HTR) or the heavy water reactor (HWR), and even some forms of the LWR, would be able to convert nonfissile material (e.g., U-238 or Th) into fissile material. However, those high converters or near-breeders are still uneconomic today compared to optimized burner reactors and, more important, they still burn

TABLE 40 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 (2,000-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 30-year lifespan.

[b] 1 man year = 2,000 hours.

[c] Overburden factor: 15 $m^3$ per ton (averaged).

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

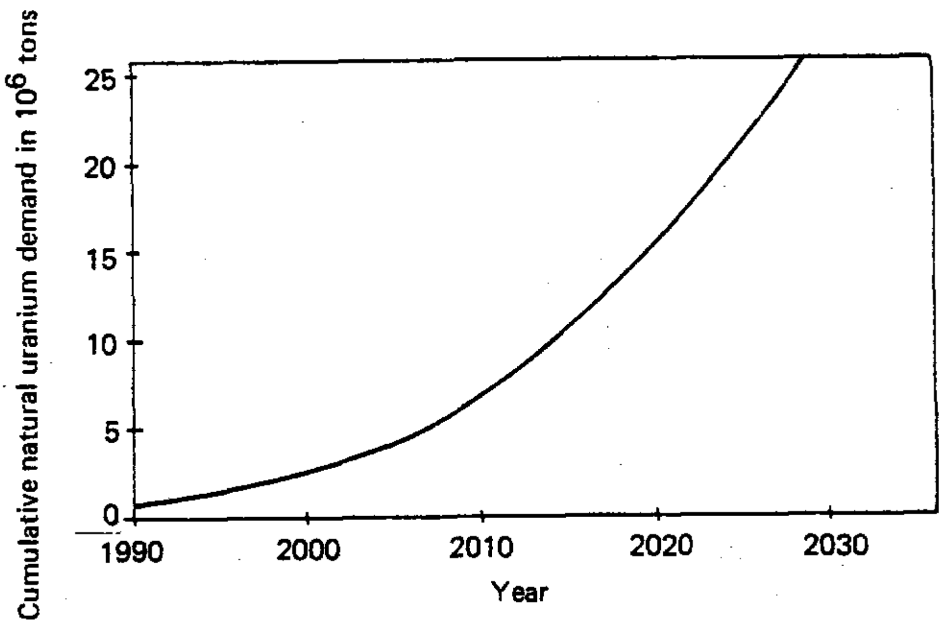



FIGURE 30 An LWR-U235 once-through strategy.

more fuel than they produce, which means that they alleviate but not solve the problem.

Breeding, in contrast, means that more fissile fuel is produced from nonfissile material than is consumed by this production. Considering the ratio of fissile to nonfissile fuel in natural uranium being 1:140, orders of magnitude are won by breeding. Just by using the uranium already mined and depleted by enrichment would add some 600 TWyr to nuclear energy--a figure comparable to economical reserves. At the same time, low-quality uranium deposits would be exploited without involving a "yellow coal" enterprise (Table 41).

Several breeder technologies are conceivable. The most advanced thermal breeder reactor design (TBR) is the molten salt reactor. Experimental units have been successfully operated, but the prototype stage has not yet been reached. Another possibility would be to use the high-neutron fluxes generated by D-T fusion, a viable alternative to electricity generation from fusion accessible perhaps even in the near term. However, as we have seen, it is not reasonable to expect fusion technology to become available on any significant scale much before 2030.

The most promising breeder technology within the time horizon under consideration is the liquid metal fast breeder (LMFBR). Prototypes in France, the USSR, and the UK are operating successfully, and the commercial threshold will probably be passed in the next ten years. Their safety is hotly debated, but technologically they could be designed to be as safe as standard LWRs. This was also one of the results of our study comparing fission and fusion reactors (Häfele et al. 1977).

The nuclear community considered the advantages of breeding rather early. In 1960 several strategies were designed combining LWR and LMFBR technologies. The plutonium produced by LWRs would

TABLE 41 Requirements for operating a 1 GW(e) Plant[a] (6.1 TWh(e) ≐ 1 yr operation at 70% 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 = 2,000 hours.

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

be used to provide the first-core inventories for breeder reactors. Thus gradually LWRs would be replaced by a self-sustaining LMFBR system. Such a classical LWR-LMFBR strategy is described in Figure 31. The consumptive use of uranium is in the order of 15 million tons, a value perfectly consistent with the resources.

But this strategy presupposes all the plutonium produced in LWRs to be used *as quickly as possible* in order to build breeders. This is not realistic in view of recent developments and the present situation of reprocessing and breeding. Therefore, the mere introduction of breeding will not enable nuclear energy to reach a level of 10 TW(e) by 2030.

Additional measures are required. The use of high converters and improvements in enrichment and reprocessing technologies might help. The crucial element, however, is to emphasize the breeding characteristics of the LMFBR and to use this technology for breeding U-233 from thorium. Thus, a lower introduction rate of LMFBRs than that calculated for the original strategies might be possible at the optimistically assessed level of global uranium resources (Figure 32).

## Secondary Energy from Nuclear Power

We have already mentioned that nuclear energy, if it is to realize its full potential, must produce an energy form other than electricity. Most alternative uses to electricity are of a limited scope only, such as for instance, district heating. The ideal candidate is hydrogen production, but it is doubtful whether significant direct uses of hydrogen for energy purposes are possible before the mid-21st century.

In the section on fossil fuels we have learned that the carbon atom, though very abundant, must be used prudently because of environmental, economic, and institutional reasons. The production of methanol by combining coal and nuclear hydrogen therefore appears as a strong possibility. The carbon atom would be used primarily as a chemical energy carrier, and thus

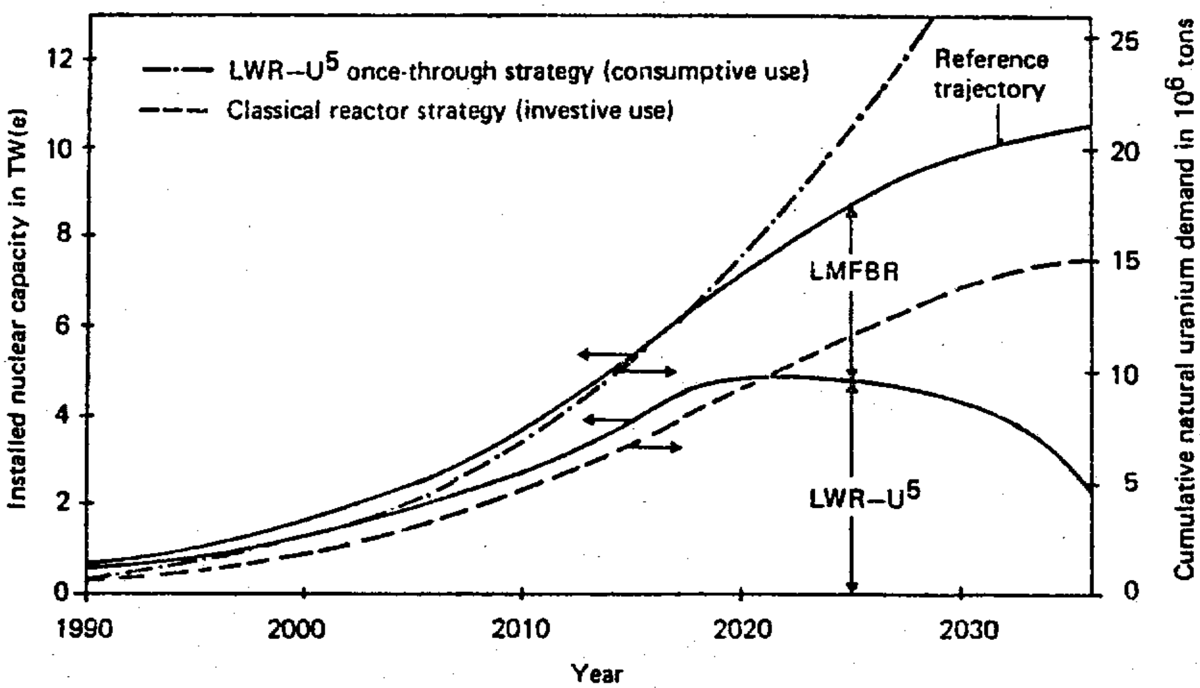



FIGURE 31 A classical reactor strategy.

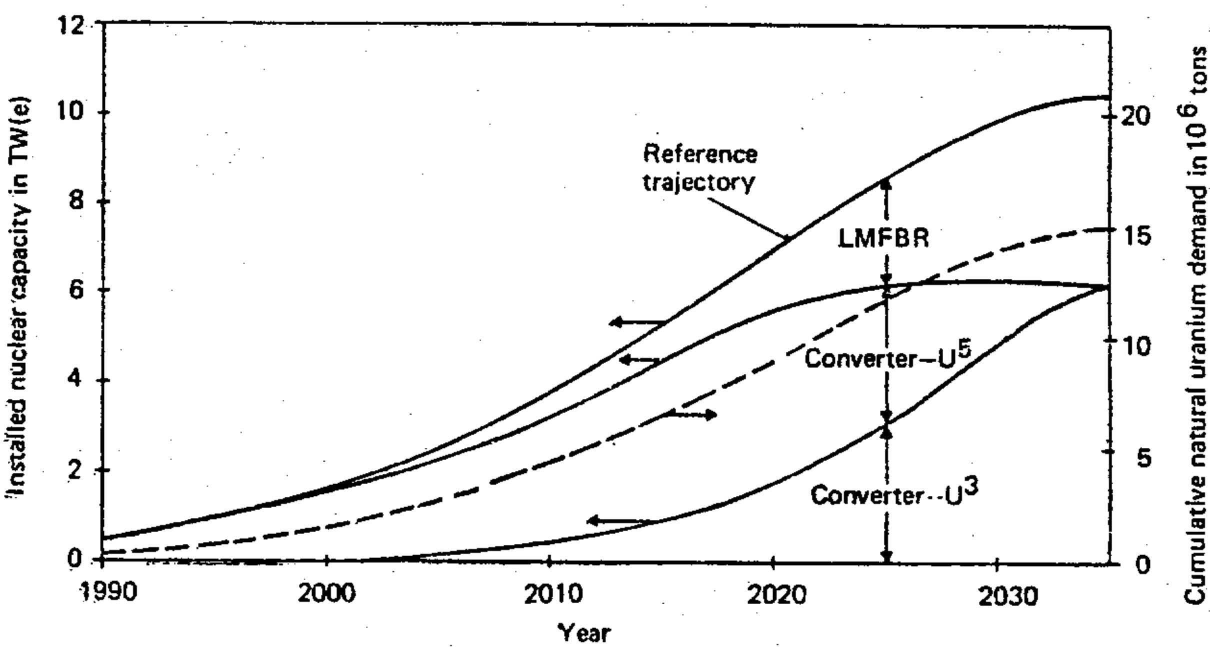



FIGURE 32 A converter-breeder strategy.

the precious coal reserves would be safeguarded. At the same time, nuclear hydrogen could be introduced into the system without a radical change of infrastructure.

Earlier, in Figure 24 we compared the efficiencies in terms of coal of various coal conversion technologies. Autothermal conversion uses four times as much coal, and if an external source of process heat such as the HTR is employed, it uses twice as much coal per unit of liquid secondary energy output as does methanol production using hydrogen from a nonfossil source, such as nuclear.

This process was illustrated in Figure 24. Natural coal by and large contains one hydrogen atom per carbon atom. At temperatures of around 1400° C coal, upon the addition of heat and steam, is transformed into city gas ($CO + 1/2\ H_2$). Combining this gas with 3/2 $H_2$ of nuclear origin leads to methanol ($CH_3OH$). This process would eliminate all carbon wastes in the form of $CO_2$ releases.

Two ways are conceivable to produce hydrogen from nuclear power. *Electrolysis* of water by nuclear electricity would be one option. At today's prices this would be too expensive. However, at US$30 per barrel of oil equivalent and assuming a reduction in the cost of electrolysis by a factor of 3 to 4--which seems possible in view of the intensive research programs under way--such a technology might become competitive around 2000.

The second option is *thermolysis* of water. One of the most interesting processes advanced so far is associated with Westinghouse in the USA. As shown in Figure 33, sulfuric acid is decomposed in a first step into $SO_2$, water, and oxygen at a temperature of 800° C. In the second step, with additional water, $SO_2$ is recomposed by electrolysis into sulfuric acid and hydrogen is released. Some 85% of the energy required is process heat to be provided by HTRs.

– Basic Reaction $H_2SO_4 \xrightarrow{<850°C} H_2O + SO_2 + \frac{1}{2} O_2$

– Electrolysis $SO_2 + 2H_2O \xrightarrow{+0.5\,Volts} H_2SO_4 + H_2$

FIGURE 33 Hybrid and thermolytic water splitting. SOURCE: Farbman and Brecher (1975); Marchetti (1973).

A Future Global Nuclear System

In the long-term asymptotic future, nuclear energy might evolve into a structure producing electricity and liquid fuels simultaneously. This system is described in Figure 34. FBRs might in the first place provide electricity and convert U-238 and thorium into Pu-239 and U-233. The plutonium would be used as FBR fuel. Uranium-233 would be burned in HTRs which would deliver their process heat for hydrogen production either for direct use if the necessary infrastructure should be available, or for coal conversion.

What would be the implications of such a system? An assessment of such a nuclear fuel cycle has been made scaling up the results of the study by Avenhaus, Häfele, and McGrath mentioned above to fit the size of 10 TW(e). This fuel cycle would require the following facilities:

- 3000 nuclear reactors with a rating of 3300 MW(e) each.
- 94 fuel fabrication plants of 1500 tons/year.
- 94 chemical process plants of 1500 tons/year.
- 650 intermediate waste storage facilities of 1000 $m^3$ (seven for each reprocessing facility).
- 47 final waste storage facilities.

Figure 35 gives a simplified summary of the results which are remarkable in several respects.

First of all, the resources requirements are unusually low, less than 8500 tons/year of uranium and thorium. The same amount of energy generated by coal would imply a yearly flow of some $18.3 \times 10^9$ tons of coal. These amounts of nuclear fuel could easily be provided even if residual deposits had to be mined. From a resources point of view, the system would therefore be sustainable over very long periods.

The yearly output of fission products would be in the order of 6634 tons, or a cube of 20m x 20m x 20m. Even today's final waste storage techniques should be suited for this volume.

Losses to waste are 1536 tons per year. Of this amount, 144 tons of plutonium, uranium, and actinides are of concern since they lead to tight confinement requirements. Table 42 summarizes the confinement factor necessary to keep the contribution of each radiation source well below 1% of the natural radiation background, which for a quick orientation can be placed at 110 mrem/year. Those calculations followed the method employed in the study by Avenhaus, Häfele and McGrath (1975) which takes into account the radioactive isotope annual flow, the various pathways the released isotopes take into the environment and whether the overlapping impacts of several facilities are taken into account or not.

In the case of Kr85, confinement in reactors would have to be improved by a factor of 3-10, which should not be so difficult. In contrast, to obtain confinement factors of 100 in reprocessing facilities requires efforts which appear technologically feasible.

Present reactor designs would be satisfactory with regard to tritium releases into air and water. Confinement factors of 100 for reprocessing plants might be necessary. They are possible but not easily obtained.

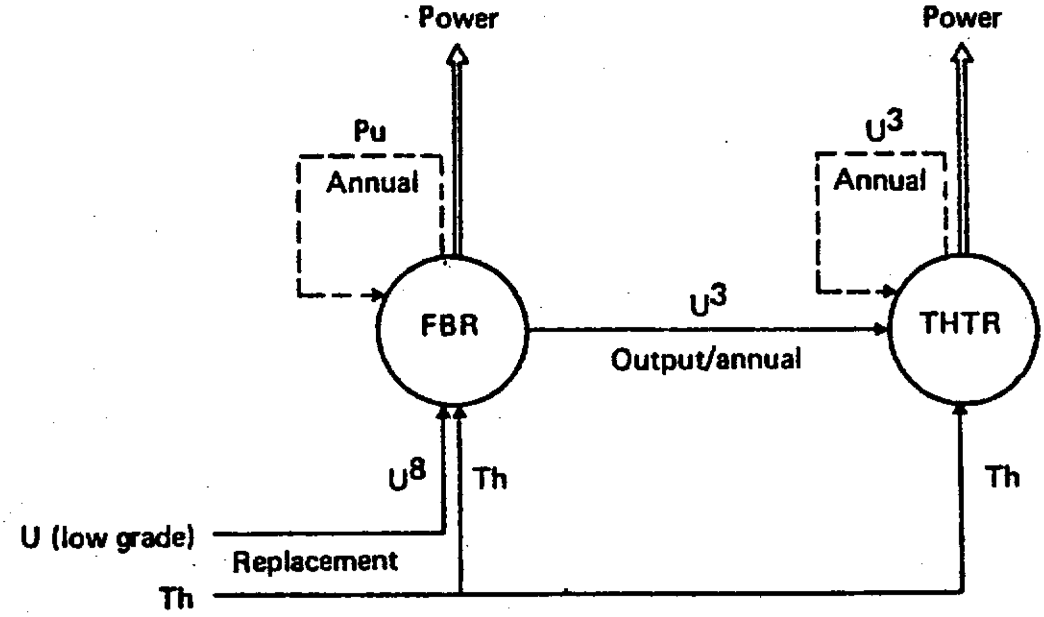



FIGURE 34 A reactor system for investive uses of uranium resources.

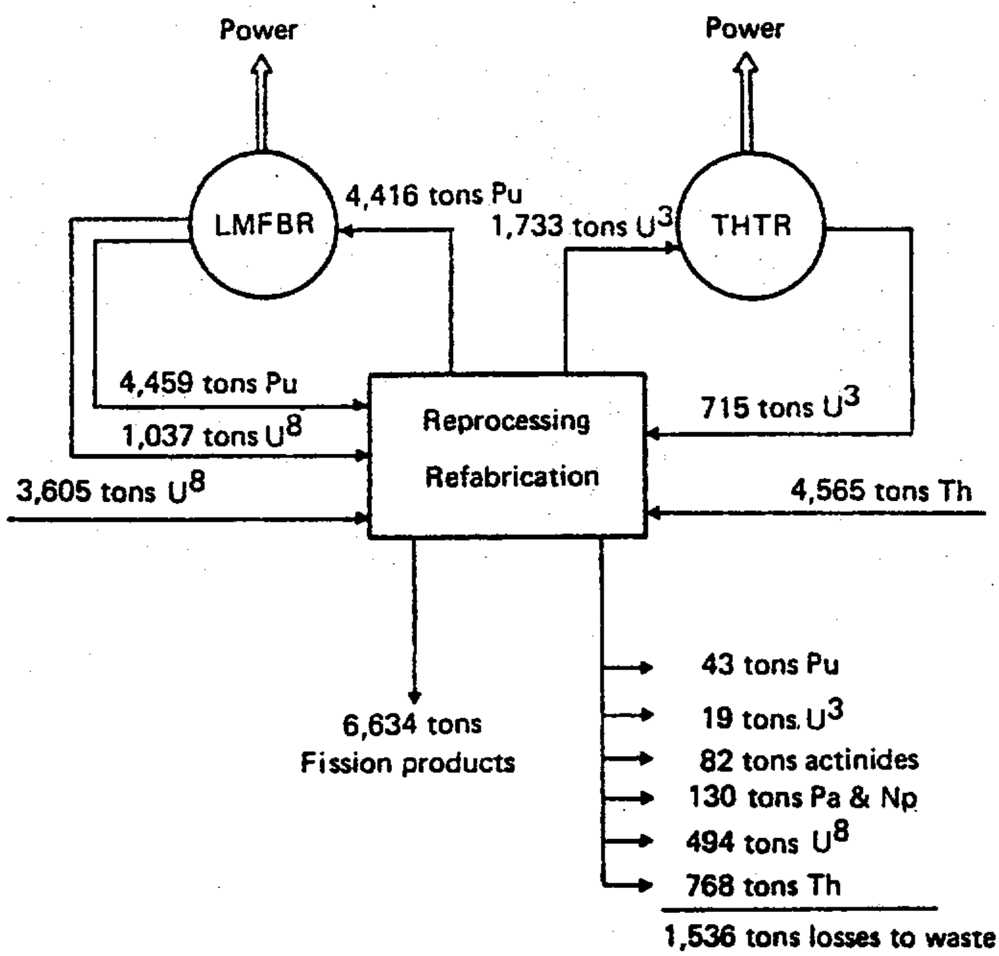



FIGURE 35 Annual throughputs and losses (in tons) for a 17 TWyr/yr, FBR/HTR operation. Only closed balances for Pu, $U^3$, and total ($U^8$ and thorium) are shown. The 6 ton mass defect associated with 17 TWyr/yr is not accounted for.

TABLE 42 Required confinement factors for making each relative dose rate contribution well below 1%.

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

It has been proven in experimental pilot plants that confinement factors of $10^9$ for reprocessing plants and $10^{10}$ in fabrication facilities should be achieved with regard to plutonium releases. Nevertheless, confinement factors of that order are tough and will definitely require an achievable but nevertheless large technological effort. Activities for confining Pu-239 and other α-emitting transuranium isotopes appear to parallel those necessary for plutonium.

Iodine-129 is released only in very small amounts but decays with a half life of 17 x $10^6$ years. Released into air at a confinement factor of $10^3$, the related body burden would build up at a rate of 1.6 x $10^{-4}$ year without saturation. The postulated limit dose rate of 1% of the natural background radiation would thus be reached after a few decades. A higher confinement factor appears necessary, but is difficult to obtain. The problem might be solved by choosing sites permitting a stronger dilution, for instance, by release into sea water.

No effort was made at IIASA to estimate the potential risk of nuclear accidents. This would have been beyond the scope of our program which certainly could not have contributed substantially in a field engaging much larger specialized groups. Yet, together with the International Atomic Energy Agency (IAEA) an effort was made to understand the discrepancy between the "objective" risks of nuclear power and its perception by the public. This work will be described in Chapter 4.

## Conclusions

Nuclear power is an existing technology no longer in its infancy. The theoretical potential is tremendous, and for all practical purposes unlimited. To realize the potential of a global option, however, other technologies than the present LWR must be implemented. The LWR, which is the main representative of nuclear technology today, cannot overcome the uranium resource limitations.

Several such new technologies are foreseeable. The most likely to materialize now as a fully commercial energy source is the LMFBR. Yet even this reactor type would come too late to contribute a share on the order of 10 TW(e) (capacity) by 2030--

if it is used in a classical reactor LMFBR/LWR strategy. Only if U-233, bred from thorium, is used to replace U-235, and with the help of fast breeders the goal of 10 TW(e) by 2030 would be reached.

A 10 TW(e) capacity requires nuclear energy to produce more than just electricity. Hydrogen from electrolysis or thermolysis is the most suited candidate. Combined with coal, a liquid secondary energy carrier--methanol--involving little change in the present infrastructure could then become available as a replacement for oil products.

After the asymptotic stage is reached, a 10 TW(e) nuclear system would practically be resource independent. But there is a price to pay for this independence. Radioactivity will have to be handled and controlled successfully. Calculations show that this should be possible without too heavy an impact on the environment if a realistic technological effort is made to obtain adequate confinement rates. A residual impact will, however, remain. Whether this price is high or low can only be judged in the light of possible alternatives and the significant benefits to be derived from the large-scale use of nuclear power.

## THE SOLAR OPTION

### The "Resource"

Of the renewable options, only one, direct solar energy, is in principle capable of providing by itself very large amounts of energy in a medium-term future. About 25,000 TWyr/yr of sunshine reach the earth's land surface. This, rechargeable and, for practical purposes, unlimited potential puts direct insolation into the same ballpark as nuclear or fossil energy.

The "resource" is quite different. Like all renewable sources it is characterized by a low density. Figure 36 illustrates the global horizontal insolation values for several US and European cities. The average values are closer to each other than one might expect; for temperate and desert regions they differ merely by a factor of 2. In Europe, for instance, they vary between 2-5 kWh/$m^2$/day, with the most typical value being 3 kWh/$m^2$/day, whereas in the sunny tropical and desert regions the annual average reaches values around 5-6 kWh/$m^2$/day. A comparison of seasonal maxima and minima produces more dramatic values. In Phoenix, Arizona, for instance, the ratio between winter and summer insolation is merely 1:2, in Europe the ratio is on the order of 1:8. Therefore, the seasonal cycle is much more pronounced in temperate zones than in areas in proximity to the equator.

A much greater divergence characterizes the availability of direct beam radiation. In central and northern Europe in some winter months as much as 70-85% of the insolation in winter is diffuse sunlight.

These physical conditions immediately point up two conclusions. First, the low density of the source makes it necessary not only to collect but to concentrate the natural energy flow. The energy thus obtained is heat, a form of energy difficult to transport and store. Wherever this heat cannot be used directly it has to

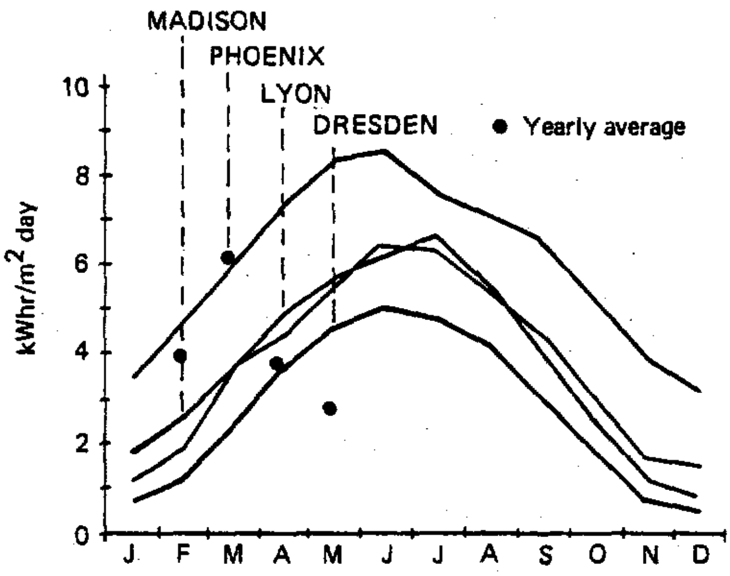



FIGURE 36. Comparison of global irradiation for different cities, 1970.

be transformed into a storable and transportable energy carrier. Second, it is obvious without substantial analysis that the economics of any large-scale solar system will require siting it in the sunny areas of the world. Accordingly, the use of solar energy could materialize on several levels:

- direct, consumer-oriented local uses, centralized or decentralized;
- centralized uses within a sectional or regional framework; and
- large-scale use within a global framework.

Decentralized Local Use : The Solar House

As part of a case study analyzing the potential for an enhanced use of solar energy in the Federal Republic of Germany (FRG), sponsored by the Federal Ministry for Research and Technology, Bonn, C.R. Bell, F. Jäger and W. Korzen (1977) examined in detail the small-scale applications of solar technology in the FRG, i.e., a typical highly industrialized nation with average insolation.

The most promising technology identified comprises roof collectors for space and water heating. Their use, however, is severely constrained by the physical conditions of temperate zones.

Figure 37 compares monthly insolation shares averaged over a ten year period and the space heat demand for several Austrian cities. In June, 15% of the total yearly insolation are available, in December only 2%. The space heat demand, by contrast attains its maximum in December/January and is close to zero in summer. Any significant development of solar energy for space heat purposes will obviously require storage and substantial backup.

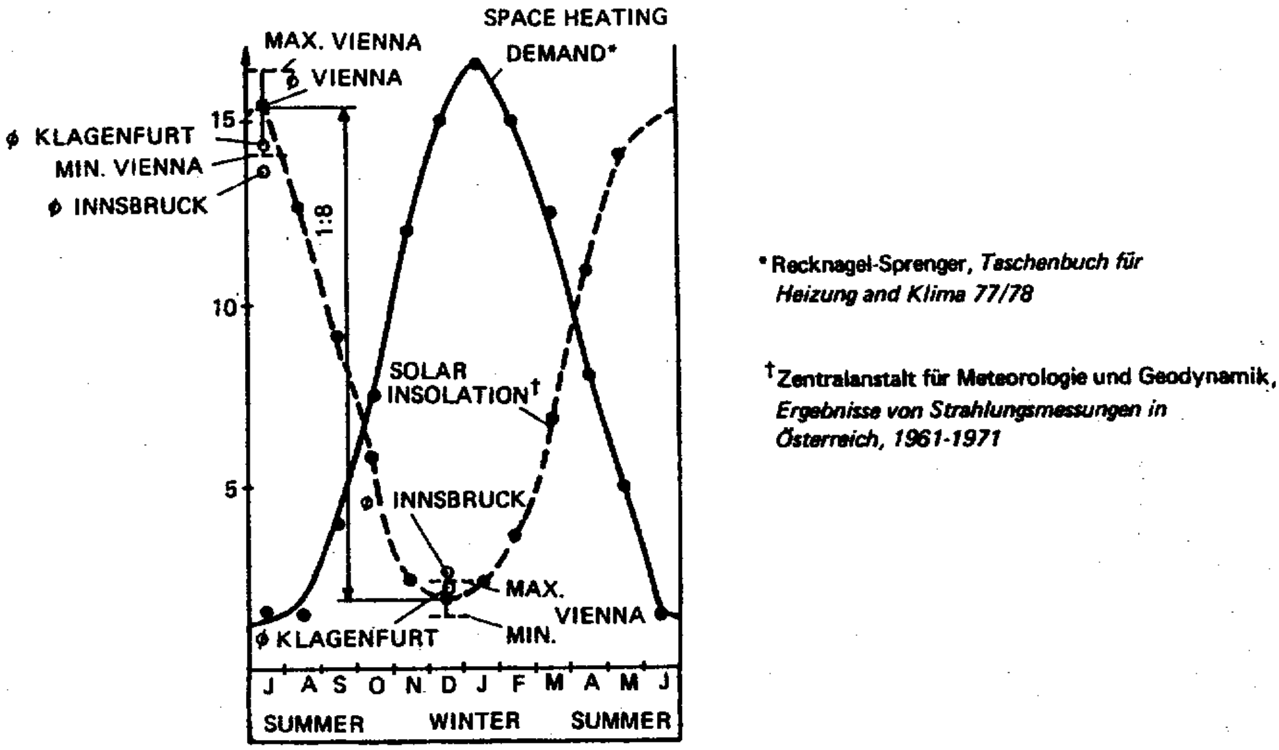



FIGURE 37 Monthly energy shares.

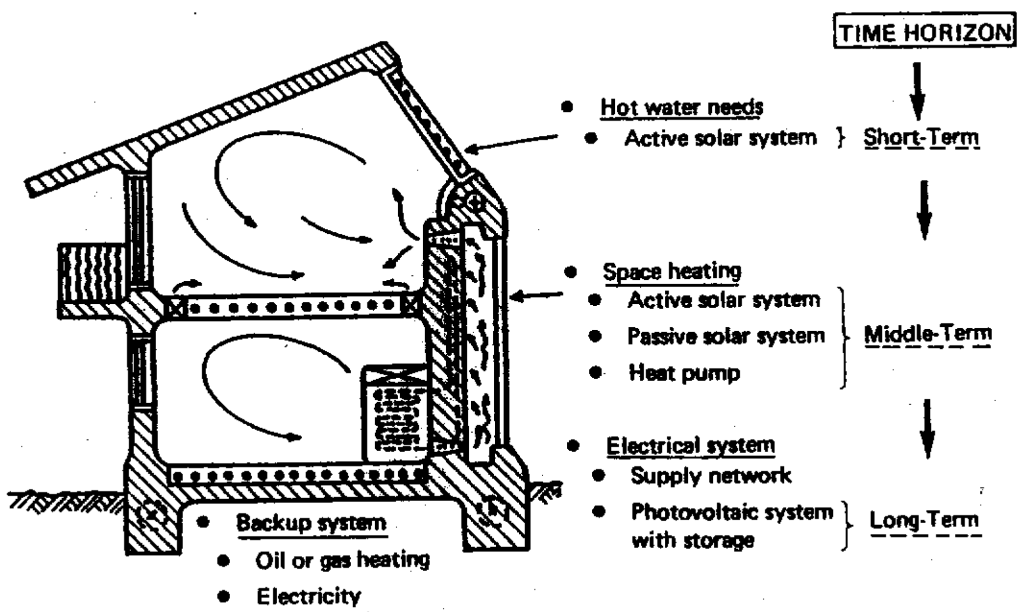



FIGURE 38 Development of the solar house.

This makes water heating appear as the most probable form of solar energy use in houses in the near future. In the medium term, space heating could be introduced--together with a host of supporting measures, such as insulation, passive solar systems, or heat pumps. Finally, linkage of a decentralized solar electricity production to the grid is conceivable in the very long term. Figure 38 summarizes these phases in the development of a user-oriented solar technology. In all cases, however, a backup system relying on fuels, gas, or electricity is necessary.

Storage requirements increase with the percentage of heat provided by solar energy. Figure 39 demonstrates the fundamental interrelationships between collector area, storage size, and storage time for a one-family house consuming 18 MWh/yr. Up to 50% of the space heat demand can be provided by some 50 $m^2$ of collectors and requires relatively little storage, a few cubic-meters over a few days. About 50%--that is, should solar cover the major part of the space heat demand--collector area and storage requirements increase rapidly. At 90% solar supply, for instance, the collector area is on the order of 160 $m^2$ and storage on the order of 80-100 $m^3$ for a storage time of a few months.

What are the costs of such systems? Assuming that the investment costs for a solar heating system meeting 50% of demand would be on the order of US$14,000 for a one-family house, this device would make up 10% of the total building cost (Figure 40). Seventy percent solar supply would raise this share to 20% and at 90% solar supply it would be 40-55% of the total investment costs for a one-family house.

How do these figures compare with the investments for a conventional oil heating system? If the oil-specific component system is estimated to cost $2100, replacing 50% of fuel heat by solar would increase the cost by a factor of 4-8, replacing 90%, by a factor of 15-30.

Of course, these estimates are highly uncertain since new technological developments, mass production, etc., might reduce the solar system cost substantially. The above diagram describes a bandwidth capturing these uncertainties. The upper limits are considered "realistic", the lower ones indicate very optimistic assumptions. Neither limit is understood to be absolute since future solar space and water heating might be cheaper but also more expensive.

After this caveat, we may conclude that for the FRG the optimal use of solar space heating would be approximately 40-60% of the heat demand, in *newly constructed, well insulated houses*. Worldwide, climatic and physical, conditions might raise or lower the percentages. Thus, we estimate that agressive policies in the Western industrialized regions will increase the possible contribution of solar space and water heating to 50-70% of the specific demand of suitable newly constructed buildings. In the Soviet Union and the other industrialized countries of the Eastern sphere only some 30% is expected, due to the high shares of district heat and generally unfavorable conditions.

Assuming no retrofitting on the one hand, but the possibility of solar equipment for *all post*-1975 centrally heated single-family houses and low rise commercial buildings, solar space and water heating might provide up to 0.2 TWyr/yr of final energy in

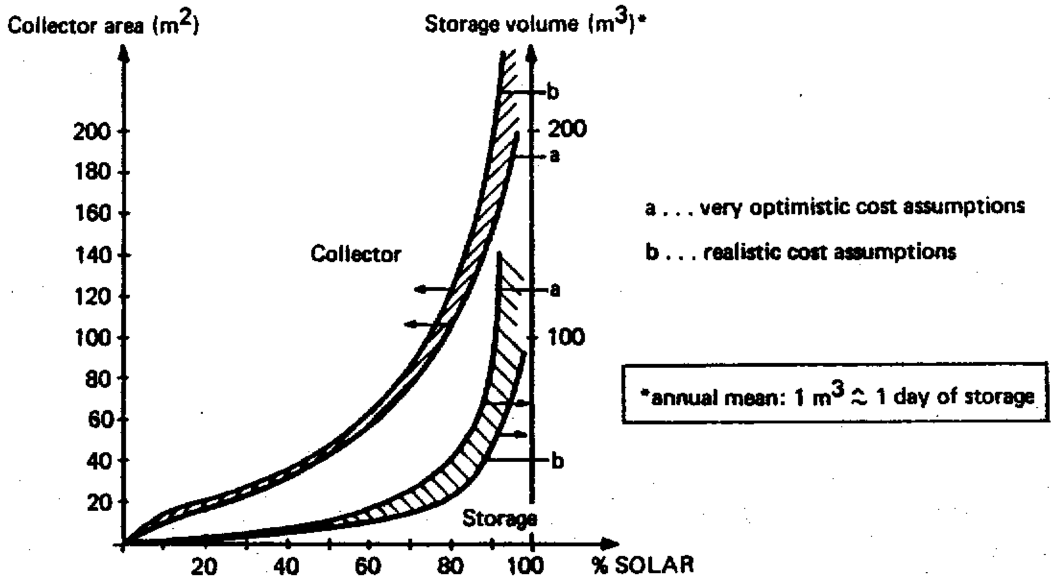



FIGURE 39 Collector area and storage volume or storage time as a function of the share of solar energy in a single family house.

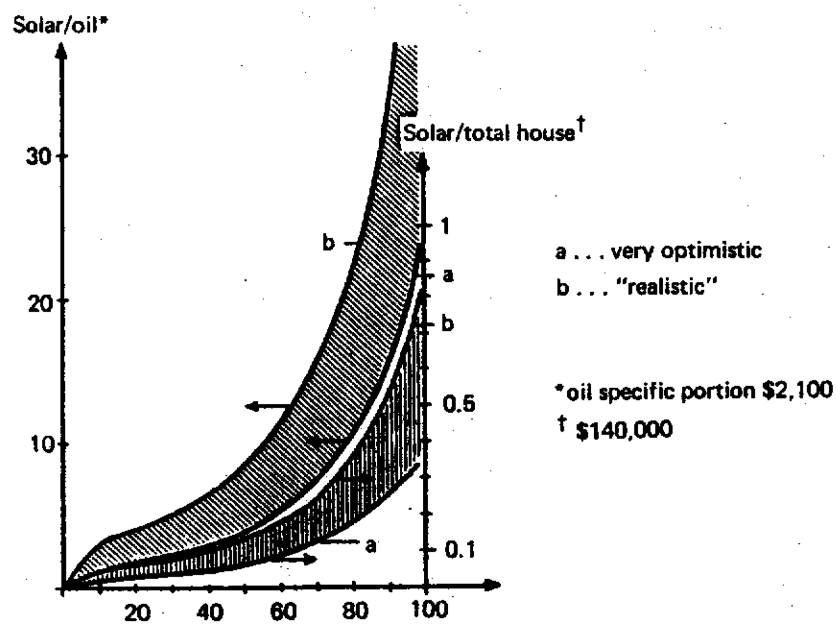



FIGURE 40 Relative investment costs, share of solar.

in the developed regions. This corresponds to slightly less than 2% of the total final energy demand of the High scenario in those regions, which puts the order of magnitude estimated in the section on renewables into perspective.

Yet, to realize this potential a substantial effort will be necessary to reduce the costs which today are still higher by a factor of 2-3 than conventional systems.

## Local Centralized Uses

Other than the solar house, solar district heating systems represent a type of locally centralized use. For small communities, this use can be conceived to be user oriented, but not so in larger settlements. It can thus be considered as a transition between user-oriented and commercial applications of solar energy.

W. Korzen (1979) has studied this option by analyzing in some detail the possibilities of introducing it in Laxenburg, the local IIASA community of about 2000 inhabitants. The community is well suited for district heating as 80% of the buildings in the center are already equipped with central heating. Its yearly final energy demand for space heating is 8.14 GWh.

To provide 100% of the community's center with solar district heat would require a land area of 50,000 $m^2$ and a storage capacity of 175,000 $m^3$. The cost of the system would amount to AS 250 million ( 19 x $10^6$ US$) compared to a cost of AS 12 million ( 0.9 x $10^6$ US$) for a conventional district heating system (Table 43). The major cost factor is storage.

A lesser solar share in the heat supply of 50% reduces the storage requirements overproportionally, but the system cost of less than 100 million is still prohibitively high.

Additional analyses of other, larger communities involving longer supply distances harden this conclusion.

It is worth noting, however, that the land requirements, which at first glance appear very high, are not really a constraint for *smaller* communities. A careful study of several Austrian agglomerations has demonstrated that enough unused land is available to harvest solar energy for district heating, should it be possible to reduce costs to an acceptable level. But we do not foresee that technological progress would allow this to be achieved in our study period. Even so the technology in question would serve only a very limited heat market.

## Solar Energy on Regional and National Levels

A significant use of the land available requires the production of energy carriers that can be integrated into the regional or national supply systems, thus opening new markets. In the very long-term future, photosynthesis is conceivable to be employed to produce, directly from sunlight, a storable and transportable energy carrier. In the nearer term future, two technologies could be applied: solar thermal electric conversion (STEC), and, perhaps, solar photovoltaic cells.

| CURRENT HEATING CHARACTERISTICS | |
|---|---|
| 80% radiator central heating, 20% individual stoves | |
| Secondary energy demand | 10,000 Goal/yr = 11.63 GWhr/yr |
| Efficiency | 70% |
| End use energy demand | 8.14 GWhr(th)/yr |

| Connection to Conventional District Heating System | | 100% Solar Local District Heating | |
|---|---|---|---|
| | | Efficiency | 30% |
| | | Minimum collector area | 24,667 $m^2$ |
| | | Land area | 50,000 $m^2$ |
| | | Storage volume | 175,000 $m^3$ |
| Cost | 12 million Austrian Shillings | Cost | ~ 250 million Austrian Shillings |

TABLE 43 Area and Capital requirements for a 100% solar local district heating, Laxenburg (IIASA, Monastery, Gemeindebau Herzog Albrecht Str., Neighboring Buildings)

In a case study of Austria, N. Weyss (1977) considered the possibilities of employing the solar tower concept; illustrated in Figure 41, to produce electricity in a temperate zone.

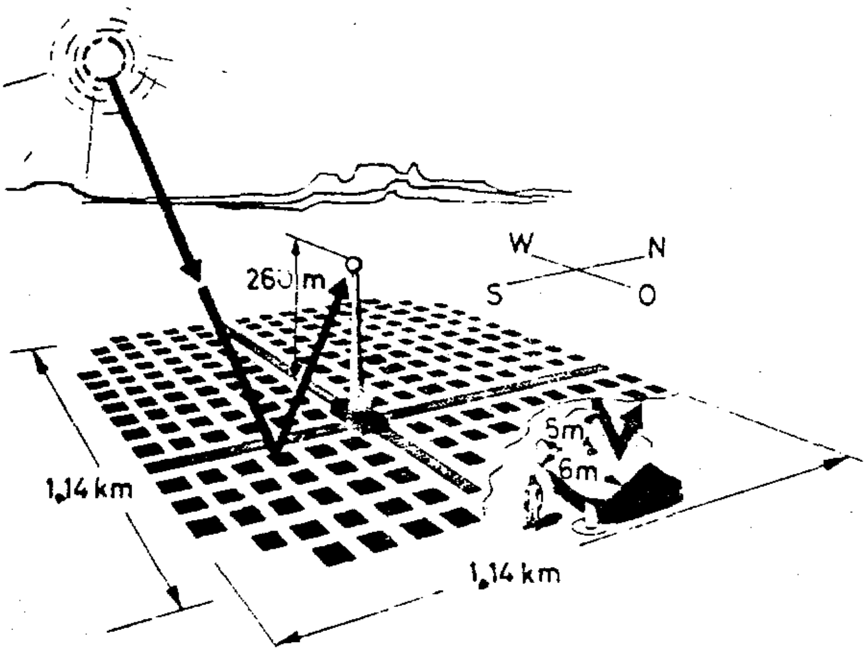



FIGURE 41 Solar Tower

Using 175 W/m$^2$ as an estimate for average sunshine, and assuming very optimistic collector costs of US\$50/m$^2$ and an 8% discount rate, the payback time for a solar tower installation turns out to be at present oil prices less than 10 years. It comes as a surprise that electrical *peak power pr duction* seems to be nearing competitiveness even in countries with basically unfavorable insolation conditions.

But there are several caveats. For one, the solar tower technology employed is still far from being mastered. Collector costs, probably the biggest factor, are still highly uncertain and the values given here assume technological progress as well as mass production. Moreover, so far only peak power production has been envisaged to require no storage but to be limited by the grid's capacity to accommodate this type of production.

If one pushes these reservations aside, there is still storage to be considered. Our studies have shown that this constraint might be overcome by coupling solar energy and hydrostorage. Yet only very few areas of the world would be able to use this option, and the economic ecological price for a significant use would be high. For instance, an electricity generation comparable to Austria's present volume of production would require building 6 hydrostorage facilities of 0.6TWh capacity each. This scheme would have severe ecological impacts on the Alpine region, besides the aesthetic burden of some 250 $km^2$ of solar power stations covering the most scenic mountain landscape.

*Photovoltaics* have definite advantages over the tower concept. Since they are modular they can be employed in a decentralized fashion involving separate and smaller patches of land. There are no moving parts and they convert both diffuse and direct sunlight into electricity. Their main constraint is economics. Today's cost of 10,000 US$ per peak kW(e) for silicone arrays are prohibitive and must become smaller by an order of magnitude. In spite of the recent substantial progress made by projects supported by the US Department of Energy, much remains to be done. To become competitive with STEC, the cost of photovoltaics would have to be reduced to 50% of the USDOE 1986 goal of $0.50/peak watt. But even if the economic constraint should be overcome, the use of photovoltaics for electricity generation in temperate zones will be limited. Photovoltaic systems would, in a sophisticated manner, have to be interconnected with the general grid in order to absorb the dispersed electrcitiy generated, and it would have to be backed up by large storage facilities. Compared with STEC, the photovoltaic situation would be better with regard to ecological impacts, worse in view of the grid problem, and qualitatively the same with respect to storage.

It applies to both technologies that they still would have to face competition by cheaper products from other sources if they were to be used for electricity generation only.

## The Large-Scale Use of Solar Energy on a Global Level

As we have seen, all the possible uses of solar are constrained by various factors. Heating of homes and district heating are limited by the mismatch of demand and supply, causing high storage requirements that impose economic and physical limits on the use of solar.

Local electricity generation is probably only feasible for peak load, though perhaps some baseload can be accommodated in regions with a high hydrogen storage potential. A truly large scale use of solar energy, therefore, requires above all a system which will permit the decoupling of solar energy from local demand patterns and physical conditions.

This means going to locations in sunny, arid regions where the "resource" can be optimally used for STEC as well as for photovoltaic cells. The use of large areas of waste land and a concurrent improvement in the economic conditions of generally poor regions are promising aspects of such a scheme. In order to implement it the sunlight would have to be converted into a suitable secondary energy carrier.

Two ways seem possible: electricity generation and transmission and production of hydrogen or another fuel, far away from the consumption centers. High voltage DC lines permit electricity transmission at low losses over about one thousand km. As regards the European communities, for instance, it would become possible to build solar power stations in Southern Europe--Portugal, Spain, Italy, and in some parts of France--that are to serve consumers in central or Northern Europe. A concept realizable in a more distant future is to employ underwater cables for transmitting the electricity from Northern Africa to Europe.

J. Weingart (1978), using several studies of STEC undertaken by various U.S. institutions, and R. Caputo (1976) have estimated the cost of such electricity to be in the range of US$ 0.04-0.1 per kW(e)h. The related transmission cost would be on the order of US$ 0.01/kW(e)h.

The relative steady solar supply in the harvesting areas as well as the integration of several sources into an overall system would facilitate the use of this electricity in base or intermediate load. However, substantial advances in central storage technology as well as in load leveling management are still required. Production would not fully be decoupled from the demand side.

In contrast, the large-scale production of hydrogen and liquid fuels that involve long distance transport and seasonal storage imply a complete decoupling of the solar source and energy needs.

Hydrogen can be transported in pipelines over continental distances of 5000 km, which is fortunate since all large consumers, except for Japan, are less than that away from the sunny zones. The cost would be in an acceptable range: approximately US$3/barrel of oil equivalent (Beghi et al. 1972) transported over 5000 km in 48-inch pipelines. Storage does not pose major problems either. Aquifers and natural formations, such as depleted oil and gas fields, provide sufficiently large geophysical storage possibilities to serve the needs for years or even decades. It would add some US$1 per barrel of oil equivalent. On the consumer side, the production of hydrogen would add additional flexibility. It could be used directly for energy purposes, converted into electricity, or used for enhancing fossil fuels (allothermal methanol production from coal).

Two ways of producing this hydrogen are conceivable. One is to use central receivers for a thermochemical splitting of water (a forseeable but not yet available technology. The cost range could be US$32-82/barrel of oil equivalent at an insolation of 2750kWh/$m^2$ year. The other possibility is to employ electrolysis powered by STEC or photovoltaics. With STEC, costs would be approximately US$63-103/barrel oil equivalent. The cost of photovoltaic hydrogen is much more uncertain. Should such arrays become available at a cost of US$2000 per average kW(e), hydrogen could be produced at an order of magnitude of US$50/barrel of oil equivalent.

An alternative to hydrogen production would be the production of a fuel, for instance methanol, by combining coal with solar-produced hydrogen. This would presuppose either proximity of the solar sites to large coal deposits or substantial improvements in coal transport technology. Figure 42 compares the cost of methanol deriving half its energy content from coal and half from either solar electrolytic or solar thermolytic hydrogen, as a function of the coal price. At US$100 per ton of coal, thermolytic hydrogen, as opposed to electrolytic hydrogen, would reduce the cost range to 30 to US$54/barrel of oil equivalent. Methanol from coal directly would cost about US$42/barrel of oil equivalent.

The factors constraining the deployment of these technologies are technological, physical and institutional in nature. Both STEC and photovoltaics have not yet reached a maturity permitting their commercialization. For instance, STEC development is estimated to take several decades and an R & D effort of the order of US$ 1 billion. Institutionally, the location of a significant portion of the world's energy supply system in desert areas, will require a stable development of international trade patterns, guaranteeing the safety of large investments in foreign countries and presupposing a general atmosphere of trust between the South and the North.

On a multi-terawatt scale, the construction, operation, and decommissioning of solar plants covering hundreds of thousands of $km^2$ will result in significant environmental impacts. The huge materials requirements will generate secondary effects in mining areas or, for instance, in steel production. The detrimental effects will partly be counterbalanced by the availability of clean energy carriers elsewhere. Furthermore, we must expect questions of a "fair" distribution of those burdens to arise. A workshop held at IIASA in 1976 (Williams, Krömer and Weingart 1977) examined the possible impacts of large-scale solar conversion on the climate. Large-scale deployment of STEC would lead to regional changes in the surface heat balance and hydrological characteristics, each possibly affecting climatological conditions.

Physically, the very high materials demand seems to be the most stringent factor. For the dispersed quality of the source requires large surfaces to be covered with materials. Even if one assumes substantial technological improvements to arise that cut down on the materials demand, it is unlikely that systems at a material density of less than $10kg/m^2$ could sufficiently withstand weather-imposed stresses over a period of decades. A system with a material density of $10kg/m^2$ might be, for example, a thin tough film of photovoltaics. Today's heliostat designs are characterized (Saumon 1977; Boeing 1977) by a material density of $30-80kg/m^2$ of steel and glass. To that figure the concrete used in the heliostats adds $190kg/m^2$ and the rest of the plant adds $210kg/m^2$. Figure 43 shows material requirements as a function of annual installed capacity. At an introduction rate of 0.6 TW yr/yr, a solar thermal chemical system would have a yearly requirement of 1000 million tons of concrete plus 100 million tons of steel. This compares to an annual (1975) global production of 700 x $10^6$ tons/year of concrete and 630 x $10^6$ tons/year of steel.

The introduction of solar energy into the market will depend on how fast these constraints can be mastered and how the general competitive situation among energy sources evolves. In the initial phase, we can expect that external support might help to overcome somewhat higher costs. Yet in the long term full commercial maturity is a must.

C. Marchetti (Marchetti and Nakicenovic 1978) (see also Chapter 5) has shown that market penetration ratios in the energy field are remarkably constant. Assuming optimistically that by 2000 the direct uses of solar energy would have captured 1% of the world primary energy market and applying historical rates of market introduction, solar energy could reach 6% of the market around 2030 as illustrated in Figure 1 (reproduced here as Figure 44).

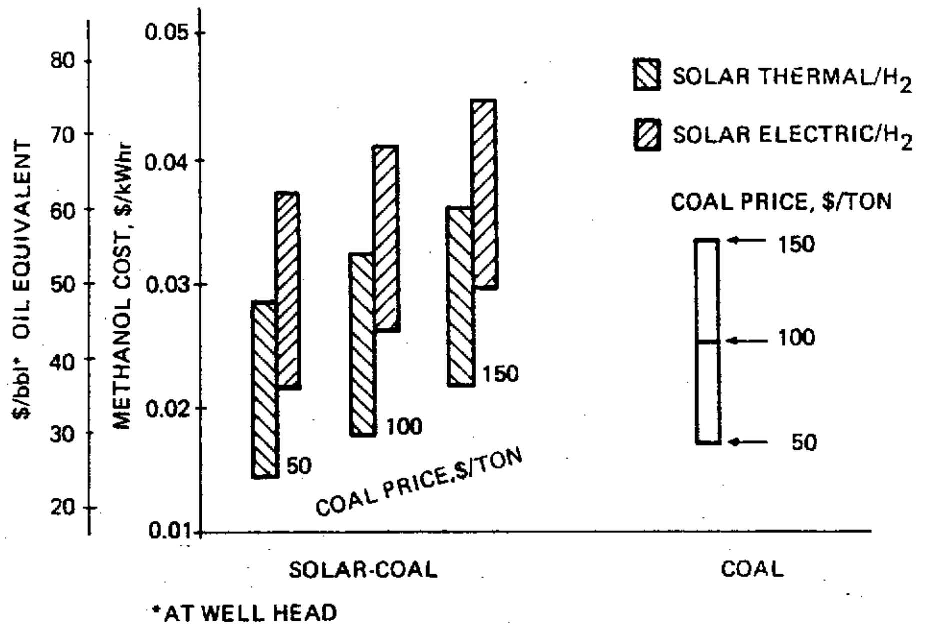



FIGURE 42 Methanol generation cost. SOURCE: Caputo (1979).

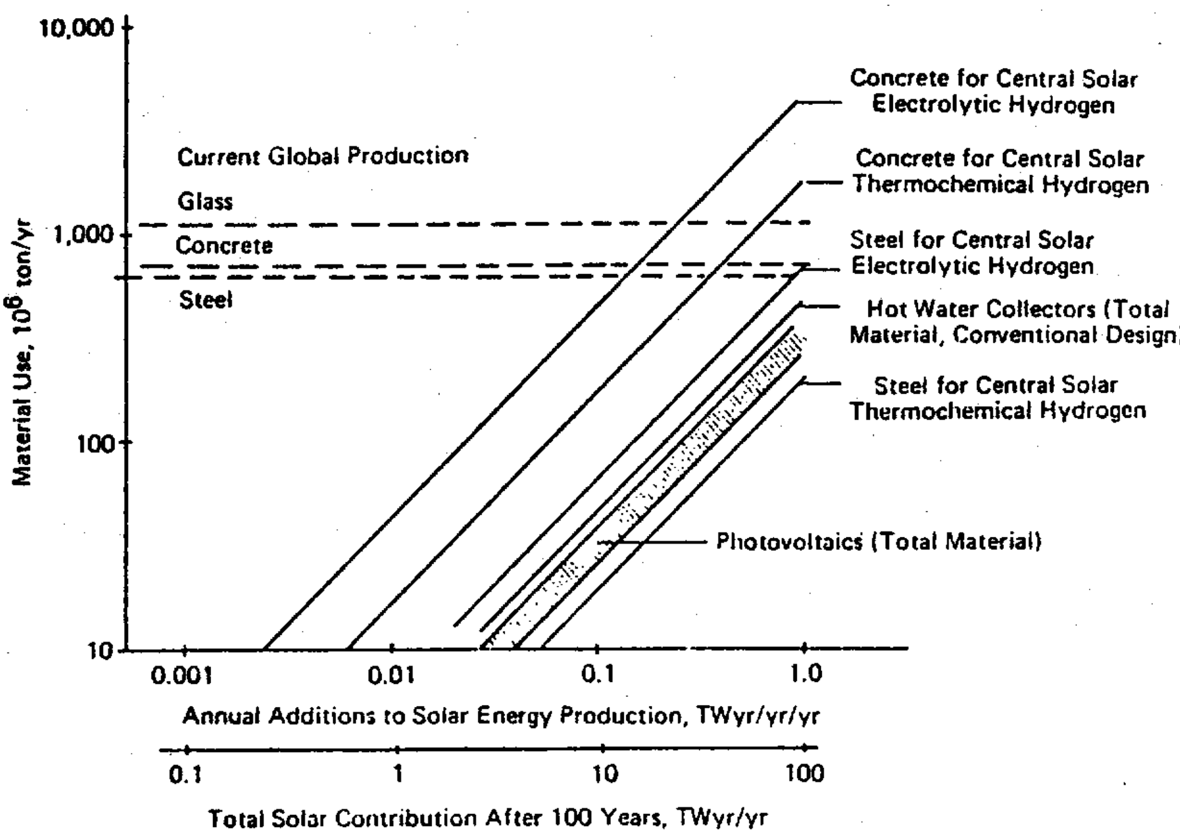



FIGURE 43 Material requirements for central solar systems.

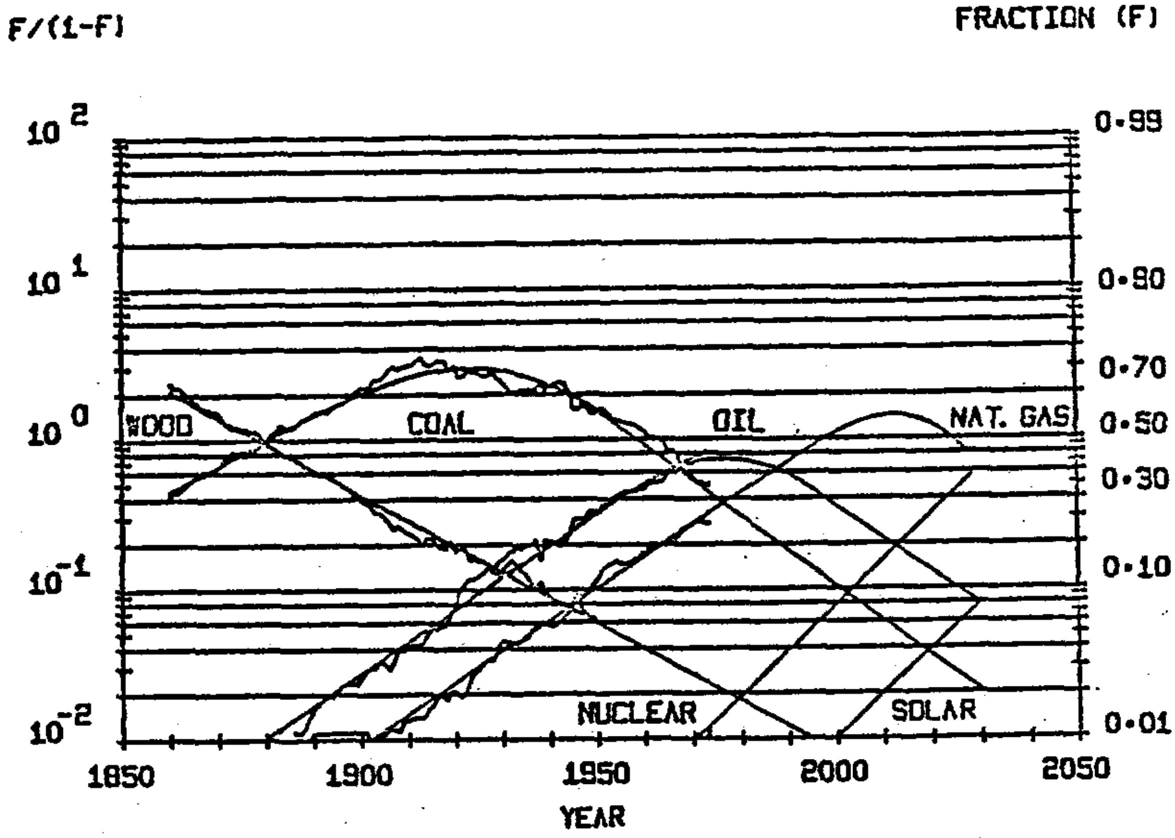



FIGURE 44 Global primary energy substitution, 1960-2030. Logarithmic plot of the transformation F/(1-F) where F is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show where energy sources follow logistic model substitution paths.

Source: Marchetti and Nakicenovic (1979)

Conclusions

The good news of this analysis is that solar energy can contribute realistically on a significant scale in the next century to the world's energy supply. Though a large-scale use of solar energy would entail environmental and other impacts, it would be probably more palatable psychologically than the large-scale use of other forms of energy. Furthermore, there is a broad spectrum of possible applications ranging from local and user-oriented (but demand limited) technologies to truly global systems.

The bad news is that solar power harvested on a significant scale will be available to us only well after the turn of the century. It would be unrealistic to expect it to substantially alleviate the energy problem of the coming decades. Yet, during this time much effort will have to go into developing and deploying solar energy so that by the middle of the 21st century the transition from the natural endowment of fossil fuels to man-made endowments can progress smoothly.

# 4 RISK AND HEALTH

## INTRODUCTION

The use of each of the energy technologies described in the previous chapter is constrained by various infrastructural, technological, institutional, economic, and societal factors. Most of these factors are specific to a given technology, such as radioactivity to the nuclear option, $CO_2$ to the fossil option, etc; some of those factors which are of a more general nature concern all supply alternatives in similar ways. ENP has studied several of those latter, so to speak "global", constraints. The interactions between energy production and the climate system were the subject of a UNEP/IIASA project called "Energy and Climate", FP-0700-75-03 (855) (Williams and Krömer 1976). The study of market penetration phenomena, i.e. the factors limiting the speed at which new technologies can be introduced, were examined under a contract from Foundation Volkswagenwerk (Marchetti and Nakicenovic 1978); this study is briefly described in Chapter 5.

UNEP/IIASA collaboration on both the environmental risks and the health effects possibly associated with various energy systems has been the focus of our research on the common constraints of energy technologies. Health and environmental risks, of course, are interlinked and, therefore, a joint project of the International Atomic Energy Agency (IAEA) and IIASA was established in 1975 to assess both subjects. In addition, a statistical evaluation was carried out to look into possible correlations between energy consumption and health as measured by longevity and infant mortality.

The magnitude and sophistication of the problem that had to be attacked--and for which often new ground had to be broken--made it clearly impossible to exhaustively examine the related issues within the contractual period. Yet we still believe that our results have contributed to obtaining a better grasp and understanding of the risks and hazards involved in energy systems as well as to laying the groundwork for future research.

THE ASSESSMENT OF ENVIRONMENTAL AND HEALTH RISKS

The Components of the Study

Substantial effort was devoted towards building a framework within which the assessment of risks could be carried out. Figure 44 illustrates the components of the scheme developed.

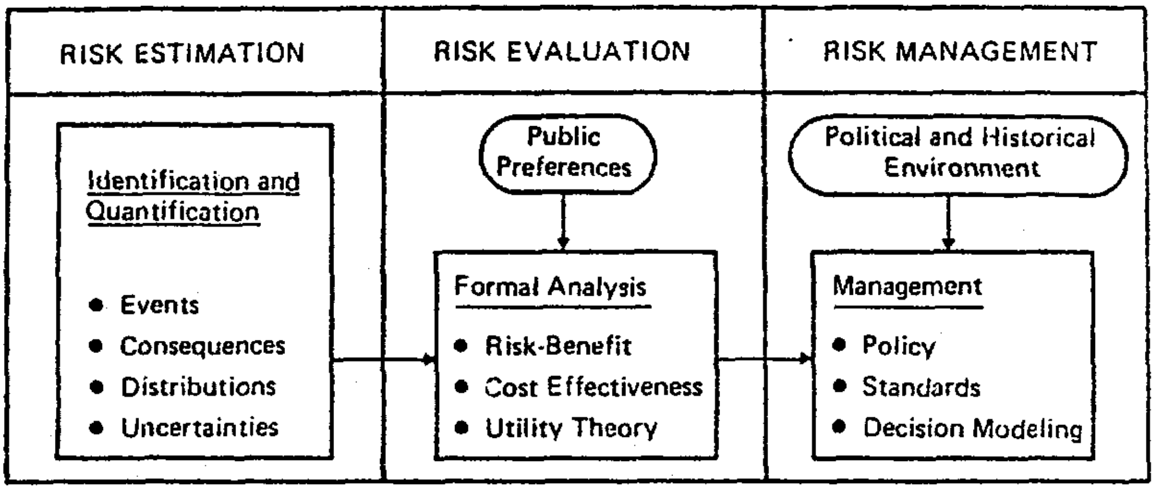



FIGURE 44 A risk assessment framework.

*Risk estimation* deals with the identification and quantification of risks. It aims at comprehending the objective consequences of operating a given technological system, describing the events that arise (emission, accidents, etc.), the probability of their occurrences, the effects (deaths, increase in illness, etc.) and their distribution within the population affected, as well as the uncertainties of the estimates. This field being by far the most widely studied aspect of the risk problem, our project concentrated on the survey and analysis of the results of past research efforts; thus duplication was to be avoided and it was attempted to conserve scarce resources rather than spend them on research for which other groups are much better suited.

Here one remark is in order. In the past, the methodology used to prepare safety decisions, for instance, relied heavily on "trial and error;" that is to say, risk was quantified through historical experience and only then controlled. This procedure is definitely unacceptable in the context of global energy systems; for experimenting with the climate or with nuclear power station accidents is just impossible. For global, long-term energy systems approaches will have to be developed that are based on a frame of reference other than experimental results proving or disproving a working hypothesis (Häfele 1975).

Our project also focused on *risk evaluation*, for identification and quantification of risks is but a preliminary step to the comparison of risks in all their dimensions to various attributes of the energy system, such as operating costs, reliability, etc. Risk evaluation is the component of risk assessment accounting for subjective aspects. This issue is complex.

How does one compare nuclear proliferation risks to the risks associated with a major blackout, or risks faced by the present generations to those affecting future generations?

The "balancing of apples and oranges" will ultimately have to depend on subjective value judgments and preferences. Even, if it is thus impossible to adopt a single, objectively correct procedure, every effort should be made to identify techniques that might help to formally and systematically incorporate subjective values into the complex and multidimensional procedure of energy policy decision making.

Finally, *risk management* addresses the organizational and political aspects of the environmental and societal management of energy systems. How does one, in practice, in order to negotiate and implement an energy strategy, handle the problems arising when competing groups disagree (more often than not) on both the estimation and the evaluation of certain risks? At IIASA, we focused on one important part of risk management: the dynamics of regulatory agencies responsible for setting standards for energy systems.

## Quantified Risks of Energy Systems

C. Starr et al. (1972) has suggested to employ the average risk of acquiring a fatal disease as a possible yardstick for determining acceptable risk levels. Many accepted technologies indeed involve risks comparable to this level, which Starr found to be $10^{-6}$ per person and hour: three weeks of work in a clothing factory, three hours of work in mining, 100 km travel by car or 500 km by plane, each of these risks involves the probability of one fatality in a million.

In comparison, Table 43 summarizes the health risks associated with the production of 1 GWyr of energy from coal, oil, natural gas, light water reactors, and solar thermal power stations. Although these data are derived from a relevant literature survey some caveats must be made:

- The data on the effects of sulfur dioxide, particulates, and radiation exposure have been based on linear nonthreshold extrapolations from high level acute exposure.
- Because acceptable data are not available the effects of vanadium releases, for example, from oil-fired plants, or radioactive emission from fossil fuels, in general had to be neglected.

In spite of these uncertainties, the data permit a ranking of the various systems considered according to their health impacts. As shown in Figure 45, coal and oil appear to have the largest impacts on the public, whereas coal and solar-thermal systems pose the highest threat to the workers concerned. For a one-dimensional comparison one fatality has been assumed to equal a loss of 6000 man-days. Of course, much more research is required to narrow down the uncertainties (which equal six times the lower estimates in the case of coal and oil, for instance) and to incorporate those uncertainties that cannot be removed into a single parameter for measuring risks.

Table 43 Estimated Human Health Effects from 1 GWyr ($8.76 \times 10^9$ kWhr) of Electricity Generation

| Power Plant Type | Accidental Injuries (in man-days lost) Occupational | Accidental Injuries (in man-days lost) Public | Accidental Deaths Occupational | Accidental Deaths Public | Fatal Diseases Occupational | Fatal Diseases Public |
|---|---|---|---|---|---|---|
| Coal | | | | | | |
| Fuel supply | 1,920-3,100 | | 1.2-1.8 | | 5.6-8.4 | |
| Transport fuel & materials | 640-880 | 1,500-1,800 | 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 | 3,940-5,360 | 1,500-1,800 | 2.0-2.8 | 2.7-3.8 | 5.6-8.4 | 3-22 |
| Oil | | | | | | |
| Fuel supply | 3,850 | | 0.38 | | | |
| Transport fuel & 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 | 5,140 | 2-3 | 0.6 | 0.0048 | | 1-7 |
| Gas | | | | | | |
| Fuel supply | 2,200 | 2,200 | 0.23 | 0.16 | | |
| Transport fuel & 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 | 2,700 | 2,200 | 0.34 | 0.163 | | 0.005-0.034 |
| Light Water Reactor | | | | | | |
| Fuel & reprocessing | 300-400 | | 0.12 | | 0.05 | |
| Transport fuel & materials | 5 | 6 | 0.0025 | 0.011 | | |
| Normal operation | 10 | | 0.03 | | 0.032 | 0.03 |
| Construction | 310 | | 0.082 | | | 0.003-0.021[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 | 580-2,300 | | 0.28-0.29 | | | |
| Normal operation | 2,200-2,800 | | 0.8-1.0 | | | |
| Total | 6,700-9,000 | 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, etc.

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 43 is the Canadian Atomic Energy Control Board's report by H. Inhaber (1978), a report which has attracted strong criticism. While the only Inhaber results that are incorporated in Table 43 are those having to do with occupational health effects during construction, we feel that we should include here some supplementary data to Table 43. Presented below are the results of J. P. Holdren's critique (J. P. 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. Although we were not able to incorporate here a proper treatment of Holdren's work, 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 | 9,400-520,000 |
| Holdren | 7,400-15,000 | 1,000-2,700 |
| Nuclear (LWR) | | |
| Inhaber | 1,700-8,700 | 300-1,500 |
| Holdren | 3,100-12,000 | 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 | 2,000-18,000 | 9,000-1,900,000 |
| Holdren | 3,000-19,000 | 9,000-1,000,000 |

[a]One fatality was assumed equivalent to 6,000 person-days lost except for coal workers, in which case a fatality was assumed equivalent to 1,000 person-days lost.

More specifically, events characterized by a low probability of occurrence and harsh consequences (low probability-high consequence events) merit special attention. Figure 46 plots the frequency versus magnitude of several man-made and natural events. The data are mostly derived from past statistical analysis; the nuclear and petrochemical facilities curves are taken from the fault tree and analyses of the Rasmussen (Nuclear Regulatory Commission 1975) and Canvey Island (1978) studies, respectively. Direct comparison between such data is difficult because of the qualitatively different nature of the impacts of low probability-high consequence events, particularly with respect to the related social cost. In fact, the ongoing nuclear debate has clearly shown that the public perceives low probability-high consequence events as being much more threatening than high probability-low consequence events.

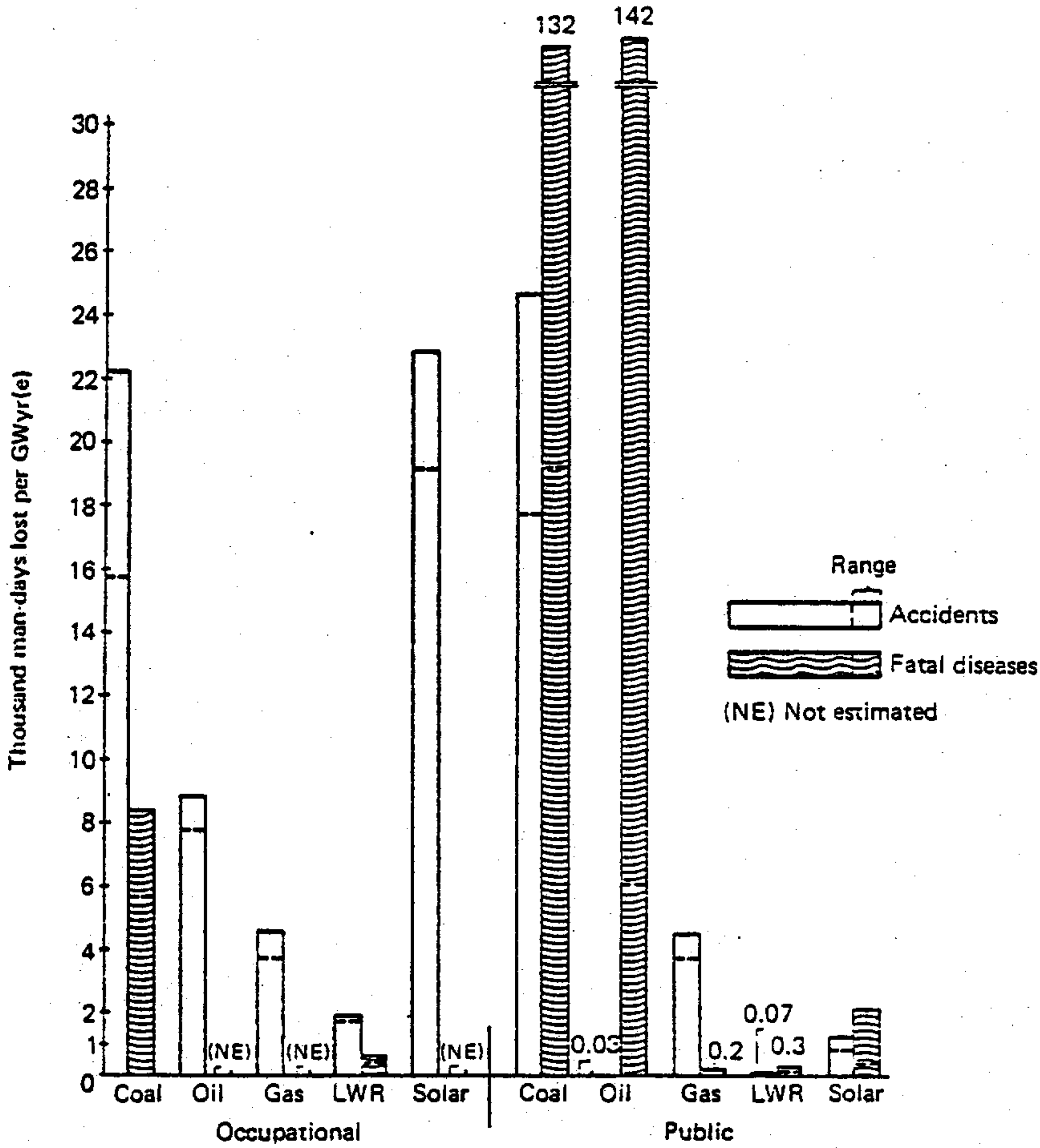



FIGURE 45 Man-days lost annually due to supplying 1 GWyr(e) from each of five sources. Power plant life is 30 years.

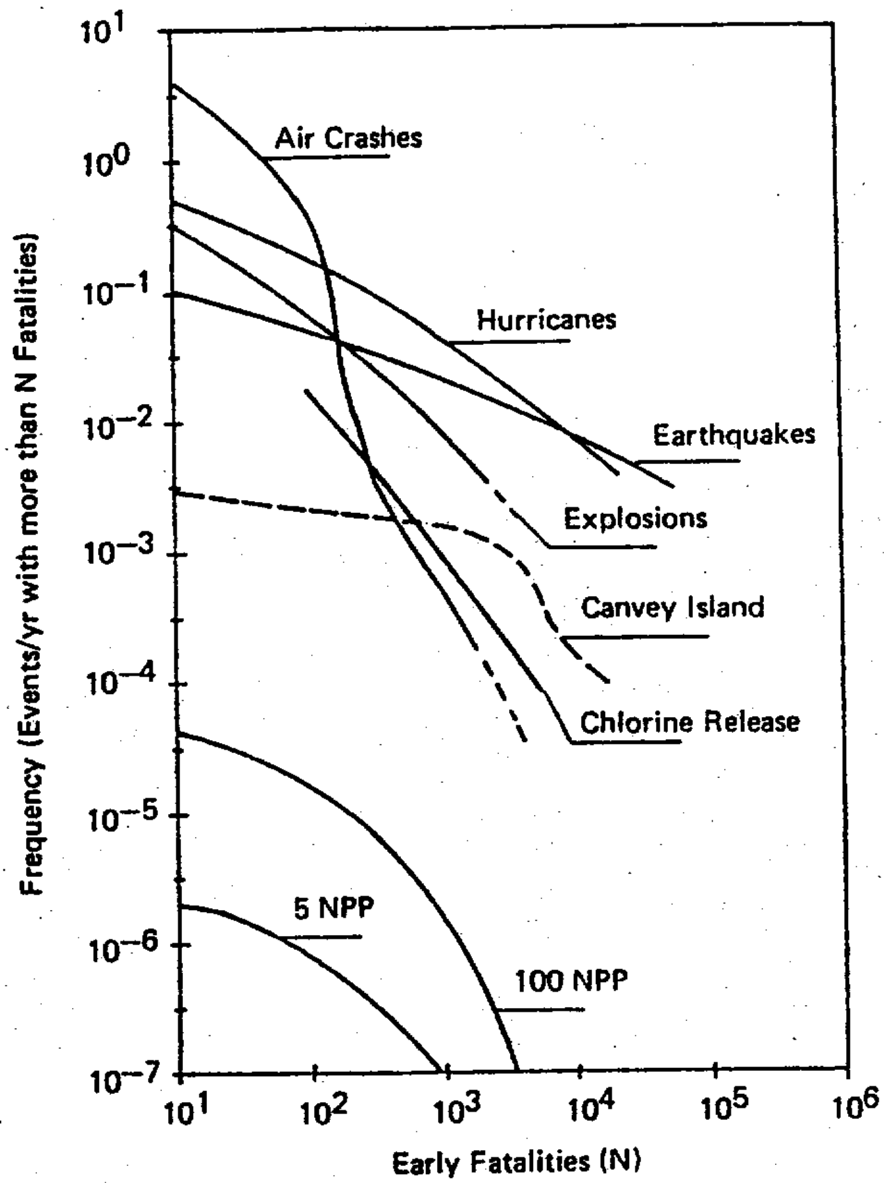



FIGURE 46 Frequency of events causing more than N early fatalities for some man-made and natural events and estimates for similar events from 5 petrochemical plants on Canvey Island and from 5 and 100 nuclear power plants (NPP) located at current sites in the U.S. SOURCE: Curves for petrochemical plants and for nuclear plants based on Canvey Island Study (1978) and USNRC (1975), respectively. Data for natural hazards and man-made events are derived from statistical analyses of past events.

Risk-Benefit Evaluations

In such an evaluation two types of cost must be considered. *Internal costs*, i.e. costs of operating a given facility and *external costs*, i.e. costs of, e.g., health impacts. This dichotomy requires expression of health effects in monetary terms.

Assigning a monetary value to human life is an obviously difficult task, which has to be done and interpreted cautiously and prudently. With this fundamental caveat in mind, we explored several approaches to determining such values (Linnerooth 1975).

- 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 redeem mortality risks; and
- willingness to pay--risk reduction is valued by the public's willingness to pay for it.

In the present U.S. context, these approaches seem to indicate a "value" of one human life of US$ 300,000, reflecting a trade-off between risk reduction and GNP maximization. *This value is therefore only meaningful in purely economic terms within the context of risk/benefit analysis.*

Table 44 compares the internal and external (health) costs of several electricity supply systems. Internal cost turns out to be much higher than external cost. In the latter category, nuclear external costs are the lowest. Only if a much higher value for human lives lost through nuclear systems were assigned in order to account for the different nature of the risk would the ordering change. Indeed, there is a striking mismatch between public opinion and the results of this cost-benefit analysis.

This divergence is also apparent in the $CO_2$ problem. Though still at the fringes of subjective public interest, $CO_2$ nonetheless poses a significant objective threat. Simulation studies indicate that a fossil fuel consumption of 700 TWyr in the coming 50 years might result in an average global temperature increase of $1^oC$ possibly affecting, among others, agricultural production. Using a study by Bach (1978) we estimated 0.3% of the global agricultural production possibly to be lost in this way, or an equivalent of US$ $3x10^9$ yr. The external production cost of 1 GW(e)yr would then be about $43.5x10^5 --a much higher figure than the external cost of nuclear energy.

Cost Effectiveness of Risk Reduction

Resources that can be devoted to risk reduction are limited in any society. It is therefore necessary to employ them most effectively. The marginal costs of risk reduction in various fields are given in Table 45. In the case of low probability-

Table 44 Costs of Electricity Generation ($10^6$ $/GWyr(e))

| Type of Cost | Coal | Oil | Nat. 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 | 8,400 |
| Thyroid nodules | 1,400 |
| Genetic effects | 8,400 |
| Property damage | 27,000 |

"Acute" as used here means either death within 30 days or illness occurring within 30 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 (1975), assuming 50 man-days lost per illness and 50 man-days lost per case of thyroid nodules.

Table 45 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] | 1,000[a] |
| Remote siting | 10,000[a] |

[a]Based on 1 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).

high consequence accidents, the marginal costs of saving one life turn out to be orders of magnitude higher than with "normal" risks. More generally speaking, the marginal cost of risk reduction seems to increase with the level of safety achieved.

In principle, adequate expenditure would apparently permit reduction of any risk to any level desired and, consequently, safety standards that represent an arbitrary trade-off between the objectives of maximum safety and minimum economic cost. However, this is only true for a single facility or portion of an energy system. For the system as a whole, reducing the risk in one facility corresponds to increasing the risk in another part of the system. Production of the components of additional safety devices implies incremental occupational and public risks. Calculations for the FRG (Black et al. 1979) show that for each billion US$ worth of machine tool and electrical equipment, 8.2 deaths result from accidents at work and during commuting as well as 52,000 lost working days.

A comparable value of the public risks involved that could be obtained in this way would be one fatality per US$ $3x10^7$ of safety equipment produced. Any risk reduction at a marginal cost greater than US$ 30 million therefore actually *decreases* the overall safety of the system.

These considerations are obviously not precise. Uncertainties are considerable and the specific national and regional conditions cause substantial variations in the data. Moreover, no distinction is made between the life lost *now* and the *expectation* of saving one life in the future--whereby the inherent moral and ethical, if not institutional, issues are disregarded. Nonetheless, these procedures help provide insights into the scope of reasonable safety expenditures, promoting an understanding of the underlying issues.

## Public Preferences

Public perception often differs greatly from the results of risk-benefit calculations. There are essentially two methods for examining group preferences.

The study of *revealed preferences* starts out by examining the choices society has made in similar situations of the past. National level statistics may give some indication, but mostly it is not possible to distill from them the actual reasons for such choices. At the same time, using past behavior as a yardstick for projecting future behavior may be misleading; especially in the fast changing environment of present industrial societies, rejection of past values is one of the strongest motives for many to oppose technology.

Because of these factors, we concentrated on the study of *currently expressed preferences* obtainable through interviews and questionnaires. "Risk perception" was considered as an *attitude* toward a particular risk situation. A person's attitude can in turn be measured in terms of the beliefs that a person holds about the attitude object, i.e., the "learned" associations existing between the attitude object and some set of characteristics or attributes. The number of salient beliefs actually determining a person's attitude is judged to average between five and nine.

The IAEA-IIASA work used the Fishbein model (Fishbein 1963, Fishbein and Ajzen 1975). This model assumes that the strength of belief, weighted by a person's evaluation of the respective attributes can be summed up to form a measure of attitude. On the basis of an earlier pilot study (Otway and Fishbein 1976), a questionnaire was developed for examining the beliefs (and consequently the attitude) held by a stratified heterogenous sample of the general Austrian public about five alternative energy systems (Otway and Fishbein 1976).

Table 46 shows that the nuclear PRO and CON groups agreed on issues of hydroelectric and solar power, but had slightly differing opinions on coal and oil. Figure 47 shows highly positive attitudes of both groups towards solar and hydroelectric power, but somewhat less positive attitudes towards coal and oil. In contrast, the attitude towards nuclear energy is characterized by three clusters around the two extremes and the neutral attitude area.

TABLE 46 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. (1979).

A factor analysis examining 39 beliefs grouped for four dimensions (Table 47) was carried out to study the reasons for the widely discrepant attitudes towards nuclear energy. It turned out that the PRO group's positive attitude resulted from beliefs in economic benefits and the perceived absence of environmental risks. The CON group's negative attitude, in contrast, stemmed from their beliefs in negative psychological aspects and sociopolitical implications (Table 48).

Finally, the attitudes held by decision makers and the general public towards nuclear energy were studied by testing the accuracy of what decision makers think is the public's opinion. The attitude of decision makers was generally found to be more favorable towards nuclear energy than that of the public, mainly because the former group was less concerned about the psychological aspects involved. Decision makers in fact tended to overestimate the positive attitudes of the PRO group. The decision makers significantly failed in recognizing the

TABLE 47 Belief Dimensions and Most Characteristic Belief Items About the Use of Nuclear Energy

| |
|---|
| **Psychological Aspects** |
| Exposure to risk without my consent |
| Accidents which affect large numbers of people |
| Exposure to risk which 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. (1979)

TABLE 48 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% level.

SOURCE: Based on Thomas et al. (1979)

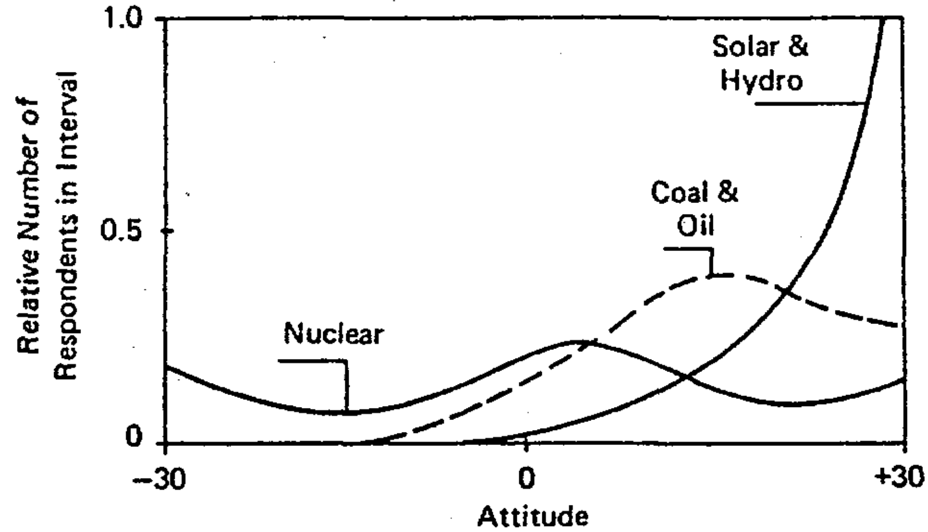



FIGURE 47 Smoothes frequency distribution of attitudes toward energy sources.

way in which psychological aspects contributed to the formation of attitudes towards nuclear energy in the public PRO and CON groups.

An experimental attempt was made to combine the results from the risk-benefit analysis with those of the studies of preferences and attitudes. By applying multiattribute theory (Keeney and Raiffa 1977), the problem of evaluating nuclear waste disposal sites was examined (Otway and Edwards 1977) with public attitudes being one kind of attribute decision makers would consider. Results indicate that the procedure is feasible insofar as decision makers can make orderly judgments of the sort required for utility measurement, and to the extent that a reasonable agreement could be reached among various judgments as to the weights characterizing the relative importance decision makers attach to each attribute.

Risk Management: The Setting of Standards

Identifying, quantifying, and evaluating risks does not yet answer the practical, crucial, question: when, where, and how may an energy facility operate? Grappling with issues of that kind requires translation of the results of our previous analysis into concrete policy and regulatory decisions.

Of the tools available (market approaches, regulations and direct interventions, etc.), standard setting has emerged as the most practical and commonly used means of environmental hazards control. Standards have thus become a major constraint--and a major driving force--for the development and deployment of technology.

The importance of standard setting, as a major factor contributing towards shaping future energy systems, has been acknowledged in several of the ENP analyses; but in most efforts of this kind, standards were at first treated as exogenous inputs.

Under a study contract by Foundation Volkswagenwerk, FRG (Winterfeldt et al. 1978), we proceeded to examine the much more intricate problem of how to reach--under a given set of social conditions as well as institutional and environmental realities--equilibrium states and cost optimal strategies for parametrically fixed constraints. Several roads were followed to that end.

(a) A literature survey of existing analytical approaches and standard setting procedures as well as of related fields (legal studies, environmental economies, policy analysis, decision theory, game theory etc.) was carried out.

(b) On the basis of the above survey we decided to study, in interaction with decision makers, three cases of past (and continuing) standard setting processes--specifically radiation standards, chronic oil discharge standards for UK offshore platforms and noise standards for the Shinkansen railway system in Japan. In so doing, we put the focus on the development of decision and game theoretical models as aids to regulatory agencies or similar institutions in performing standard setting tasks.

Examination of the three processes clearly revealed the variety, complexity, and intricacy of standard setting pointing up the need for more formal and more highly organized approaches.

Biological information on the effects of low-level oceanic hydrocarbon concentration is scarce. The UK, therefore, was led to set chronic oil discharge standards according to the "best practical means" principle, i.e., on the basis of equipment availability, cost, and performance. These standards were binding.

Japan, in contrast, set its standards of noise control of the Shinkansen railways system using a noice-complaint relationship for minimizing the number of complaints. These environmental quality standards, ignoring more or less available technical and cost data, were formulated as targets rather than as directly binding standards.

The long-term evaluation of radiation standards shows how definitions of standards can be shaped by the availability of information, practical necessities, and changing opinions. In 1955 the ICRP recommended that "every effort be made to reduce exposure to all types of ionizing radiation to the lowest possible level." In 1958 the wording was changed to "as low as practicable," in 1965 "that all doses be kept as low as readily achievable, economic, and social considerations taken into account," and in 1973 it was suggested to replace "readily" by "reasonably."

However, in spite of this sometimes puzzling diversity, all standard setting processes are similar in some important ways. In particular, the main *actors* and their goals tend to be the same.

The *regulator*, i.e., the agencies or institutions determining a standard, usually pursues important political objectives (e.g. consistent policies). The *developer*--firms, industries or organizations whose activities are thus being regulated--is, as a rule, chiefly interested in the economic consequences. The *impactees*, i.e. those who "benefit" from the standard are obviously interested in minimizing the potential risks. In addition, international organizations, expert scientists, pressure groups, and, of course, the public might influence the process by pushing their respective interests.

Based on those findings, two decision theoretic models were developed. Both assume that only the regulator, the developer, and the impactees influence the standard setting process.

Höpfinger and Avenhaus (1978) constructed a multi-stage game theory decision model, attempting to capture in a probabilistic manner the possibilities for the actors to learn and adapt themselves to the various stages of the standard setting process. Höpfinger and v. Winterfeldt (1978) applied this model to the Shinkansen railway system noise problem, and Höpfinger (1978) analyzed the standard setting for environmental carbon dioxide concentration. The tests showed that the model developed might provide some insight into the structure of the conflict between the three actors. It remains to be seen whether models of this kind could be refined providing quantitative results that could be useful to decision makers.

A simpler, one-stage decision theoretic model was conceived by v. Winterfeldt (1978) and applied to the problem of chronic oil discharges in the North Sea.

The structure of the model is schematically outlined in Figure 48. Given the regulator's announcment of his standard r, an expected utility model is used to determine the optimal response of the developer, d(r). The impactees are assumed to respond to the developer's decision d(r) with an optimal response a d(r). This set of decisions, together with the associated utilities $U_R$, $U_D$, and $U_A$ accruing to the three decision units, permits exploration for decisions to be made later of the relative benefits of given standards in the views of all the parties affected.

The model was applied. In terms of dominance analysis, a few alternatives open to each actor were examined. The model quantifications were hypothetical as they reflect the author's perception of the actors' values and opinions. Nevertheless some interesting results were obtained:

- Nondominant standards tended to cluster around points at which the cost of the next best treatment is equal to the expected cost of the discharge.
- Location of these points is largely controlled by the physical uncertainties governing detections.
- Penalty variation and nonlinear utility function do not strongly affect these points.

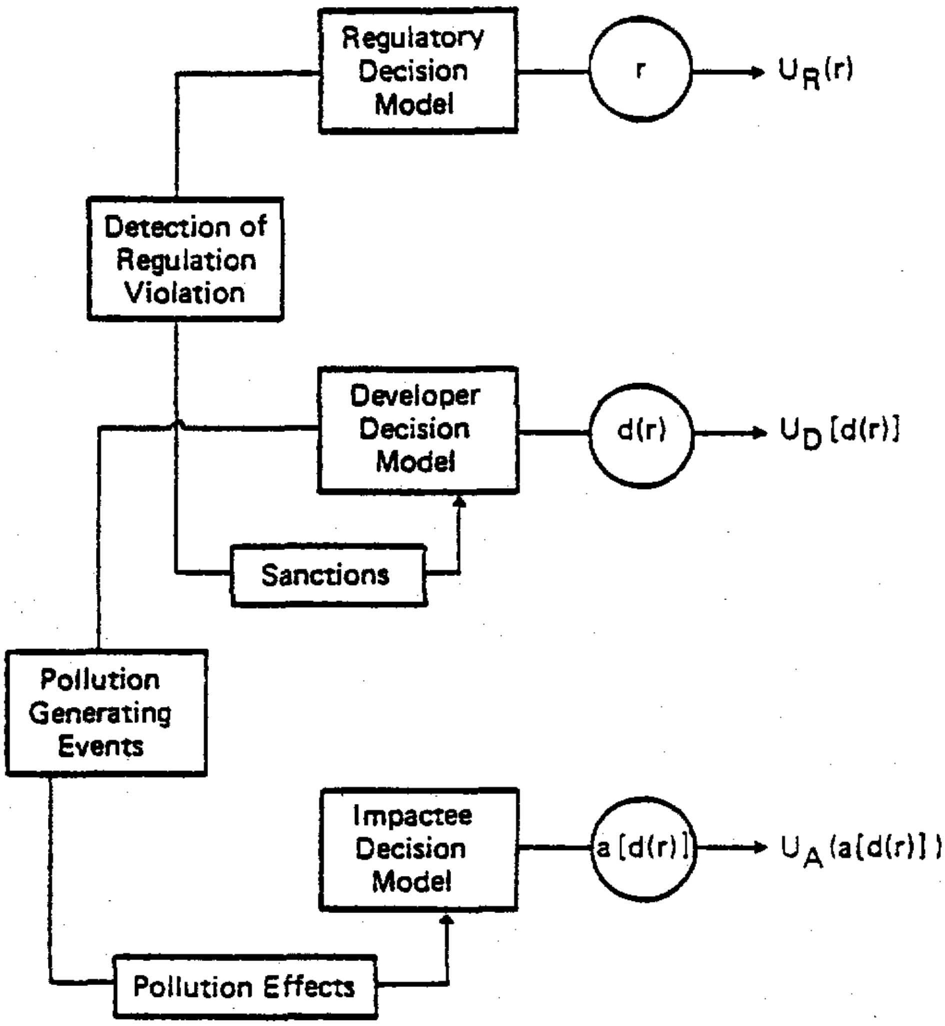



FIGURE 48 Schematic representation of the single-stage decision model

Conclusions

The analysis of the risk assessment problem carried out at IIASA has not been conducted in a comprehensive, encyclopedic form. Although much remains to be done, within the given limits of time and scope, it could not have done otherwise. Its aim has been to identify and better understand the elements, the sum of which might constitute a "way" of handling energy risks under hypothetical conditions, i.e. conditions precluding traditional "trial and error" methodology.

In so doing, we focused on some specific problems and types of solutions, by illustrating the difficulties that one encounters in this field, and by spotting various roads that might lead toward an organized, formalized procedure of dealing with risk problems.

There were some *concrete* results. For instance, the results from risk-benefit analyses of various electricity supply systems are quite illustrative. Nuclear power was shown to present the lowest human health hazard potential per unit of electricity supplied, for both normal operation and accidents. Other than coal, nuclear hazards are relatively well understood. In general, safety measures in the energy field were seen to approach a point where risk reduction is counterbalanced by the risk of producing the necessary safety equipment.

The study of attitudes towards energy-related risks has revealed a marked dichotomy between the *objective* size and the *subjective* perception of hazards. Groups in favor and against nuclear power tend to perceive the issue in very different value dimensions, which largely explains their difficulties in communicating with each other. Lastly, examination of the decision makers' perception of public attitudes towards nuclear energy indicates that appropriate methodologies might help to alleviate the discrepancies between objective risk assessment and the risk perception by the public.

## ENERGY CONSUMPTION AND HEALTH DEVELOPMENT

### Introduction

Here the particular concern has been to unravel the dependence of improved health on energy consumption and other factors of development, and to assign some quantitative value to those relationships. Economists generally select gross national product (GNP) as a standard of economic growth. We have chosen to use the closely-related measure of per-capita (commercial) energy consumption, which is more advantageous for our purposes in several respects.

(a) Being measured in constant physical units, e.g. kilogram of coal equivalent, no arbitrary adjustments are necessary in international comparison nor for inflation.
(b) National energy consumption, a measure used to account for industrial and commercial activities, avoids the implied assumption of GNP presupposing that health is related to the consumption of goods and services.
(c) In times of resource scarcity, when efforts are afoot to "decouple" energy consumption from GNP, information about the relationship of health to energy consumption has its own inherent interest. To what extent can energy consumption be restrained or reduced without affecting people's well being?

Both GNP and energy consumption suffer from a common defect--they fail to reflect improvements in technology over time. The former does not express improvements in products available at steady prices; and the latter fails to account for the increase --developed over time--in the thermodynamic efficiency of fuel conversion.

In the present context energy consumption is used as a proxy for industrial development. This must be stated explicitly, for we do not wish to imply that energy consumption *per se* produces health benefits.

Energy Consumption and Longevity

The most suitable measure of health appeared to be mortality rates. The aggregate measure of death rates represents longevity from birth, or life expectancy, as it is sometimes called. This is a hypothetical statistic which assigns to a child born today an age-specific death rate (in correspondence with current rates), and which assumes that the risks involved will remain unchanged throughout the child's life. Infant mortality, which we have also studied, refers to all deaths during the first year per 1000 live births (children surviving the first 24 hours of their lives).

Data for 150 nations for 1975 have been analyzed. Longevity was best fitted to a logistic function with a "take-off" at an annual energy consumption of about 100 kg coal per capita followed by a rapid rise and upper plateau at 2000 kg coal per capita (Figure 49). Less than 9% of the world's population is below the threshold of 100 kg coal per capita, two-thirds is in the transition phase, and a quarter is in the plateau above 2000 kg coal per capita.

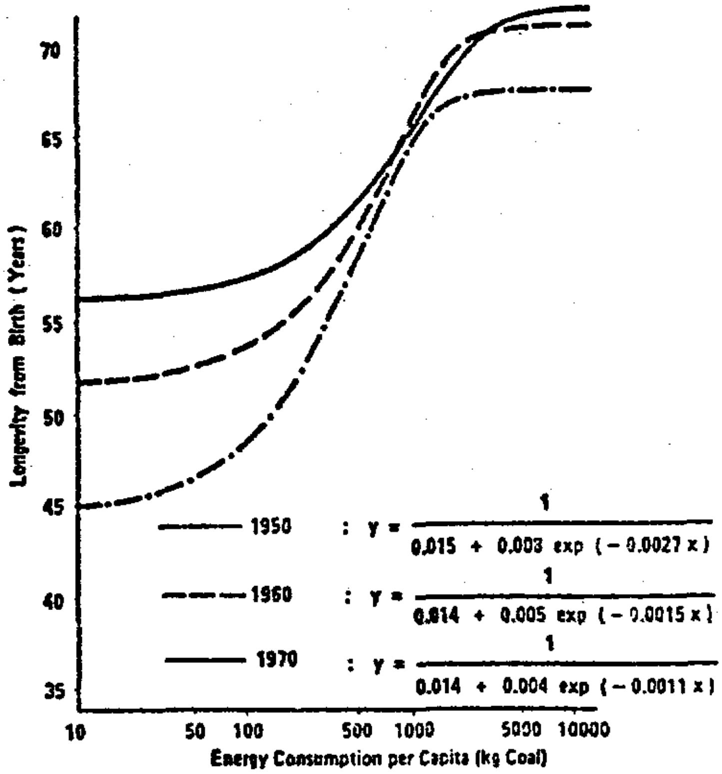



FIGURE 49 Relationship between energy consumption and longevity for 42 countries (1950-1960-1970 data)

In our longitudinal studies covering a smaller sample of 44 nations over the period 1950-1970, almost half (46%) of the improvement in longevity could be "explained" by increased energy consumption. The remaining improvement, equivalent to approximately five years of longevity, which could not be explained was noted for all levels of development. The 35-year advantage of the developed nations over the developing nations did not reduce over this period. In other words, the benefit of economic development remained constant.

## Literacy, Development, and Longevity

There were also other factors reducing death rates. In examining different intermediate variables and their association with longevity, we identified a persistent and highly significant correlation between literacy and longevity. This relationship was stronger than the correlations with certain nutritional and/or medical variables. In particular, the literacy variable was more highly correlated than other measures of education, such as, eligible population enrollment in schools in percent. Literacy, defined as the percentage of persons above age 15 able to read and write a simple statement, is interpreted as a measure of the development of "human capital" and a reflection of what sociologists call "modernization" of values.

We have also studied the use of a new, statistically derived, index of health development that combines the effects of both energy consumption and literacy. The index relates longevity and energy consumption logistically, and longevity and literacy in a linear manner.

$$\text{Crude index} = 0.288 \text{ literacy} + \frac{1}{0.0439 + 0.0185\, e^{-0.00514 \text{ energy}}} \quad (1)$$

Conversion of the index into a more convenient form, with values 0-100, requires the transformation

$$\text{Index} = 100(\text{crude index} - 16.015)/35.56 \,. \quad (2)$$

The equation obtained is a good description of longevity over the years 1900-1975, given the index. This index, which does not account for the time effect, can be used as is in cross-sectional data, but cannot be used to predict longevity in longitudinal data. The equation involving the latter is

$$\text{Longevity} = \text{crude index} + \frac{1}{0.0428 + 0.337\, e^{-0.0582(\text{year}-1900)}} \qquad (3)$$

(Similar models can also be shown to serve as tools for studying fertility and infant mortality.) The equation consists of the index plus a component representing a time factor that is independent of development. The equation allowed us to split longevity for each of the 303 cases investigated into two components: that due to health development as is estimated by the index, and that due to the time effect as is measured by the second function in Equation 3. The two components are shown separately in Figures 50 and 51.

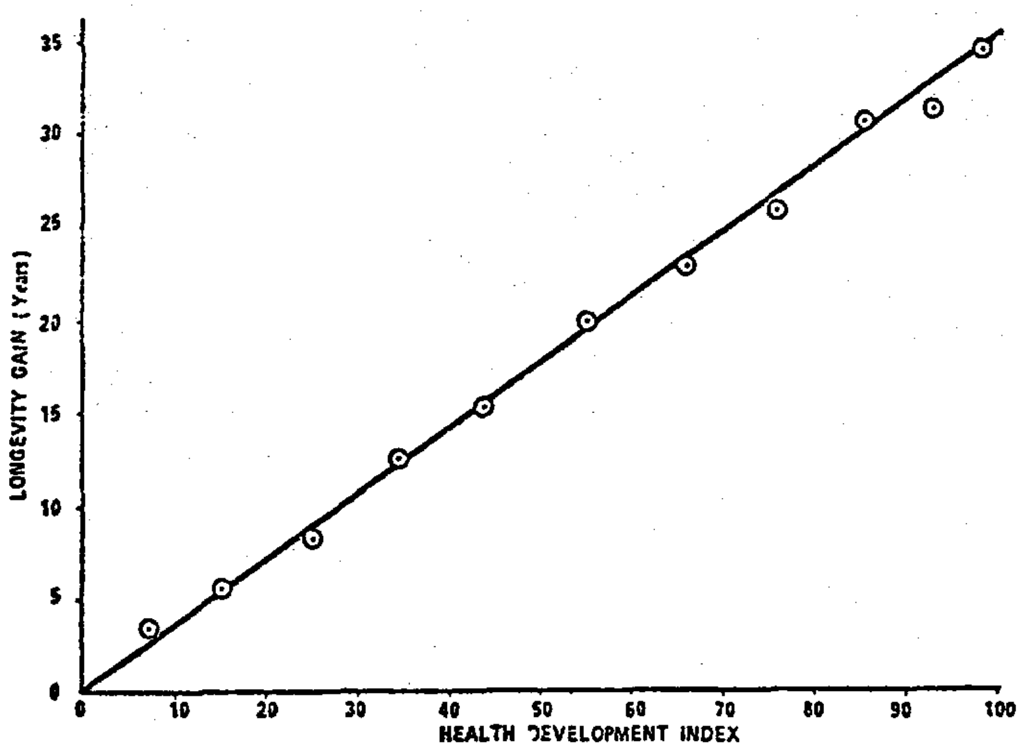



FIGURE 50 Longevity gain versus health development index, 303 data points, 1900 to 1975

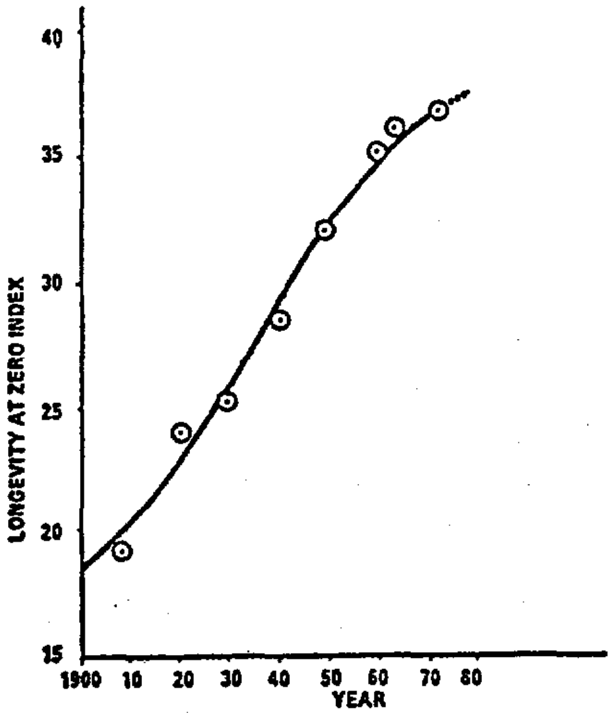



FIGURE 51 Longevity at zero index versus time (years), 303 data points

Rate of Health Development

Several typical countries for which a long-time series of indices were available were plotted against year. The rate of increase in this index appeared to be quite consistent over approximately 50 years for which most of these countries had data. This stability was truly remarkable for certain countries subject to considerable political turmoil and/or devastation during the period. It appeared that there was an inherent momentum to growth of health development once commenced, and that this was quite predictable.

Therefore, a systematic examination of each of the 303 cases ranked by index was undertaken, and the number of years required to progress from each decile to the next was estimated. From that analysis we were able to estimate a regression, the equation for which is

$$\text{Index} = 8.53 + 0.72(\text{years}) \quad . \qquad (4)$$

In this equation, time is measured from the calendar year in which the country reaches an index value of 10. Then the national data were fitted to this slope, with the mean index value placed on the slope and other index points being added at the appropriate number of years prior or subsequent to the mean index value year. Results are shown in Figure 52.

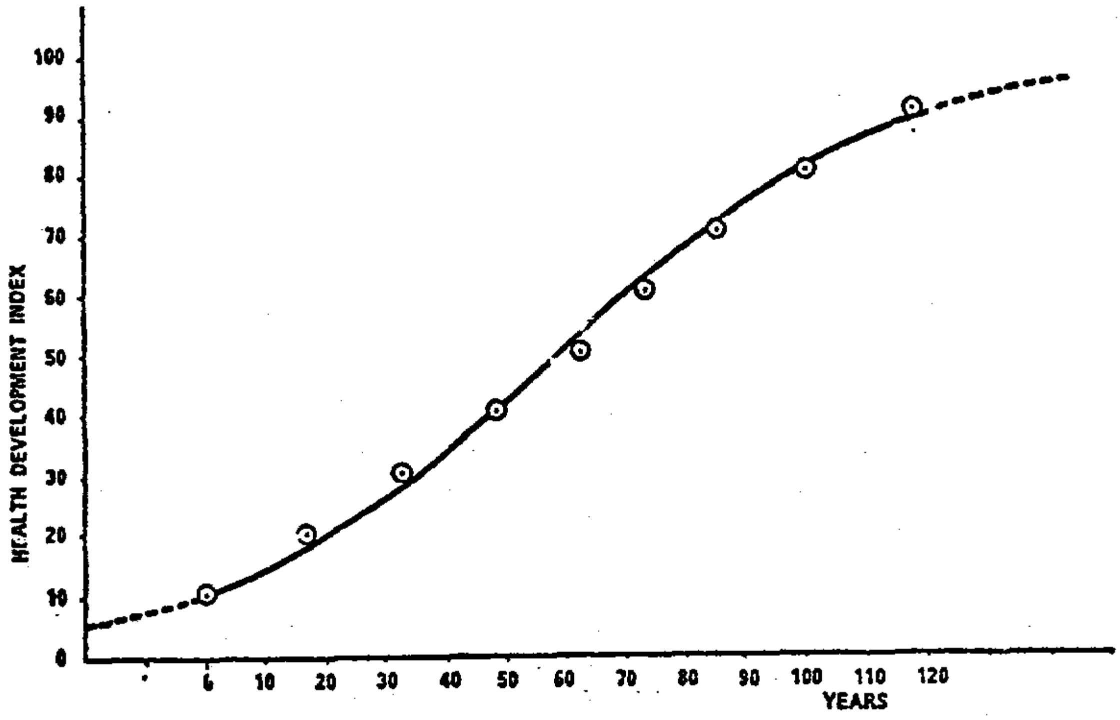



FIGURE 52 Health development index as a function of time

Discussion and Summary

We have found the use of a simple index a useful tool for investigating some demographic variables. Although any simplistic equation purporting to explain much of human health and behavior is to be treated with scepticism, it is believed that the high degree of precision with which this index predicts longevity and infant mortality lends credibility and justifies careful consideration. We are not the first to be impressed with the significance of the relationship between literacy and energy. Rottenberg (1965) has written: "The critical importance of knowledge in the economy can be perceived if all productive inputs are collapsed into two classes: knowledge and energy. Nothing can be said about the relationship of the two classes because each is an aggregate of diverse things; if they were decomposed, some kinds of *knowledge* would be seen to be substitutable for some kinds of energy, and other pairs would be clearly complementary."

We agree with those comments suggesting substitutability of one element for the other, but would add that the two components are not of equal weight. If those two components could be hypothetically isolated, then literacy, in rising from zero to one hundred percent, would add 28 years to longevity whereas energy consumption, in rising from zero to infinity, would add only seven years, a ratio of 4 to 1. The contribution of each of these elements to the health development index varies considerably from country to country. Figure 53 shows a graph of some selected countries to illustrate those variations. Liberia, for example, with a relatively low literacy level of 9%, but a relatively high per capita energy consumption level of 463 kg coal equivalent, achieved an index of 23.9 with a predicted longevity of 45.5 years and actual longevity of 44 years. Seventy percent of this longevity is "due" to energy, in contrast to the mean energy-related share of 20% for all the countries. Sri Lanka, on the other hand, reached a longevity of 68 years, with a high literacy of 76% and a very low per capita energy consumption: the level of 147 kg coal in 1973 was lower than that of India, whose longevity in the same year was 50.

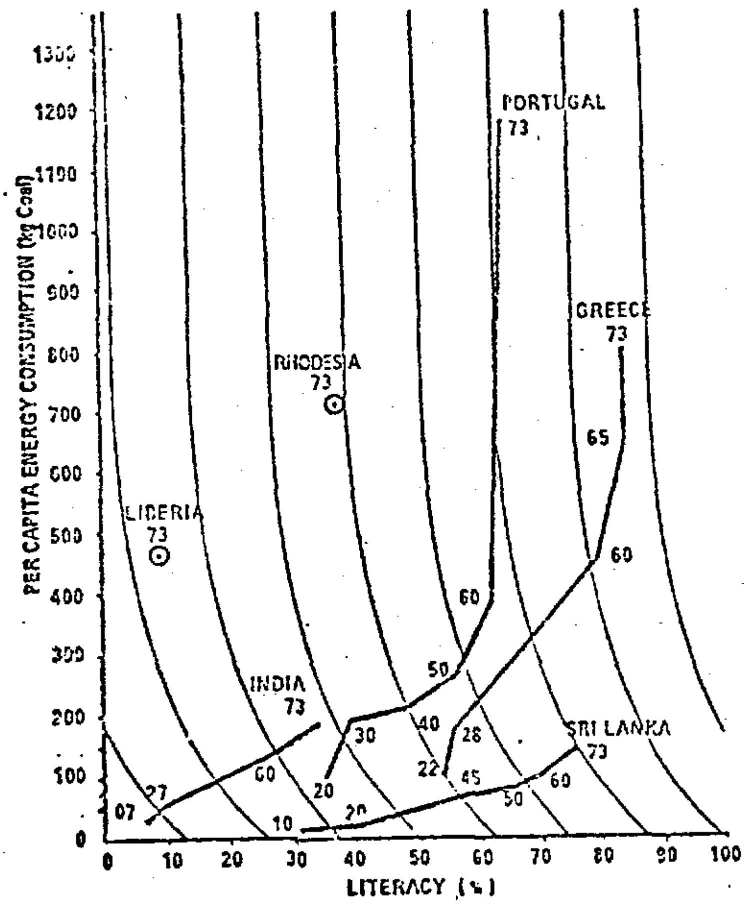



FIGURE 53 Contours of health development index and experience of selected countries

In summary, data have been presented supporting the use of a national health development index which has two components, energy consumption and literacy. Of the two, the latter is four times more powerful than the former. Evidence has been found to indicate that a time effect operates independently of health development. The two factors are additive, the former producing 36 years of added longevity, the latter 18 years over the past 75 years. The index was also shown to be useful in studying infant mortality and fertility.

# 5 STRATEGIES FOR BALANCING ENERGY DEMAND AND SUPPLY

## TOOLS AND AIMS

From the beginning of its work, IIASA's Energy Systems Program has been strongly aware of how important it is not only to describe new systems that may help solve the energy problem but also to identify ways of introducing and deploying these systems that permit a smooth transition from the present supply situation to the requirements of the future.

The first tools we used to study strategic energy options were decision trees. In a straightforward and transparent manner, decision trees illustrate what decisions are necessary for the implementation of a given option. See, for example, Figure 54 for the nuclear option (Häfele and Sassin 1975). It summarizes the steps in implementing a large nuclear system and identifies alternative choices at each decision point. But decision trees, though generally helpful in clarifying and conceptualizing complex relationships, turned out to be inadequate for analyzing a long-term energy strategy in depth and detail. Therefore, a more formalized approach was needed for our work.

Next, we applied the linear programming approach, which we found to be well suited for studying energy strategies. This was due not so much to its capacity for identifying optimal solutions as to the possibility of including constraining factors in the consideration.

The first LP model we developed and operated was the so-called Häfele-Manne model (Häfele and Manne 1974). It was conceived in order to study cost optimal transitions from fossil to nuclear fuels for meeting an exogenously given energy demand. The main constraints considered were the scarcity of oil and gas resources as well as the limits on related investments. The resulting strategy showed what capacities of what technologies were required at what time. The model was extended and improved by Voss, Agnew and Schrattenholzer (Agnew,Schratten-

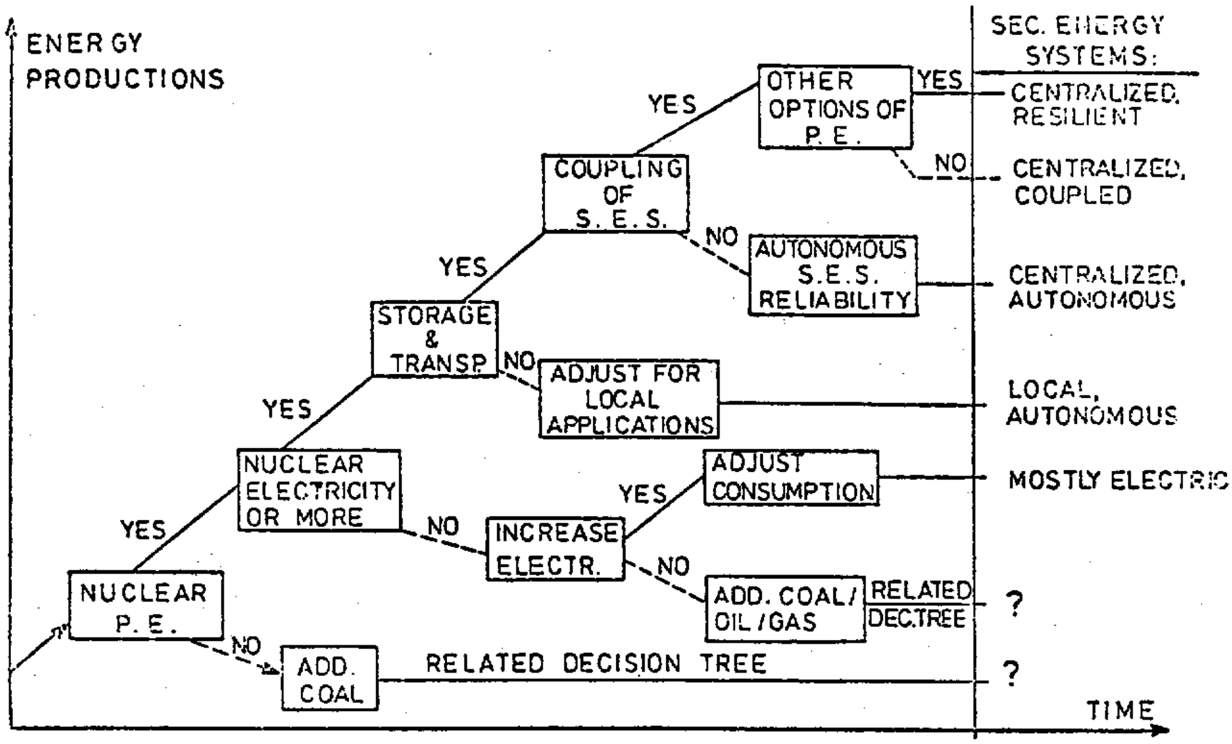



FIGURE 54 A decision tree for advanced energy systems.

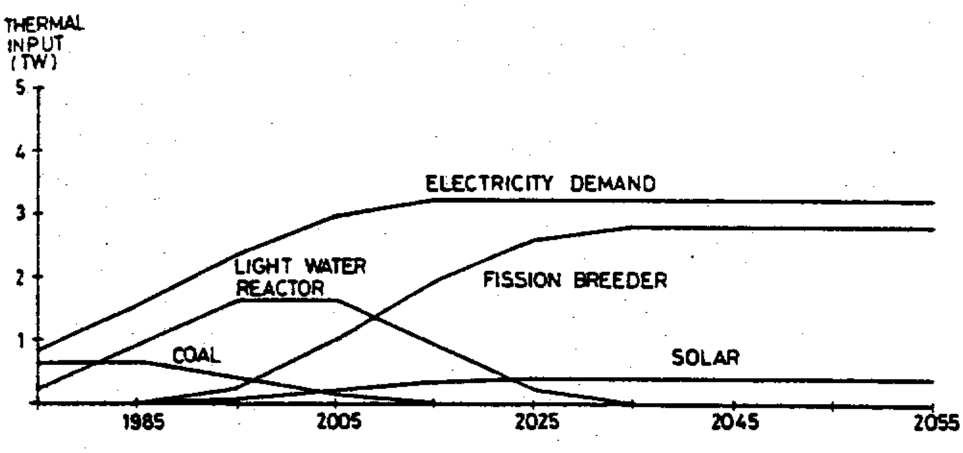



FIGURE 55 An example of optimal allocation of primary energy sources for meeting electricity demands.

holzer and Voss 1979) to include solar and other sources if so desirable. A typical result generated by the model is given in Figure 55.

In November 1975 Academician M. Styrikovich of the Soviet Academy of Sciences suggested that the Energy Systems Program should develop a set of computer models to capture the complexities of energy strategies and the high interdependence of world regions.

Conceptualization of this project began in 1976 when a scheme was devised for developing and describing what models would be required and how they could be interlinked. As is illustrated in Figure 56, three time phases: the present (until 1985), the transition (1985-2030), and the long-term future (after 2030); were identified and three strata: the world, the regions, and technology; were defined. Long-term lifestyle scenarios and conceivable evolutions of energy demand patterns served as modeling targets. Representation of the economies in transition on a regional level translates the targets into concrete data on energy needs, which in turn serve as inputs to a model exploring technological strategies. This model feeds into another model identifying detailed investment requirements on the regional stratum. On the global level, separate consideration of international energy trade patterns establishes the consistency in the allocation of supply technologies in the various regions.

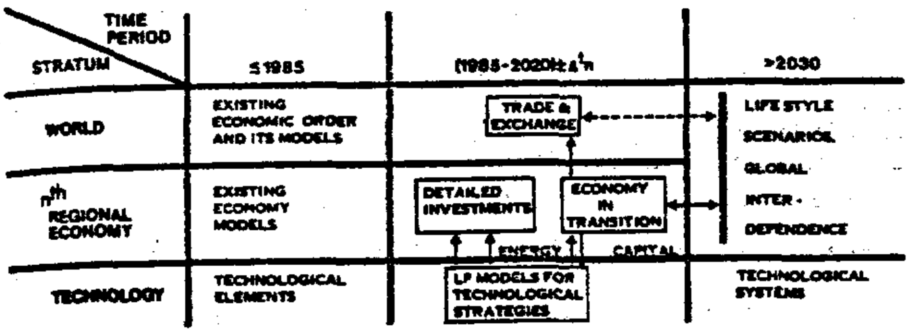



FIGURE 56 Interlinking models for energy strategies

From this scheme a methodological approach evolved that is described in Figure 57 and which was first mentioned in the Introduction. The upper part of the scheme describes the development of the economy and the evolution of energy demand; these were explained in some detail in the Energy Demand chapter. The lower section, in particular, the supply model MESSAGE and the economic impact model IMPACT, is considered in the following.

MESSAGE and IMPACT were our key instruments for identifying supply strategies and for assessing their impacts.

## The MESSAGE Model

As mentioned, MESSAGE (Model for Energy Supply Systems Alternatives and Their General Environmental Impact) is a dynamic

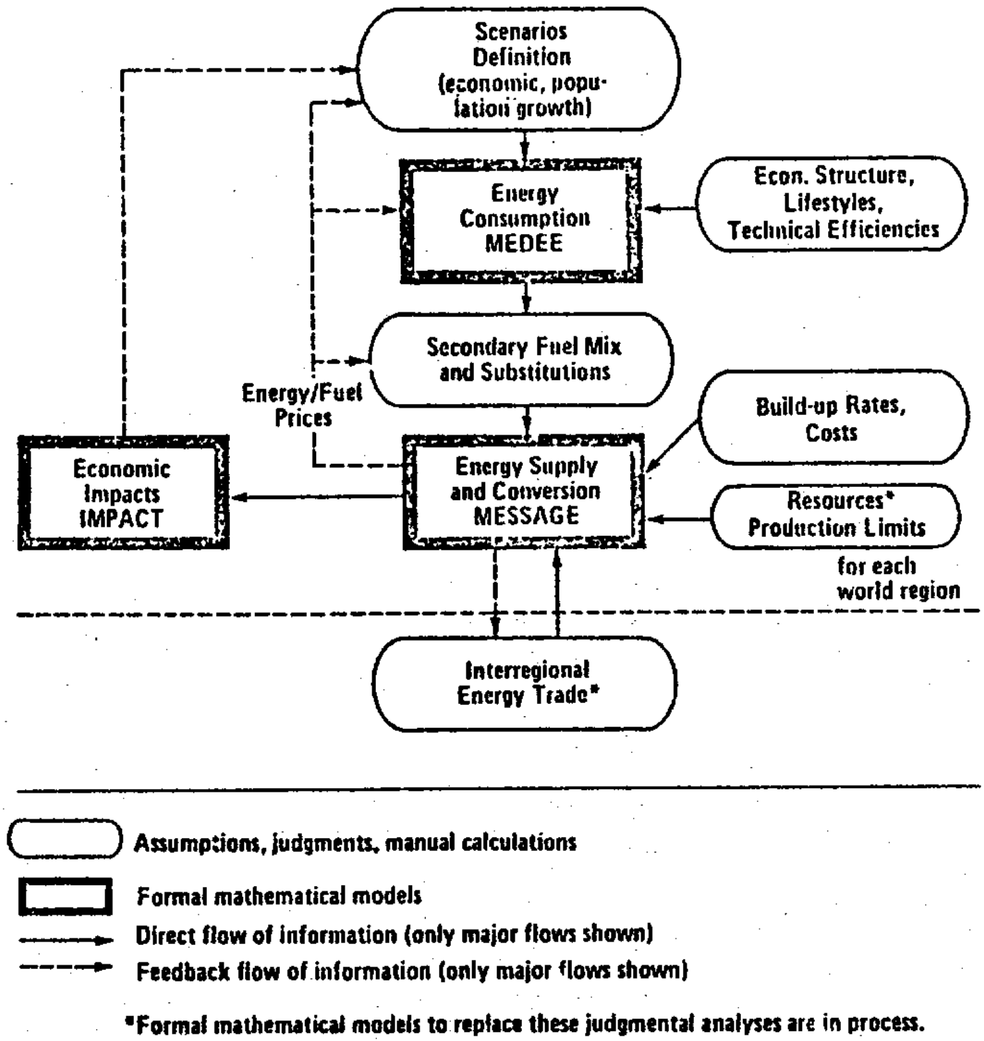



FIGURE 57 IIASA's set of energy models: a simplified representation.

linear programming model conceived at IIASA by Voss, Agnew, and Schrattenholzer. It has evolved on the basis provided by the Häfele-Manne linear programming model.

MESSAGE functions as the central balancing element in IIASA's set of energy models by allocating energy resources and technologies in order to satisfy a given energy demand. It optimizes costs of energy supply and conversion over a 50 year time horizon. The impacts these technologies may have on the environment are monitored by the model. By changing the assumptions, several alternative supply cases--and alternative supply futures for that matter--can be explored in order to identify possible transitions towards new energy systems based on technologies that are less constrained by resource availability. The major constraints the model considers are primary energy resource availability, conversion technology characteristics, technological introduction rates, and environmental impacts.

## The Objective Function of MESSAGE

The objective function of the MESSAGE model is the sum of discounted costs of capital, operating/maintenance, and fuels (primary energy):

$$\sum_{t=1}^{n} \beta(t)\ 5\{b^T r(t) + c^T x(t) + d^T y(t)\}$$

where t = current index of time period

n = number of time periods

β(t) = discount factor

5 = number of years per period

b = vector of energy resources costs

r = vector of resource activities (LP variables)

c = vector of operating/maintenance costs

x = vector of energy conversion activities (LP variables)

d = vector of capital (investment) costs

y = vector of capacity increments (LP variables)

The discount factor is calculated from an annual discount rate of 6%, applied to a constant dollar investment stream. As MESSAGE is intended to minimize societal costs this discount rate is to be understood as a pre-tax one[1].

The cost of increments to capacity still operating at the end of the planning horizon is corrected by a "terminal valuation factor", tv:

$$tv^t = (1 - \beta^{5(n+1-t)})$$

e.g. the terminal valuation factor for the last period is

$$t_v^n = 1 - \beta^5.$$

1 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 it, the discount factor here may be thought of as a "social" discount factor, applied equally to all regions of the world.

The model covers

- primary energy resource consumption and transport,
- central station conversion
- decentralized conversion energy; and
- the environmental impacts of each of the above activities, i.e., discharge of residuals. The fundamental features of the model are summed up in Figure 58.

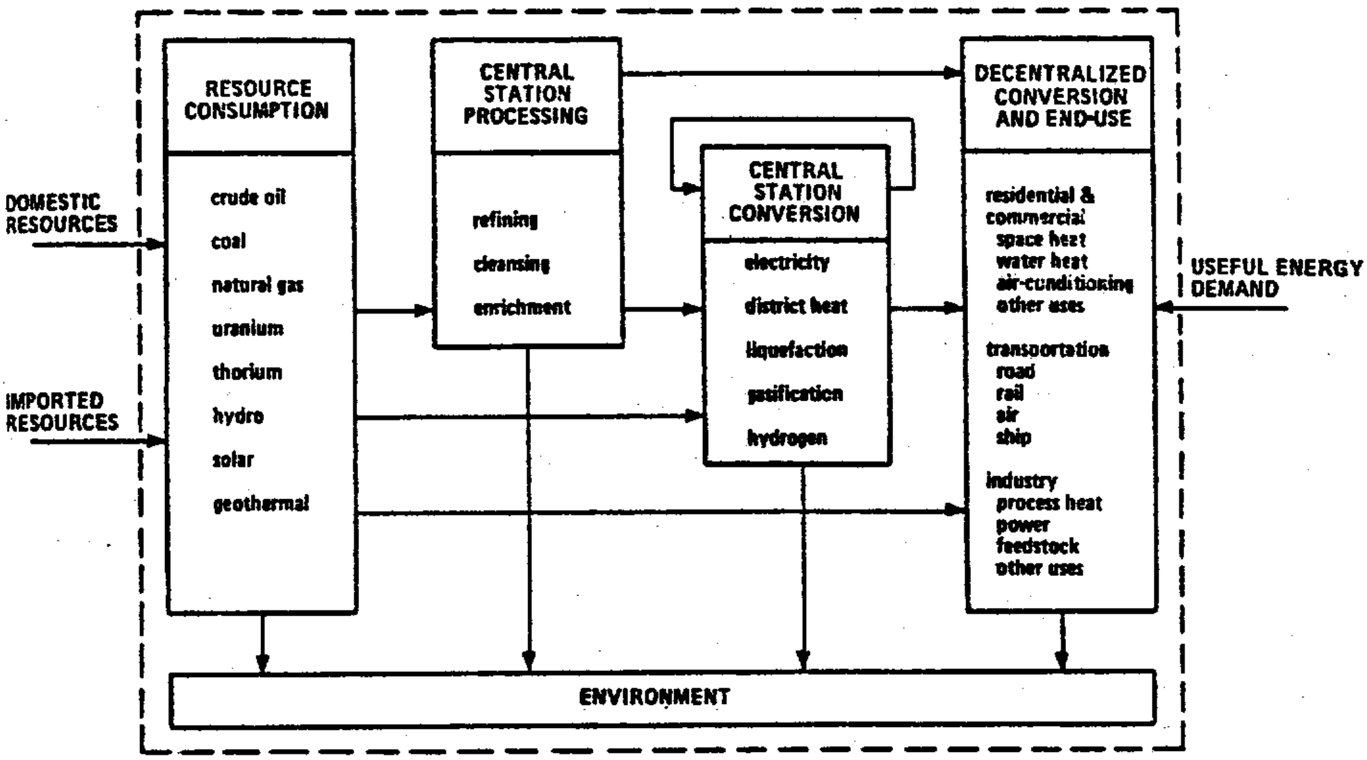



FIGURE 58 The components of the energy supply system modelled by MESSAGE.

In a first step primary energy sources (except solar and hydropower) are subdivided into an optional number of classes according to the cost of extraction, purity of resource, and location of deposit. The central station processing and conversion section describes the various processes transforming these resources into secondary energy carriers which meet an exogenously given secondary energy demand; the latter is provided by MEDEE as time series data per type of energy carrier (electricity, solar, solids, liquids, gas,and district heat). Figure 59 illustrates the primary energy flows through the conversion and processing stages. The model deals with the various technological steps in a way that permits consideration of a multitude of possible pathways from a given primary energy source to the various secondary energy carriers.

Transportation, distribution, and end-use of energy are considered in a separate module, where impacts are minimized and savings are maximized by choosing the most efficient and least costly path to the consumer. Each end-use sector can

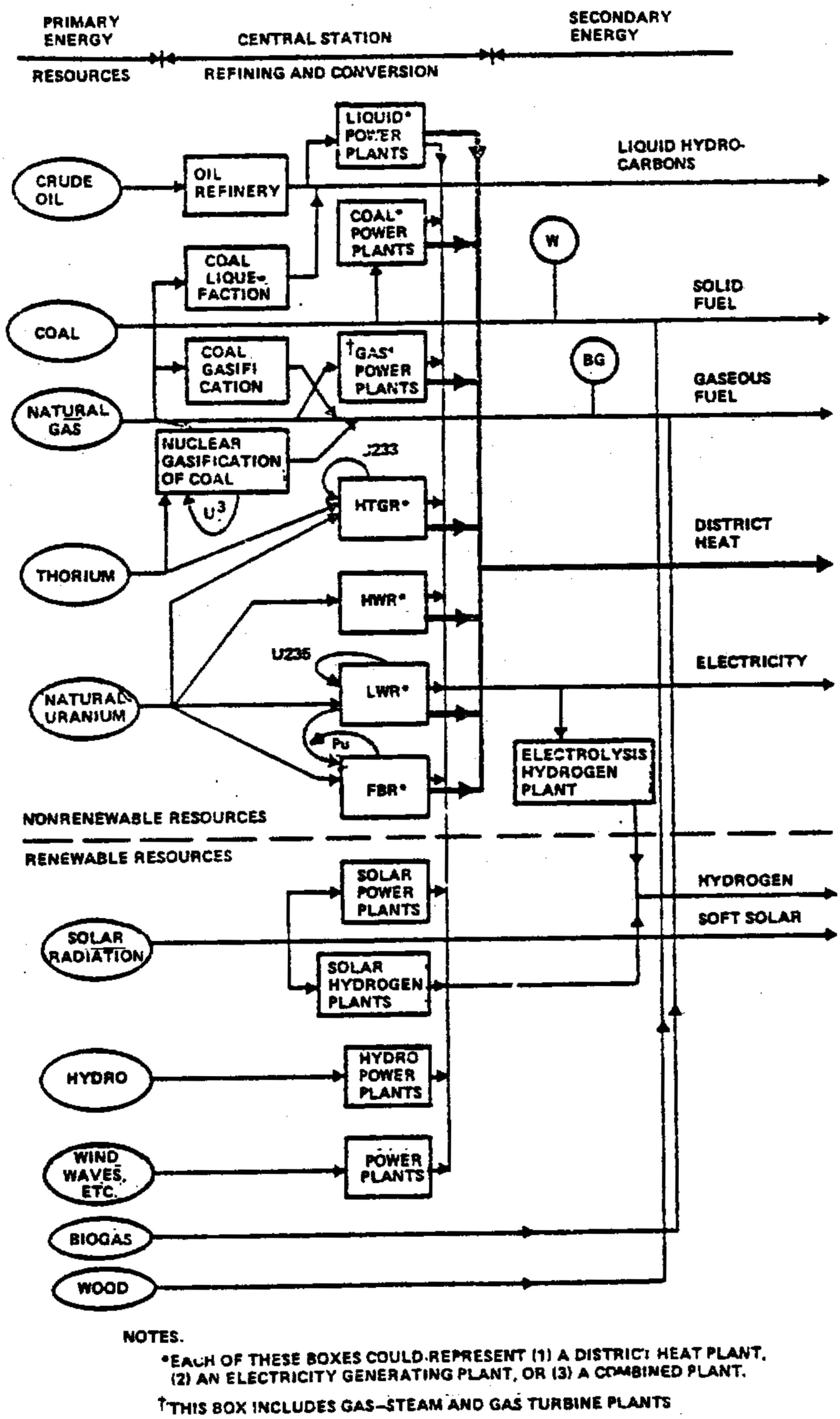



FIGURE 59 Structure of the central station conversion technology module.

in turn be supplied with energy by way of various end-use technologies. Given certain assumptions on the distribution and transportation costs as well as on the availability of end-use technologies the shares of a certain end-use technology can be determined. Via the secondary energy requirements for these technologies a link is established between this module and the central processing and conversion section of the model.

A final environmental module facilitates assessment of the impacts of a strategy on the environment. Several pragmatic simplifications were required to make this module more easily manageable. Discharges are grouped by severity and type of impact on the environment in Table 49. Emissions of classes A and B are converted to average ambient groundlevel concentrations in two ways: local effects are accounted for by a simple dispersion model, and global effects by dilution factors. A model of population distribution relates local concentrations to the local population if applicable. Global concentrations of class B are assumed to affect the world's population as a whole. By varying the standards of environmental burden one can investigate the influence these standards may have on the energy supply strategy. $CO_2$ and residual discharges (class E) are treated differently. Only the total amounts are calculated to reflect the aggregated impact on a region.

Constraints affect strategies in two ways, namely by the choice of a given technology or by the introduction of abatement measures.

TABLE 49 Classification of Impacts

| | |
|---|---|
| Class A: | Atmospheric emissions with local impact including short-lived radioisotopes.<br>- Sulphur oxides<br>- Nitrogen oxides<br>- Particulates<br>- CO<br>- Xe133 |
| Class B: | Emissions of relatively long-lived radioisotopes to the atmosphere and water with global impacts.<br>- Tritium<br>- Krypton |
| Class C: | Emissions of $CO_2$. |
| Class D: | Occupational accidents. |
| Class E: | All other residual discharges like water, thermal pollution, land requirements, solid wastes, etc. |

## Balancing Oil Imports and Exports

Some of the input values and constraints used in the MESSAGE code depend on international oil trade dynamics. These include among other things prices of oil and coal imports, costs of domestic production, and the maximum amounts of oil available for imports. The procedure developed permits us to assess three dynamic elements of the world oil market: regional domestic oil production, interregional oil trade, and oil prices. This procedure is schematized in Figure 60. It was a first attempt to incorporate into the models the problem of world trade. More sophisticated approaches, such as a gaming model, are under development.

For this procedure, Regions II and VII are assumed to be self-sufficient and Regions I, III, IV and V act as potential importers. Region VI which dominates the market, exhibiting a cartel-like behavior, maximizes its revenues and thus acts as the main driving force. Oil exporters other than those in Region VI follow the price levels set by this region.

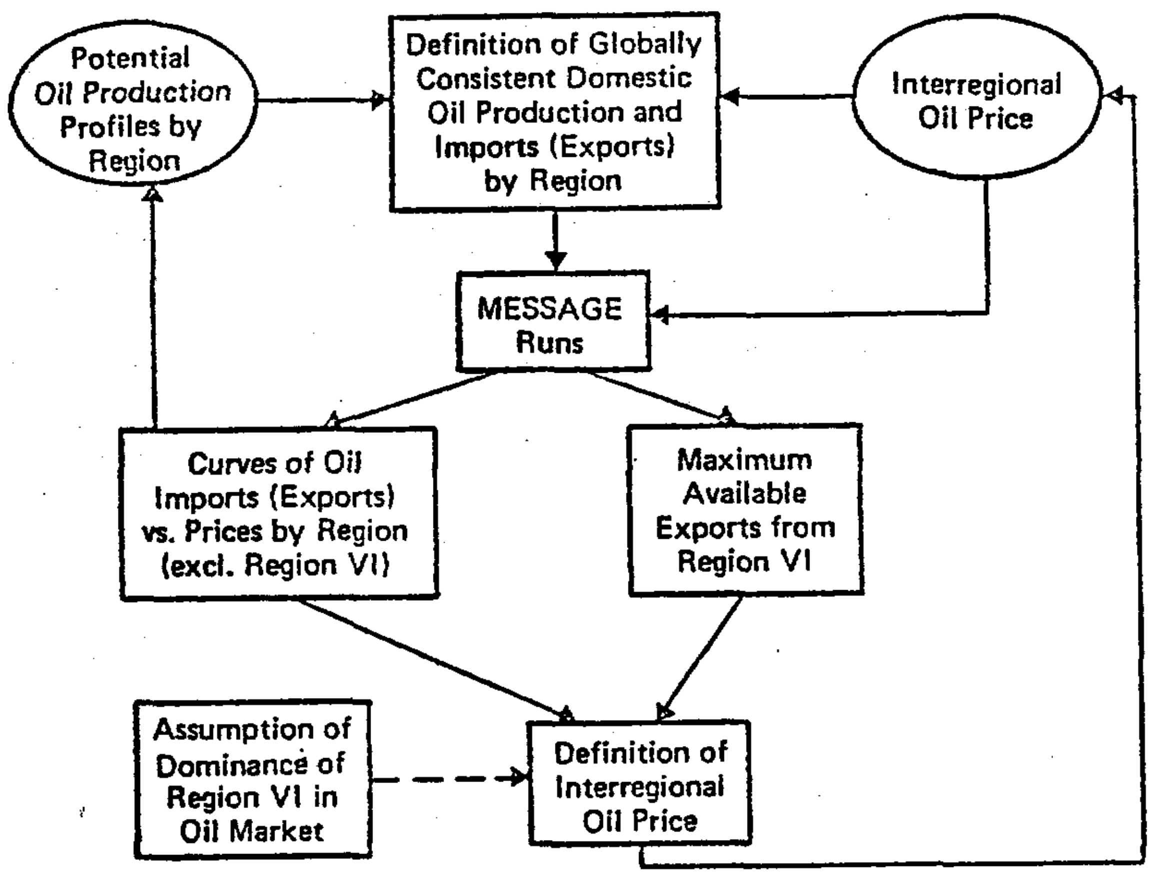



FIGURE 60 Interregional oil balancing methodology.

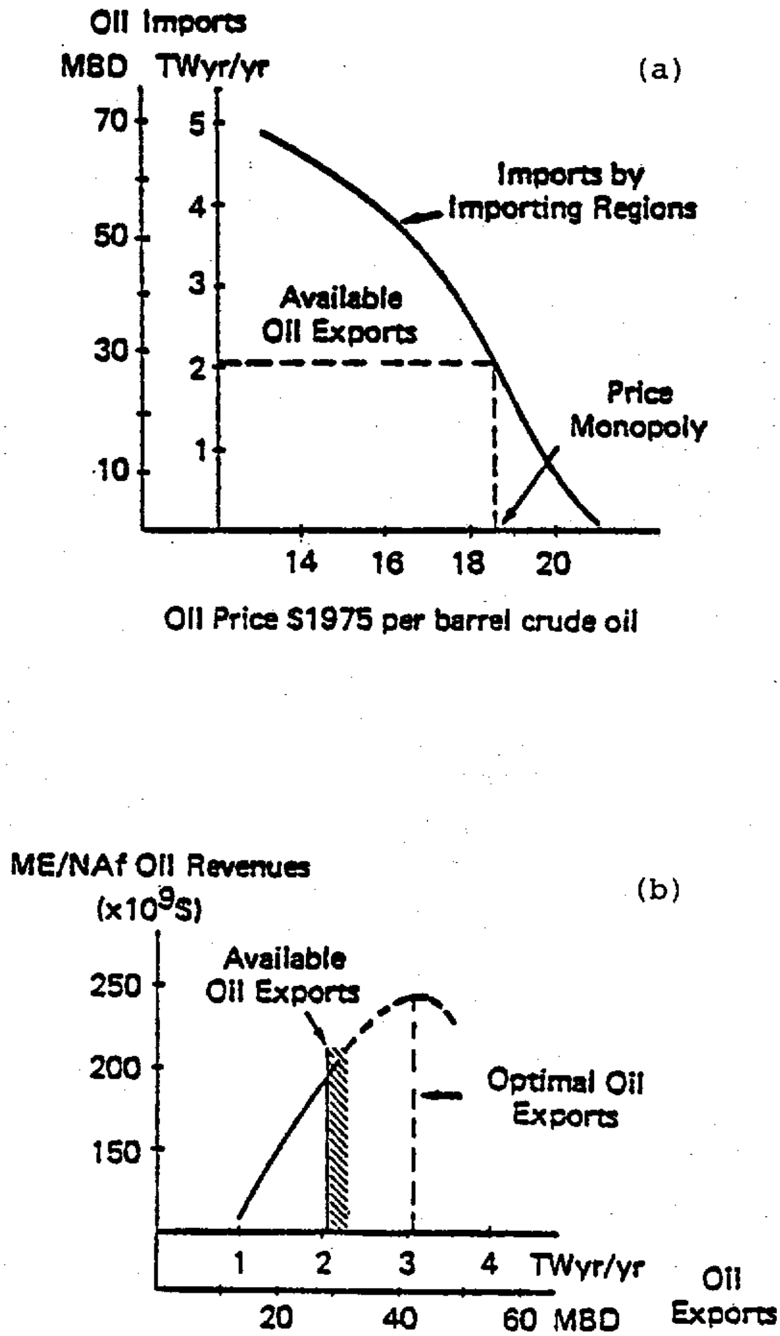



FIGURE 61 Oil imports (a) and exports (b) vs. price, Low scenario, 2015.

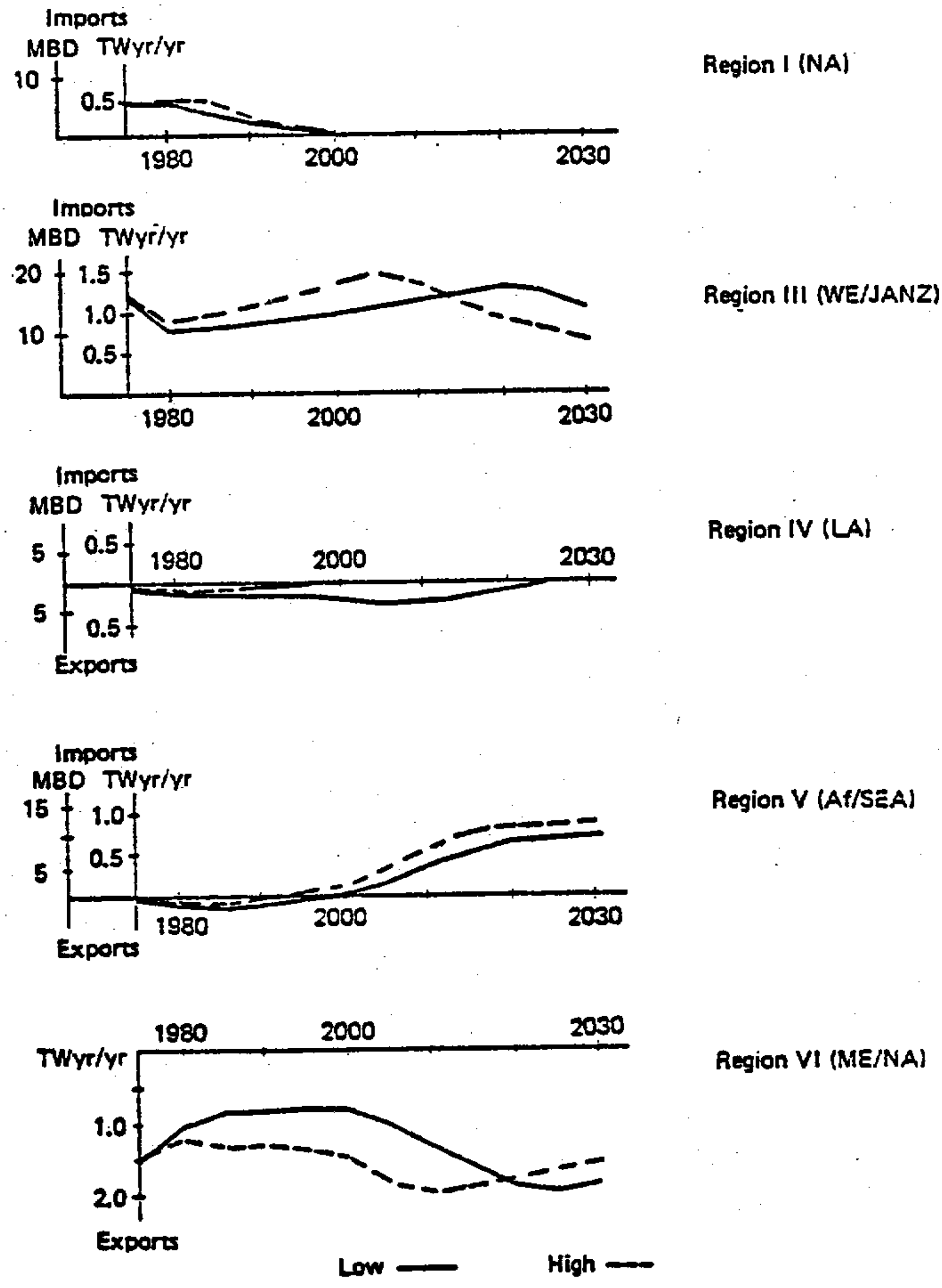



FIGURE 62 Interregional oil trade, 1975-2030, High and Low scenarios, primary equivalent.

Under such conditions, the way in which importing regions respond to oil price increases depends on their domestic oil supply elasticities. These elasticities are generated on the basis of the oil production profiles given in Figures 20 to 21, incorporating different estimates of various types of oil resources available at varying prices. The price dependent profiles of potential regional oil production that are obtained in this way are a first major input to the procedure. Other inputs are the dynamic demand for liquids and the cost of synthetic liquids produced from coal.

The next step in the oil balancing methodology is to compare, region by region, domestic oil supplies available at varying prices and liquid demands. The curves obtained describing regional economic oil imports vs. prices can be generalized for the entire group of importing regions (e.g. Figure 61a). The import and price levels selected accordingly provide exporters with maximum profits within the preset export limits (Figure 61b).

To obtain satisfactory results, several iterations must be run. For instance, oil prices influence the amount of synthetic liquid production from coal that can be considered economical, affecting in turn the availability of coal for other purposes. These feedbacks are handled with the help of the energy supply model MESSAGE, and permit us to test the consistency of the results of the balancing procedure with an acceptable general development of the energy supply systems.

The horizon of this procedure is long term. While the method does not serve to explain short-term prospects of the oil market--which would presuppose a much more disaggregated and detailed consideration of national policies--it enables us to better understand the forces governing the oil market over the study period.

Under the conditions set forth in our scenarios, prices are projected to increase in real terms by 4%-5.5% per year, reaching US$(1975) 19-21 per barrel in 1990 and remaining constant thereafter until 2030. Figure 62 illustrates the corresponding world oil trade dynamics. The demand for oil imports from Region VI declines over the next 10 to 15 years as a result of the price jump in the 1970s. After the turn of the century, domestic resources of importing regions become increasingly expensive, and overall the volume of oil exports increases.

In our scenarios, this is the time when North America would become self-sufficient, relying on its own relatively large resources of cheap oil and very large resources of cheap coal. Self-sufficiency also is expected for Region IV, Latin America, which could make use of its remarkable unconventional resources. Regions III and V will be left to import oil from Region VI.

## The IMPACT Model

The IMPACT model, if applied to a given strategy for developing an energy supply system,evaluates the direct and indirect requirements in terms of investment, material, equipment, and

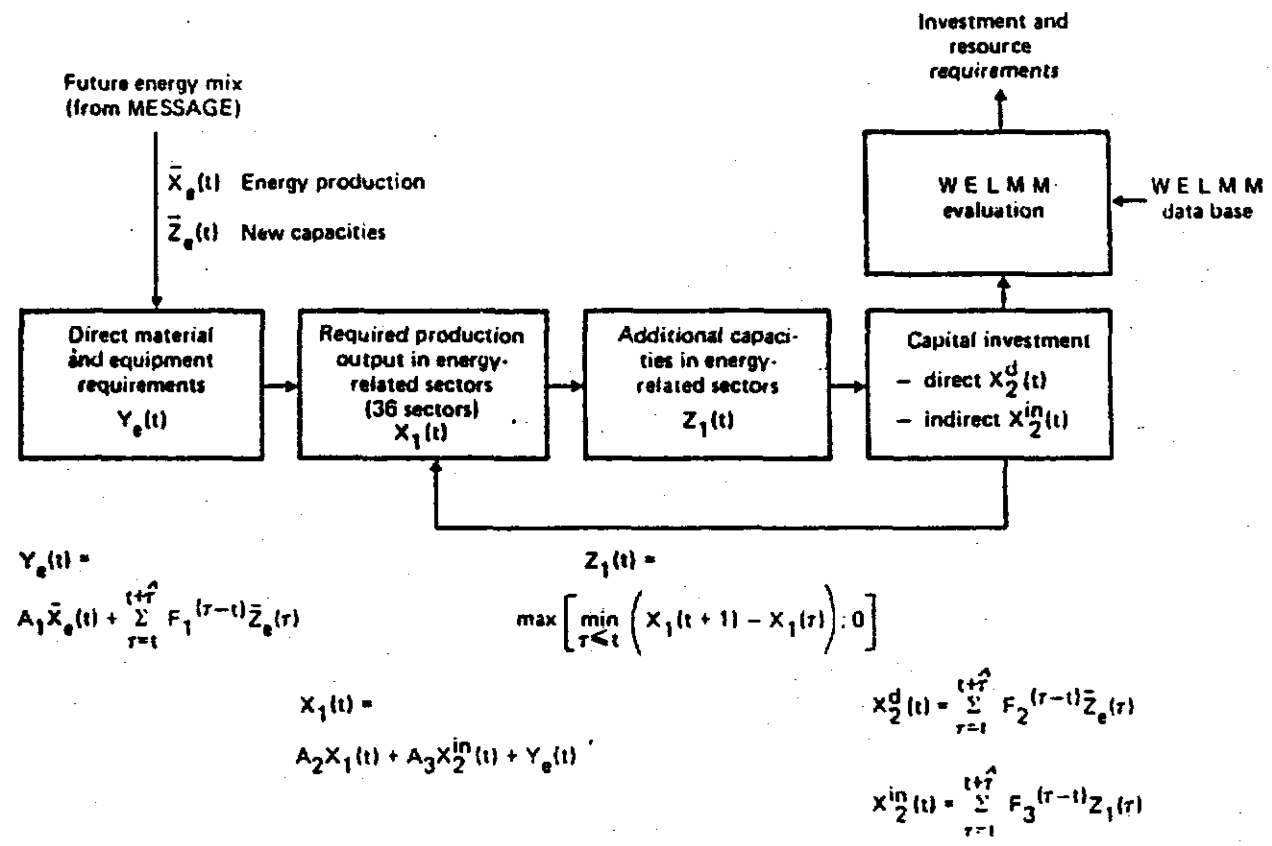



FIGURE 63 Schematic description of IMPACT.

TABLE 50 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 Chapter 3, Tables 30, 32, and 35. 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.

manpower, to be provided by the major sectors of the economy. Direct refers to energy system investments and WELMM* needs. Indirect requirements encompass resources and investment requirements of nonenergy sectors, the additional development of which is induced by the development of the energy supply system.

The first version of IMPACT was conceived by Kononov and Tkachenko at the Siberian Power Institute, Irkutsk, USSR. At IIASA, Kononov (Kononov and Por 1979) has adapted the model to meet the requirements of the long-term study period (50 years) of our energy systems investigation.

IMPACT is an energy-oriented dynamic input-output model. It accounts for lags between the inception of investment activities and the putting into operation of production capacities. For each year of the period considered the model identifies:

- the necessary level of production of certain products and services;
- the resulting requirements for operating and building up the energy supply system and its related branches of the economy;
- the conditions for introducing extra capacities in the energy-related branches;
- the respective *investment and WELMM requirements*.

The modeling process is outlined in Figure 63.

The main difficulty in operating the model arose from its high data intensity. We are much indebted to Bechtel Corporation (1978, and Gallagher et al. 1978), whose data sources were particularly useful. In addition, several other data sets were analyzed and used. Tables 50 to 53 summarize the data so deduced, giving cost structures of resource extraction, power plants, and energy conversion facilities. Whereas costs of extraction vary greatly under local conditions, the variation in the specific investment indices (and their structure) of power plants is not so significant. Therefore, the plant indices in all the regions were assumed to be similar to prospective US data.

Given a lack of information particularly for the developing countries, it was not possible to compute average regional indices for the input-output and capital coefficients of the nonenergy sectors of this level of aggregation. "Typical" countries had to be chosen instead, such as India for Region V, or the FRG for Region III. For each representative country, the coefficients were aggregated and then generalized for the entire region.

## MARKET PENETRATION AND BUILDUP RATES

Mansfield (1961), pioneer of the analysis of technological substitution, developed a model to explain rates at which an innovation is introduced by a number of firms in a market.

*WELMM stands for Water, Energy, Land, Materials, Manpower requirements.

TABLE 51 Composition of Costs of Energy Production and Conversion Facilities as Used in the IMPACT Model (%)

| | Oil | | Gas | | Coal | |
|---|---|---|---|---|---|---|
| | On-shore | Off-shore | On-shore | Off-shore | Under-ground | Sur-face |
| 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 U.S. 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, etc.

TABLE 52 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 | 1,900 | 28-60 | 297 |
| Synthetic Fuels | | | |
| Crude oil refinery | 50 | 3.7 | 75 |
| Coal gasification ("high Btu") | 480 | 40 | 125 |
| Coal liquefaction | 480 | 40 | 125 |

District Heat Technologies
Combined Heat and Power (Region II - SU/EE)

| Type | Elec./Heat Ratio | Capital Cost (1975$/$kW_{SE}$[a]) | Variable Cost (1975$/$kWyr_{SE}$[a]) | Final Product Cost (1975$/$kWyr_{SE}$[a]) | LF[b] |
|---|---|---|---|---|---|
| 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 50-year planning horizon.
*Capital cost:* Capital costs per kW of capacity. Assumed to represent average capital costs (paid at once) for standard facilities of 30-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 (30 years, hydro 50 years) and on the load factor (70% hydro and 57% solar) enter the calculations, as does the discount rate (6%). For a time interval of 5 years and a plant life of 30 years, the formula for the annualized capital cost is

$$\text{cap} \cdot \frac{\beta^5 - 1}{(\beta^{30} - 1)\ \beta^{2.5}\ 5} \qquad (1)$$

where $\beta$ is the one-year discount factor ($\frac{1}{1.06}$ here) and cap is the total capital cost. In order to get the levellized capital costs per kWyr of output, (1) must be divided by the load factor. For example, a LF of 0.7 yields a levellizing 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%. 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.

TABLE 53 Expected Production and Investment Costs for Sources of Liquid and Gaseous Fuels (1975 U.S.$)

| 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 off-shore 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 40 to 50 years ahead is meaningless. Still, this does not diminish the utility of models as tools for exposing new trends and problems in energy futures.

His basic hypothesis was that the adoption of a new technology is positively related to the profit it may create and negatively related to the investment this requires.

Fisher and Pry (1970) considered the fractional shares of two competing technologies in a market. They postulated that the rate at which a new technology penetrates the market is proportional to

- the fraction of the market already conquered, and
- the fraction of the market still held by the old technology.

The resulting path of substitution takes on the S shape of a logistic function.

At IIASA, Marchetti and Nakicenovic (1979) extended the Fisher-Pry approach to include more than two competitors. In so doing they introduced the constraint that all the market shares must add up to 1, assuming the oldest technology that is still growing to supply the market residual.

This model has undergone extensive empirical testing by the authors. Sixty data bases in the field of energy alone were used to examine over 300 examples of primary energy consumption and energy use by various subsystems in 30-odd countries or regions. In almost all the cases, the quality of prediction of the historical substitution process was consistently very good.

Figure 64 compares the historical data (straight lines) with the model calculations (smooth lines) with the estimation of the model coefficients relying on an analysis of the period 1900-1920. Significant deviations from the trend lines appear to be scarce, and the actual development quickly returns to the long-term trend.

Two interesting observations can be made. First, that the slopes of practically all the technologies represented by logistic market contributions are almost identical. This indicates that it would take a new technology in the world primary energy market some 100 years to increase its market share from 1% to 50%. Second, that some time is needed for a new technology to stabilize and adjust to the long-term trend. For example, oil penetrated the market faster than other technologies until it reached 2%, whereas gas remained almost constant at 1% for a decade. Table 54 summarizes the characteristics of several energy markets in terms of buildup and penetration rates.

TABLE 54 New Technology Buildup Rates

| | Technology | Penetration[a] Rate (%/yr) | Build-Up[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 ln (F(t)/1-F(t)).

[b] Buildup rate is the exponential growth rate of the new technology in absolute terms as it grows from 1 to 10% of the market it serves.

Peterka and Fleck (1978) complemented the phenomenological approach pursued by Marchetti and Nakicenovic by undertaking a theoretical study of market penetration. Peterka, who treats economic conditions as the engine driving the substitution process, assumes a simplified investment policy and compares the costs with the expected profits. Prices are eliminated by the introduction of fractional shares of total production levels, and only cost or price ratios are used. In general, Peterka's theoretical approach of multiple substitution processes fits the phenomenological projections well--even if the assumption that specific investments for all energy sources are equal is allowed to be relaxed slightly.

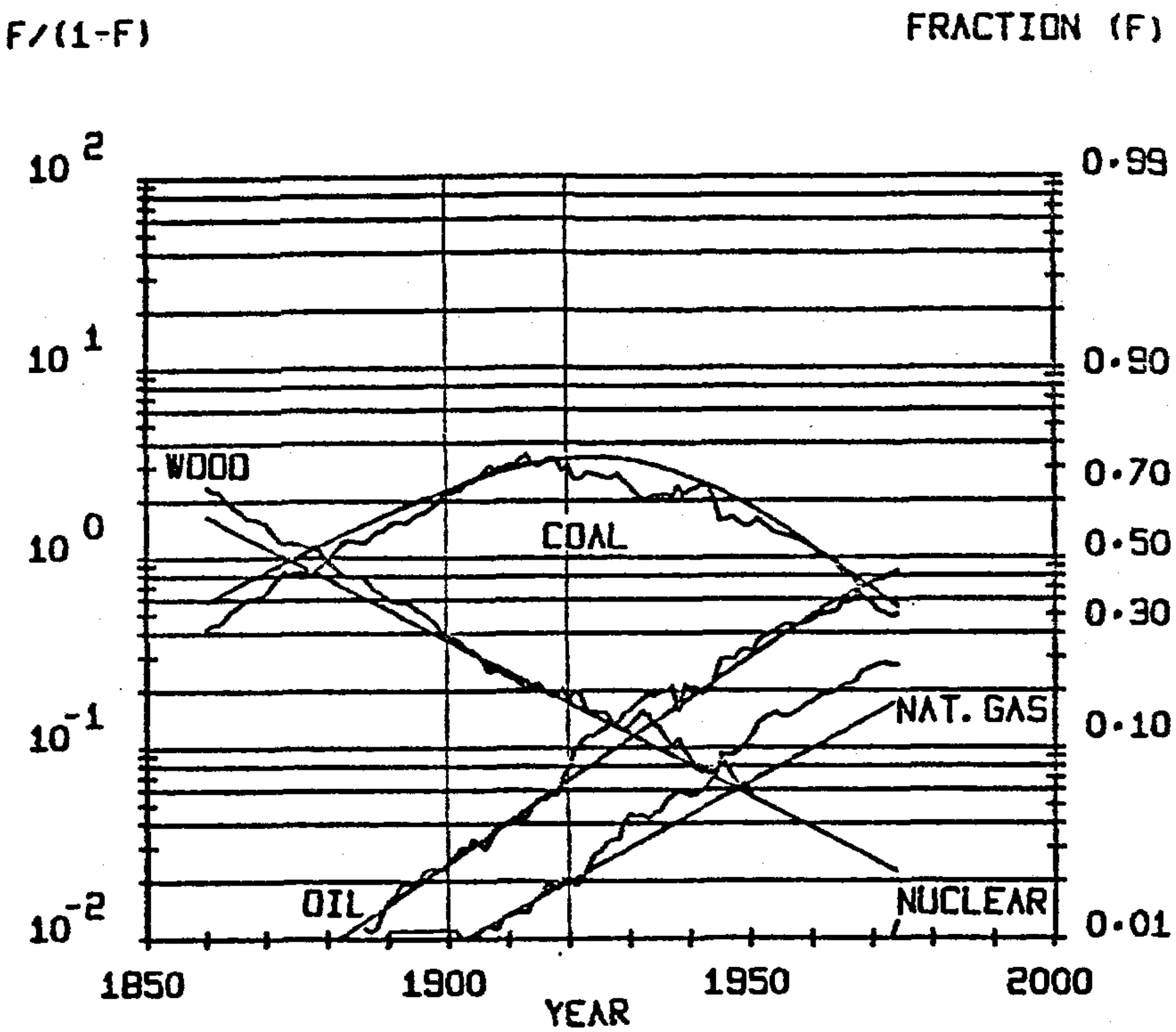



FIGURE 64 Global primary energy substitution, short data base. Logarithmic plot of the transformation F/(1-F where F is the fractional market share. Smooth lines are "backward and forward" extrapolations of energy use from 20-year historical data segment although data for entire historical period are plotted; straight lines show the logistic model substitution paths.

Fleck's model in contrast follows a microscopic approach. Several assumptions are made for an innovation that is adopted by a single individual. His decision to accept an innovation once it has proved successful depends on his imitation behavior.

TABLE 55 Startup and Buildup Constraint Assumptions for New Energy Technologies

| | Increment, As % of Previous Period's Expansion | Start-up 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 | 2000 |
| Coal gasification | 140 | 2 | 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) build-up constraint is also imposed

[c] The year 2000 for Region I; 1995 for Regions II and III.

[d] Regions IV (LA), V (Af/SEA), VI (ME/NA) and VII (C/CPA).

NOTE: The numbers in Table 55 are transformed into constraints for the MESSAGE model as follows: The asymptotic increment and start-up parameters refer to $\gamma$ and $g$, respectively, in

$$y^t \leq \gamma y^{t-1} + g \qquad (1)$$

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 in 5[yrs] × 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 build-up 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, etc., making up the start of an S-shaped curve toward the asymptotic value above.

The model postulates that the rate of imitation of all individuals together is proportional to the market share achieved: the higher the level of adoption, the larger is the flow of information and, consequently, the incentive to adopt the new technology. The non-stationary, absorbing Markovian chain is applied to describe the substitution process of two competitors, where the transition probabilities can be interpreted as the rate of imitation.

This body of phenomenological and theoretical work clearly indicates that the rate of introduction of a new energy technology cannot exceed certain limits. In order to capture this constraint for our modeling effort, relative maximum buildup rates were defined, with the annual buildup rate in one five-year period being smaller by a given percentage than the buildup rate of the previous period (Table 55). The initial startup condition was made a parameter. Furthermore, care was taken to reflect characteristics of the developing economies, such as lower productivity, lack of infrastructure, etc.; and somewhat more divergent constraints were assumed for these regions.

## ENERGY SUPPLY AND DEMAND BALANCES

### The Global Energy Supply in 2030

In Chapter 2 we identified two distinct demand scenarios which we labeled "High" and "Low." In the subsequent chapter we examined the potential of several different resources and technologies to contribute to meeting energy demand. In the present chapter we have introduced the MESSAGE model and the constraints within which this model seeks to balance demand and supply. The next step in the analysis, then, was to apply the MESSAGE model iteratively to arrive at a balancing of supply and demand for each scenario. The final results aggregated for the world, are summarized in Figure 65 and in Table 56.*

The use of *hydrocarbons* is not over. Their share in primary energy supply declines in both scenarios, but they still provide very large amounts of energy (2.5 times the 1975 value in the High scenario), with a large fraction derived from unconventional sources. Thus, in spite of the assumed shifting of liquids to essential uses (Chapter 2), oil supply will remain the crucial problem in the decades to come.

*Coal* use will grow quickly in importance after the turn of the century. Increasingly through conversion into synthetic liquids, it will capture part of the market share held by hydrocarbons.

*Nuclear energy*, though expanding rapidly to a level where it would fill all new nonpeak load electricity demand in the developed regions, nonetheless remains significantly beneath its potential.

*Renewable energy sources and solar*, by 2030, contribute a noticeable, nonnegligible share in the primary energy supply. But even if a significant portion of their potential were realized (suppose one third of the realisable potential in the High scenario) they do not represent a dominant factor in the supply system.

*The results presented here were derived by implementing MESSAGE in a somewhat simpler form than what was described earlier as the conceptual framework of the model.

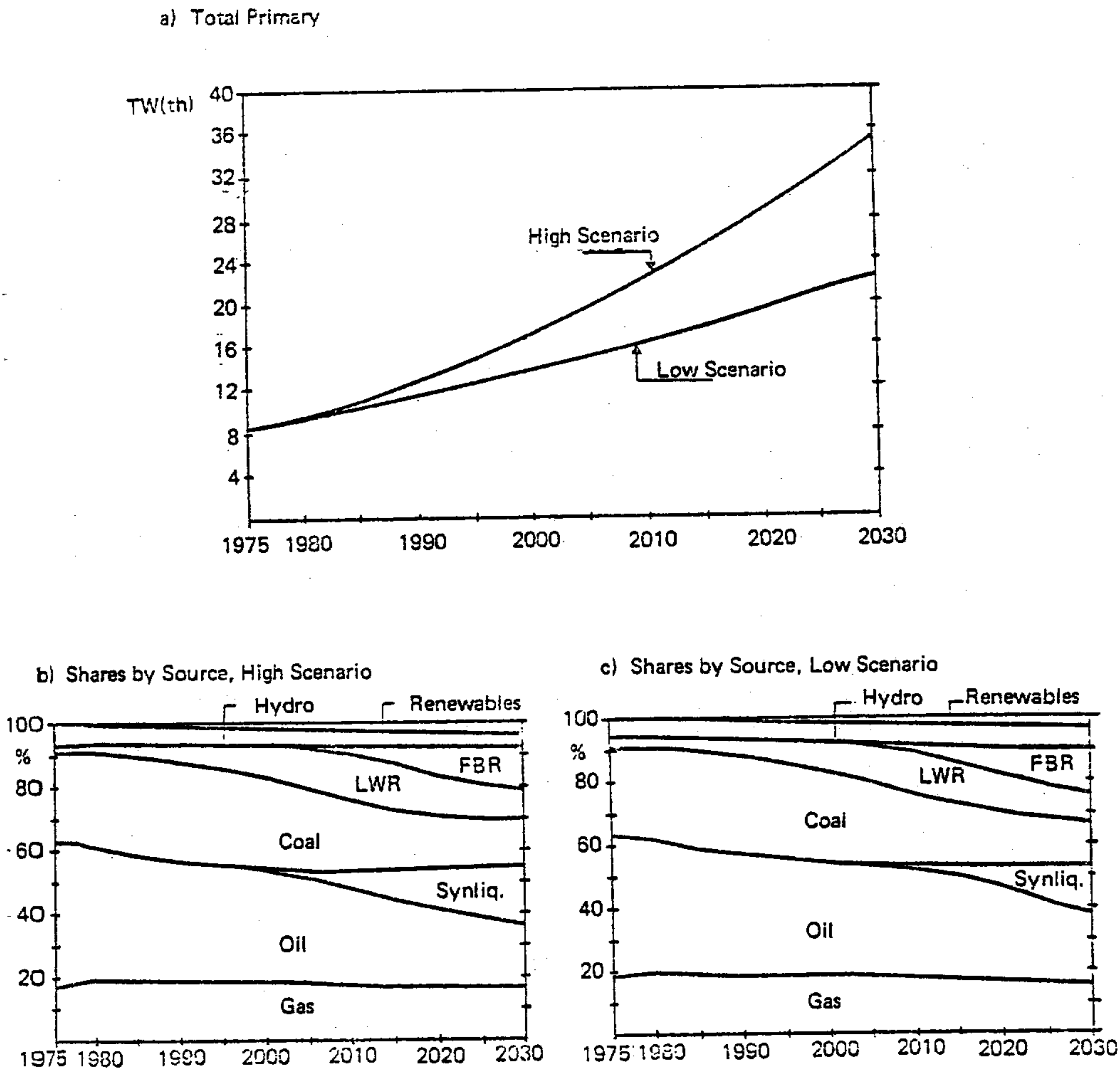



FIGURE 65 World primary energy: two supply scenarios, 1975-2030.

Notes for Figure 65

| | |
|---|---|
| Gas: | Natural gas production, including conventional and unconventional gas |
| Oil: | Crude oil production, including conventional and unconventional oil, oil shales, heavy crude oils and tar sands |
| Synliq: | Synthetic liquid fuel produced from coal; counted here as primary coal input |
| Coal: | Coal production |
| LWR: | Converter (burner) reactors; assumed to be mostly light water reactors |
| FBR: | Advanced reactors and breeders; assumed to be mostly light water reactors |
| Hydro: | Hydroelectric primary equivalent; also includes small amounts of geothermal |
| Renewables: | Soft solar heat systems; centralized solar electric systems; also other such as biomass, wood, municipal wastes, etc. |

TABLE 56 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 | 3.62 | 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] | 0.21 | 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.

[b]Includes mostly "soft" solar--individual rooftop collectors; also small amounts of centralized solar electricity.

[c]"Other" includes biogas, geothermal, commercial wood use, as well as bunkers used for international shipments of fuels; for 2000 and 2030, bunkers are not estimated.

[d]Columns may not sum to totals because of rounding.

Comparing the two scenarios we find that the associated primary energy mixes in 2030 are strikingly similar. While in absolute terms the amount contributed by any source is greater in the High scenario (except for hydro) than it is in the Low scenario, the percentage contribution from each source changes little between the two scenarios. Perhaps the only difference worth mentioning is that the High scenario is a little more coal dependent (34% compared to 29% in the Low) and the Low scenario is a little more oil dependent (22% compared to 19% in the High).

In summary, it can be said that up to 2030 the transition from today's resource-constrained technologies to ones sustainable in the long run is not complete. By 2030, a mere first step of the necessary transition will have been taken, preparing for and introducing to a certain extent a second step, towards the dominance of "unlimited" technologies (i.e. technologies unrestricted by resource scarcity) in the world's energy supply system in the second half of the 21st century.

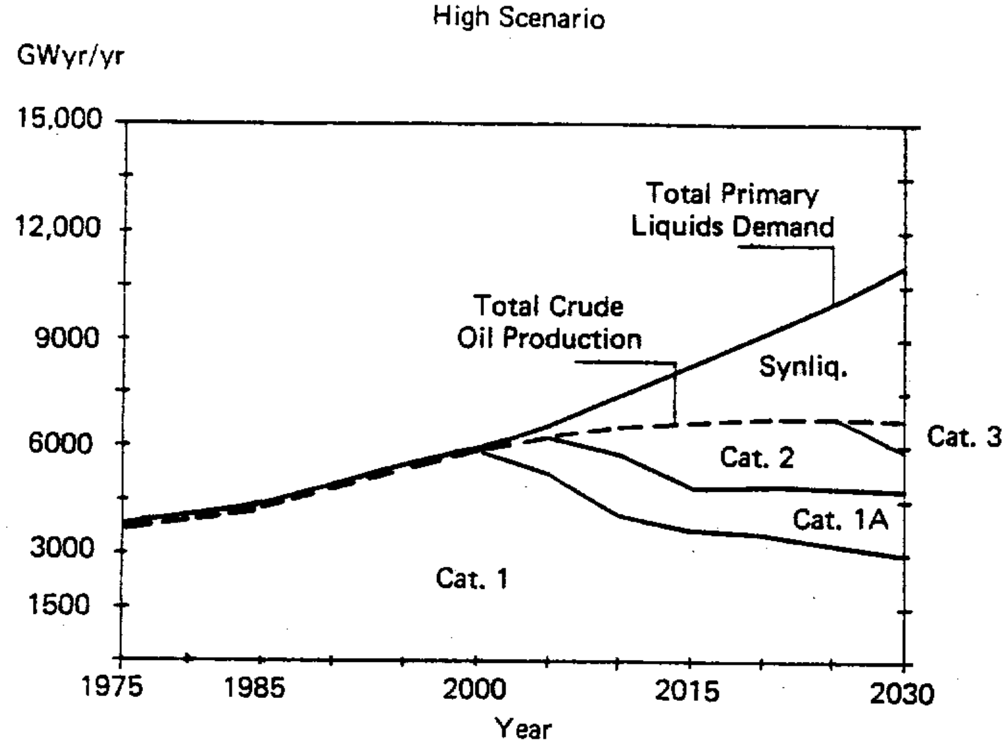
This is the aggregate global background derived from our studies on balancing supply and demand. Although these overall results are significant in themselves, it is important to look more closely at the various features certain options and certain regions exhibit in the analysis.

Balancing Liquid Demand and Supply

The most prominent change in the world's liquid energy system will be its move towards unconventional oil and synthetic liquids.* The share of conventional oil will decline in the High scenario from nearly 100% in 1975 to 80% by 2000 and 30% by 2030. The corresponding figures for the Low scenario are 80% and 47%. According to our analyses, economic production from natural sources of unconventional oil will not exceed 3.5TWyr/yr in the High and 1.6TWyr/yr in the Low scenario, however. Therefore, to meet a primary liquid demand of, respectively, some 11TWyr/yr and 7.3TWyr/yr, some 4.4TWyr/yr and 2.2TWyr/yr of synthetic liquids from coal would be needed. World oil production would thus peak (Figure 66) around 2020 in the High case with 6.9TWyr/yr and around 2015 in the Low case at 5.6TWyr/yr, declining slowly thereafter. (These production rates can be compared to total resource estimates given earlier in Table 30.

The situation of North America (Region I) is of its own kind. (Figure 67) Due to its significant resources of very cheap oil and enormous resources of less cheap oil, this region should become self-sufficient by the turn of the century. In the High scenario, the peak of oil production would be reached hy 2000 at a level of 1.2TWyr/yr (2010 and 1.1TWyr/yr in the Low). Coal liquefaction starts around 1995 in the High scenario (2000 in the Low) and could provide 1.0 TWyr/yr by 2030 (0.75 TWyr/yr in the Low).

*Note that while the term conventional usually includes at least all of Category 1 oil and only some of Category 2 oil, the terms Category 1 oil and conventional oil are not generally interchangeable.



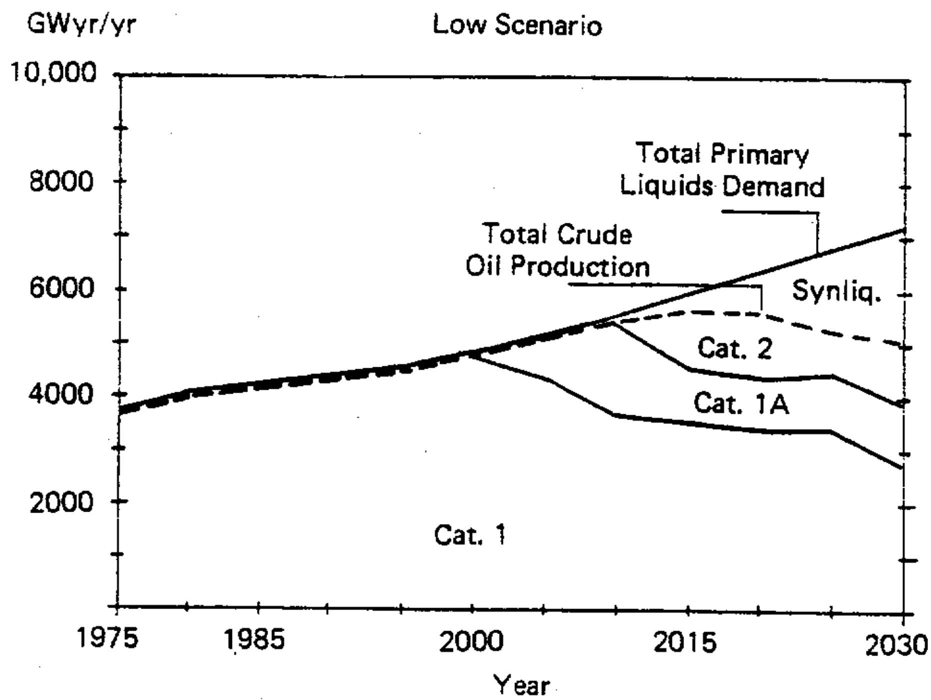




FIGURE 66 World oil supply and demand, 1975-2030 (crude oil equivalent).

The developed planned economies (Region II) are projected to stay self-sufficient for the next 50 years exploiting their large resources of oil and cheap coal (Figure 68). By 2030 a gap of 0.4-0.9TWyr/yr could develop between liquids demand and conventional oil supply. Coal liquefaction might therefore start around 2010-2015 as well as oil shale production. By 2030 coal liquefaction could provide 0.3-0.7TWyr/yr.

The remaining developed countries (Region III) continue to be highly import dependent. Their domestic oil production would peak around 1985-1990 at a level of 0.5TWyr/yr, but will rapidly decline thereafter. In 2030, therefore, 1.9TWyr/yr and 1.5TWyr/yr, in the High and Low scenarios, respectively, will have to be imported. Some 1.7TWyr/yr of coal providing 1.2-1.3TWyr/yr of liquids would be included in these imports, whether as liquids made from coal or as solid coal yet to be converted. In the Low scenario the dependence on imported oil is almost total: oil is easier to get and still cheaper than coal liquefaction (Figure 69).

Diversity among the developing regions is also quite considerable. The situation of Latin America (Region IV) is outlined in Figure 70. Its conventional oil resources are small. By the year 2000 the demand will exceed production by 0.3TWyr/yr and 1.0-1.6TWyr/yr by 2030. Therefore, the region will have to fall back on its remarkable resources of heavy crudes. In the High scenario it would become self-sufficient; in the Low scenario it could possibly export 0.2-0.5TWyr/yr around 2005-2010, but no more exports are expected as of 2025.

Region V, the fastest growing developing region of Africa and Asia, is a net exporter today. Under the scenario conditions it could become a net importer starting between 1990 and 2000 (Figure 71). Although some liquefaction of domestic coal resources is possible, by 2030 liquid demand will by

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Notes to Figure 66

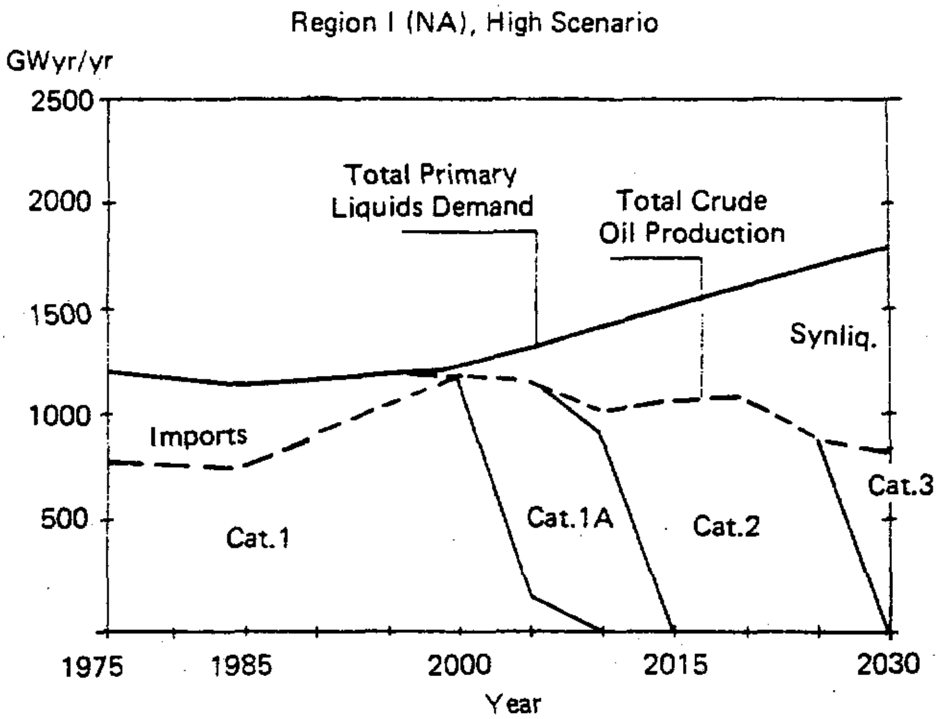
Cat. 1: Oil available at production costs of \$12/barrel of crude (conventional known oil reserves and some remaining to be discovered)

Cat. 1A: Oil available at production costs of \$12-16/barrel of crude (this special category for Regions I and IV only include some shale oils, tar sands and heavy oils)

Cat. 2: Oil available at production costs of \$12-20 (or 16-20)/barrel of crude (some remaining to be discovered resources; enhanced recovery, polar areas, deep offshore oil resources)

Cat. 3: Oil available at production costs of \$20-25/barrel of crude (mostly shale oils, tar sands, and heavy crude oils)

Synliq: Synthetic liquid fuels produced from coal, at a cost of about \$21.50/barrel of refined product



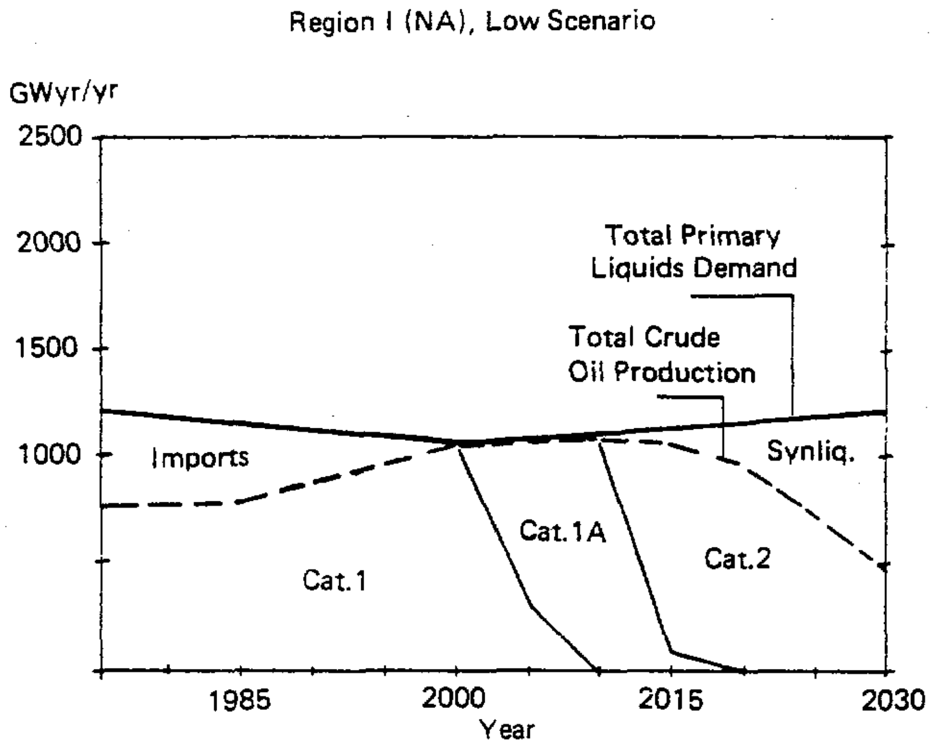




FIGURE 67 Oil supply and demand, Region I, 1975-2030, High and Low scenarios, crude oil equivalent. (See Table 66 for definitions of categories.) All the plots of this figure result directly from the linear programming MESSAGE model runs and do not include constraints for the gradual buildup and depletion 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 is the base for the scenario calculations.

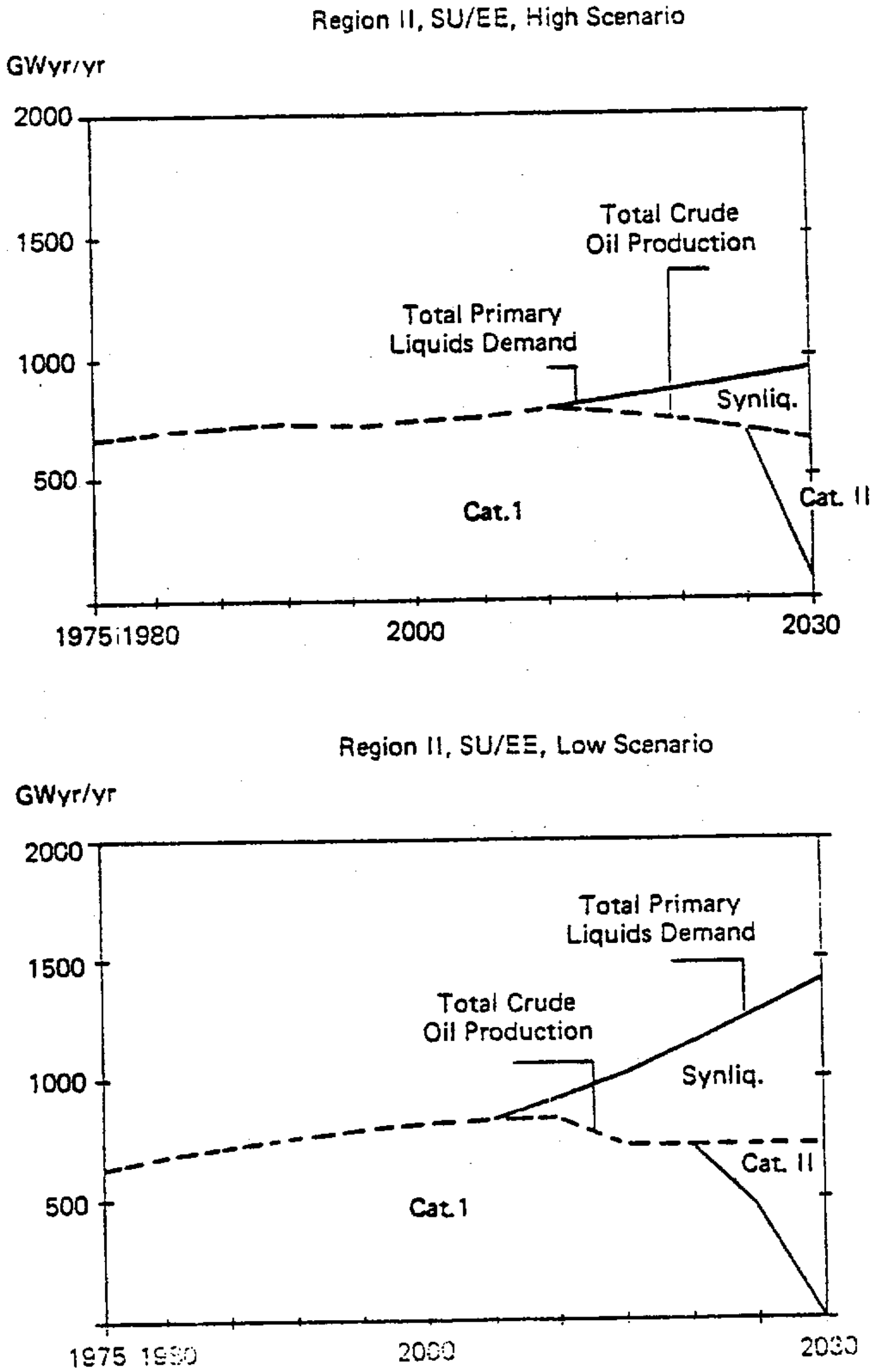
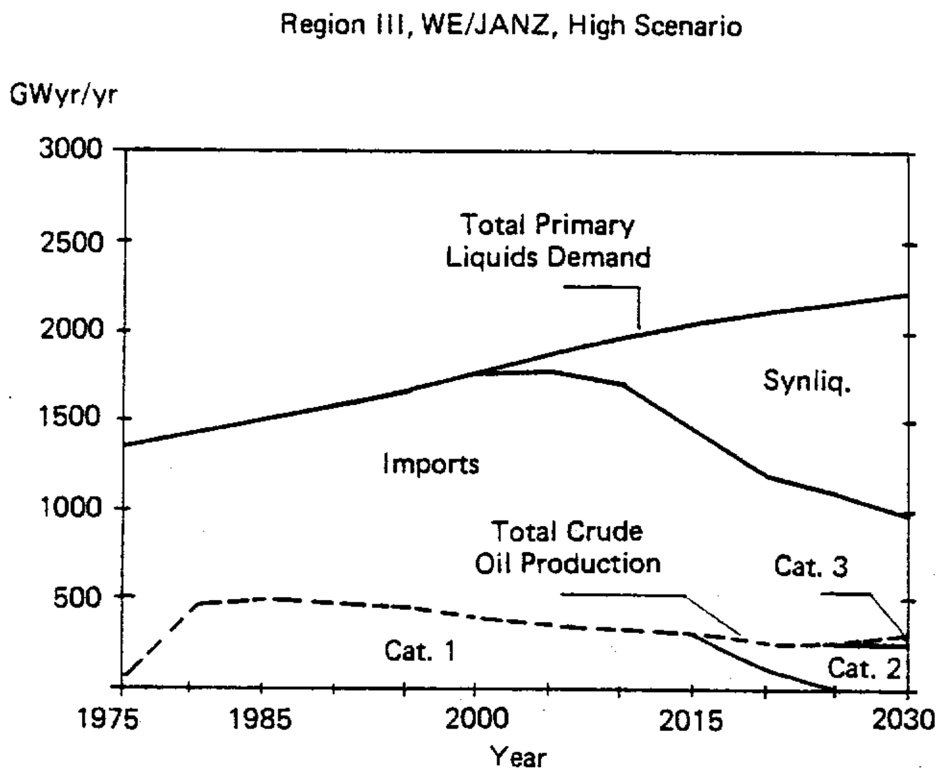



FIGURE 68 Oil supply and demand, Region II, 1975-2030, High and Low scenarios, crude oil equivalent.



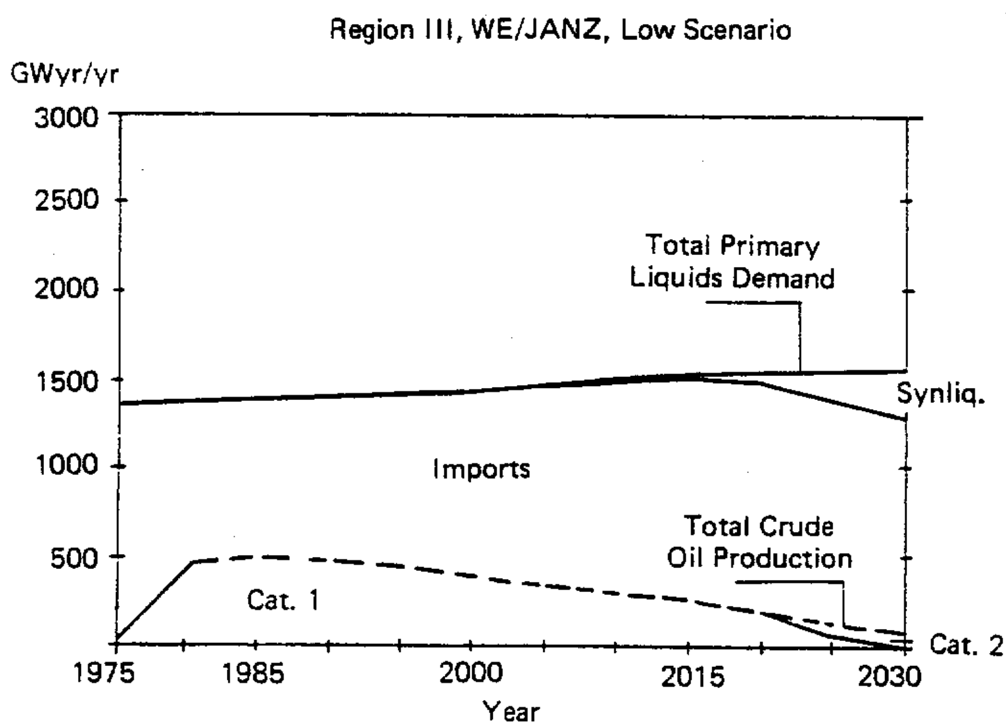
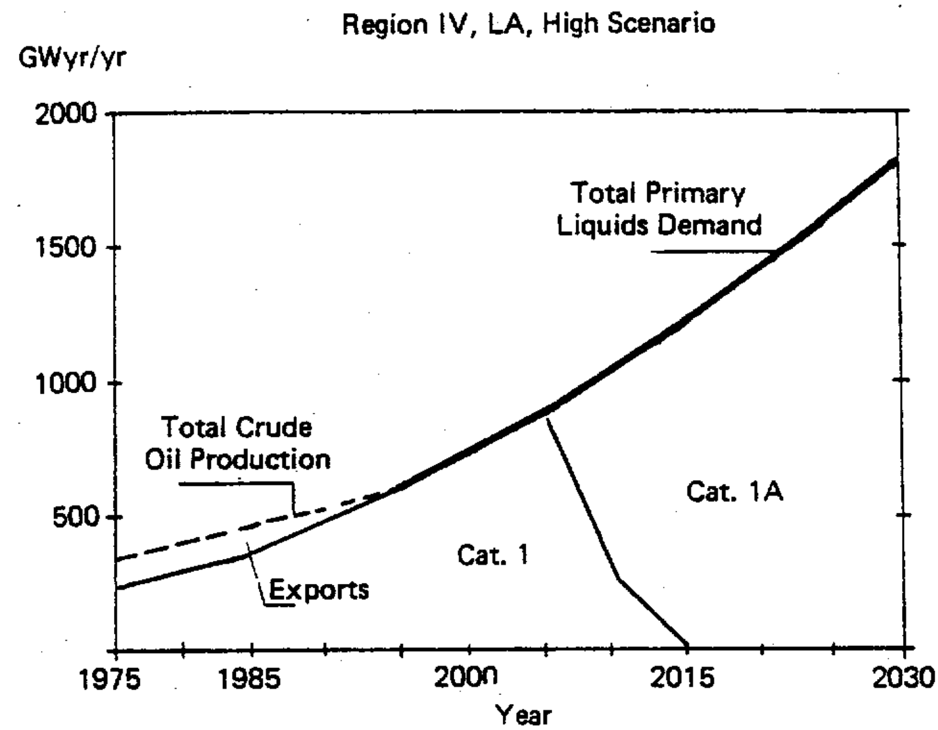




FIGURE 69 Oil supply and demand, Region III, 1975-2030, High and Low scenarios, crude oil equivalent.



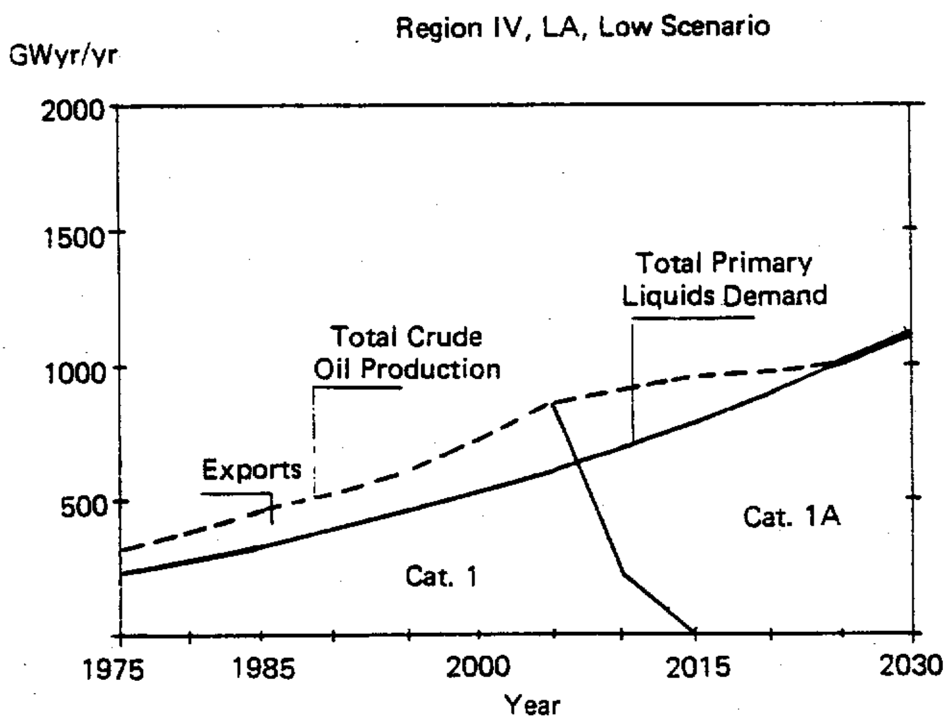
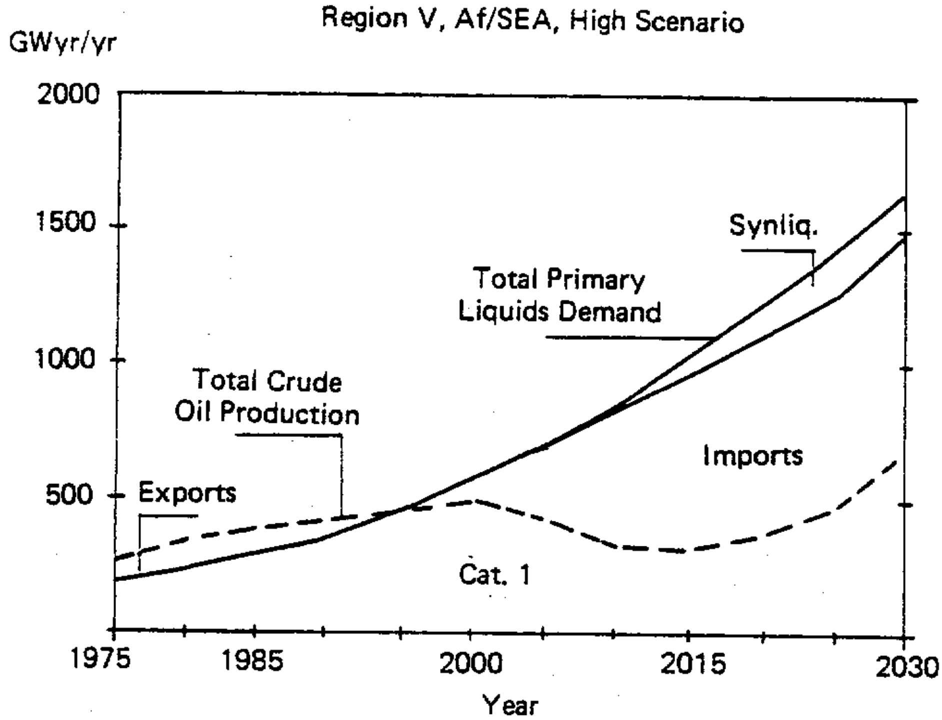




FIGURE 70 Oil supply and demand, Region IV, 1975-2030, High and Low scenarios, crude oil equivalent.



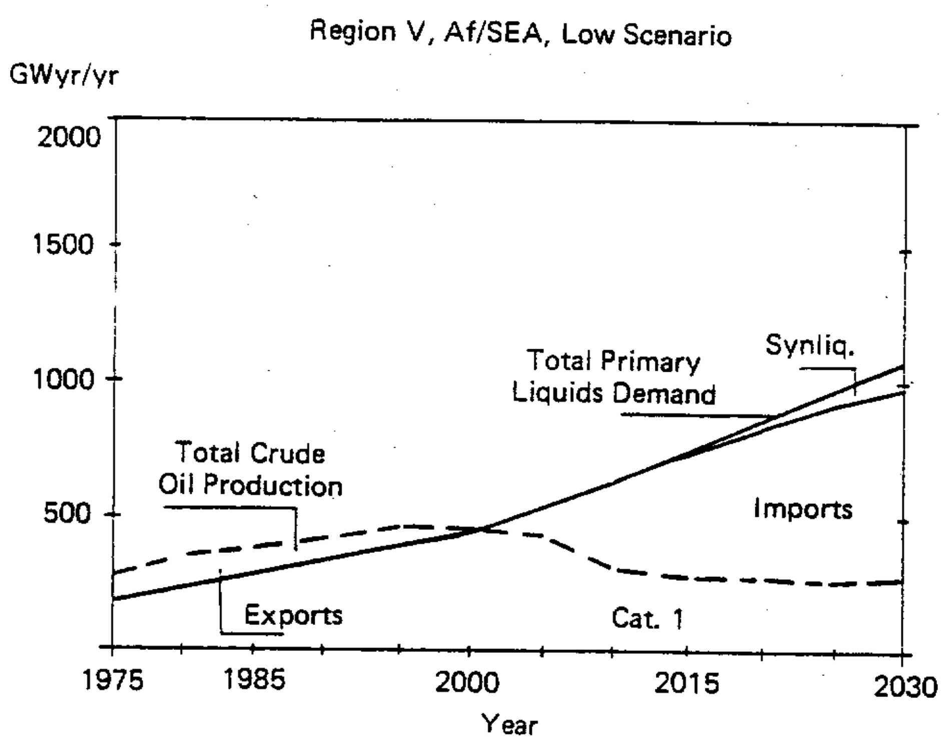




FIGURE 71 Oil supply and demand, Region V, 1975-2030, High and Low scenarios, crude oil equivalent.

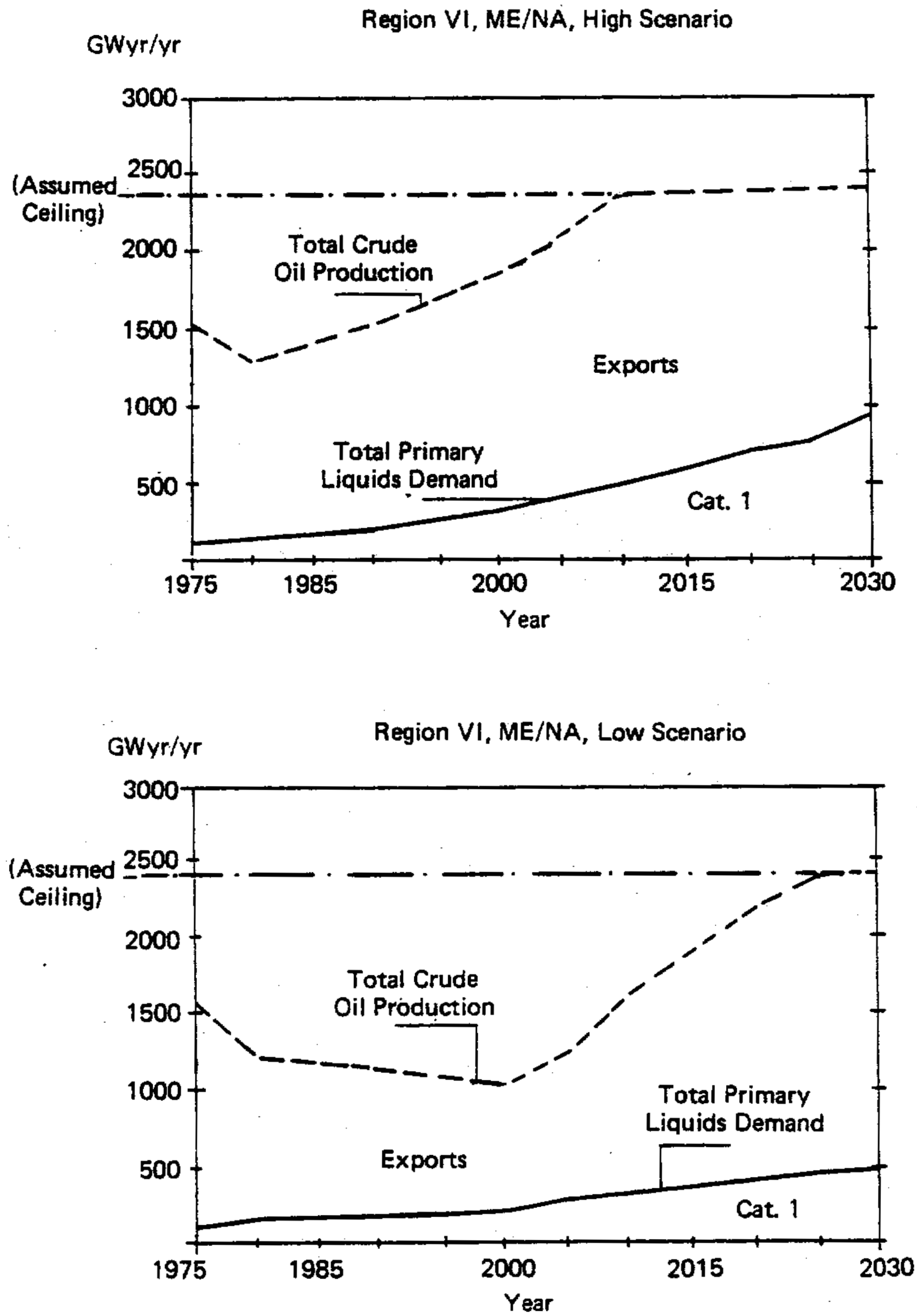



FIGURE 72 Oil supply and demand, Region VI, 1975-2030, High and Low scenarios, crude oil equivalent.

far outstrip domestic production, and 0.7-0.8TWyr/yr will have to be imported.

Region VI, North Africa and the Middle East, continues to be the main conventional oil supplier. By 2030 in our scenarios, this region will have produced 63%-80% of its available (conventional) oil. Domestic uses will grow and reach 20%-40% of the oil production by 2030 (Figure 72).

Finally Region VII, the planned economies of Asia, will as is indicated in Figure 73 experience a rapid growth of both liquid demand and liquid production. Domestic oil and coal resources might prove to be adequate for the region to stay self-sufficient. Large-scale coal liquefaction might enter the market after 2000.

Balancing Gas Demand and Supply

Both scenarios project the use of natural gas--a clean but difficult to transport energy source--to increase significantly in the developed regions possessing or being close to large gas resources. With the exception of Region VI, whose gas consumption will jump dramatically given the enormous domestic resources, the use of gas in the developing regions will not exceed a moderate level, due to infrastructural reasons. Figure 74 illustrates these discrepancies: North America and the planned developed economies have large resources of their own while the remaining developed regions would import substantial amounts from the Soviet Union. Region V, in contrast, would produce a limited amount of its domestic conventional resources and use biogas covering 13-17% of its demand.

Figure 75 presents the global picture. The demand in both scenarios exhausts the cheap conventional resources costing less than US $12/barrel of oil equivalent (boe), and draws on some 35% (High) and, respectively 15% (Low) of resources costing US $12-20/boe.

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Note for Figure 72

The drop in Region VI oil production (and exports) from 1975 to 1980 is due to a combination of two complementary factors: 1) world liquids demand would level off or even decline from 1975 to 1980 (as a result of various assumed conservation measures), and 2) non-Region VI crude oil production would increase markedly from 1975 to 1980 (from about 2200 to about 2600 GW), due to North Sea, North Slope and other new fields. In retrospect, it may be that these assessments, made in 1977 and 1978, were overly optimistic; the course of events so far (at this writing, mid 1980) would not bear them out. The implications of *higher* global liquids demands, and *higher* requirements for Region VI oil could well have greater difficulty in reaching and sustaining the assumed production ceiling in this region after the year 2000. Perhaps a recognition of this is partly motivating the constrained production and high prices characteristic of Region VI in 1979 and 1980.

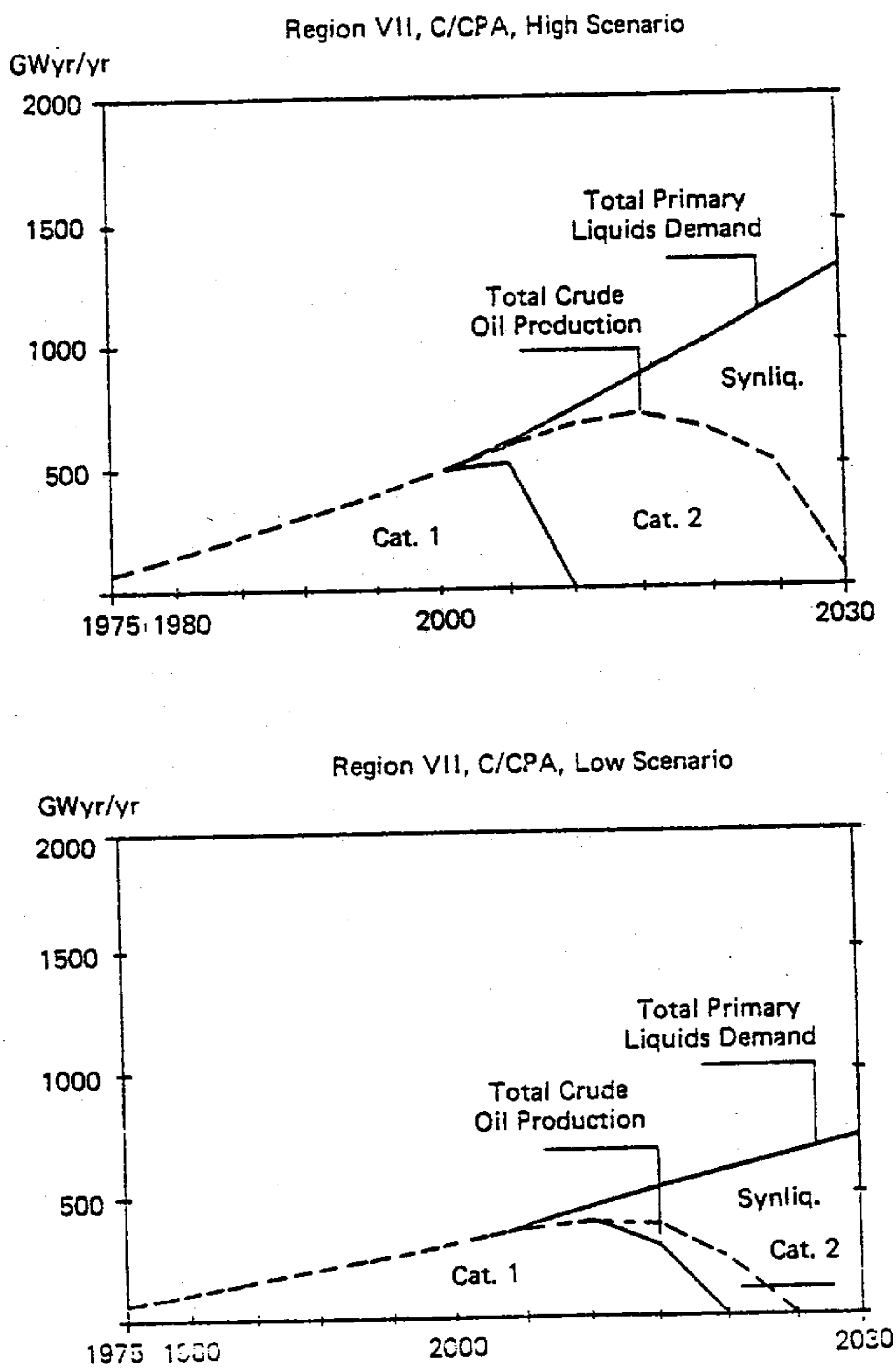



FIGURE 73 Oil supply and demand, Region VII, 1975-2030, High and Low scenarios, crude oil equivalent.

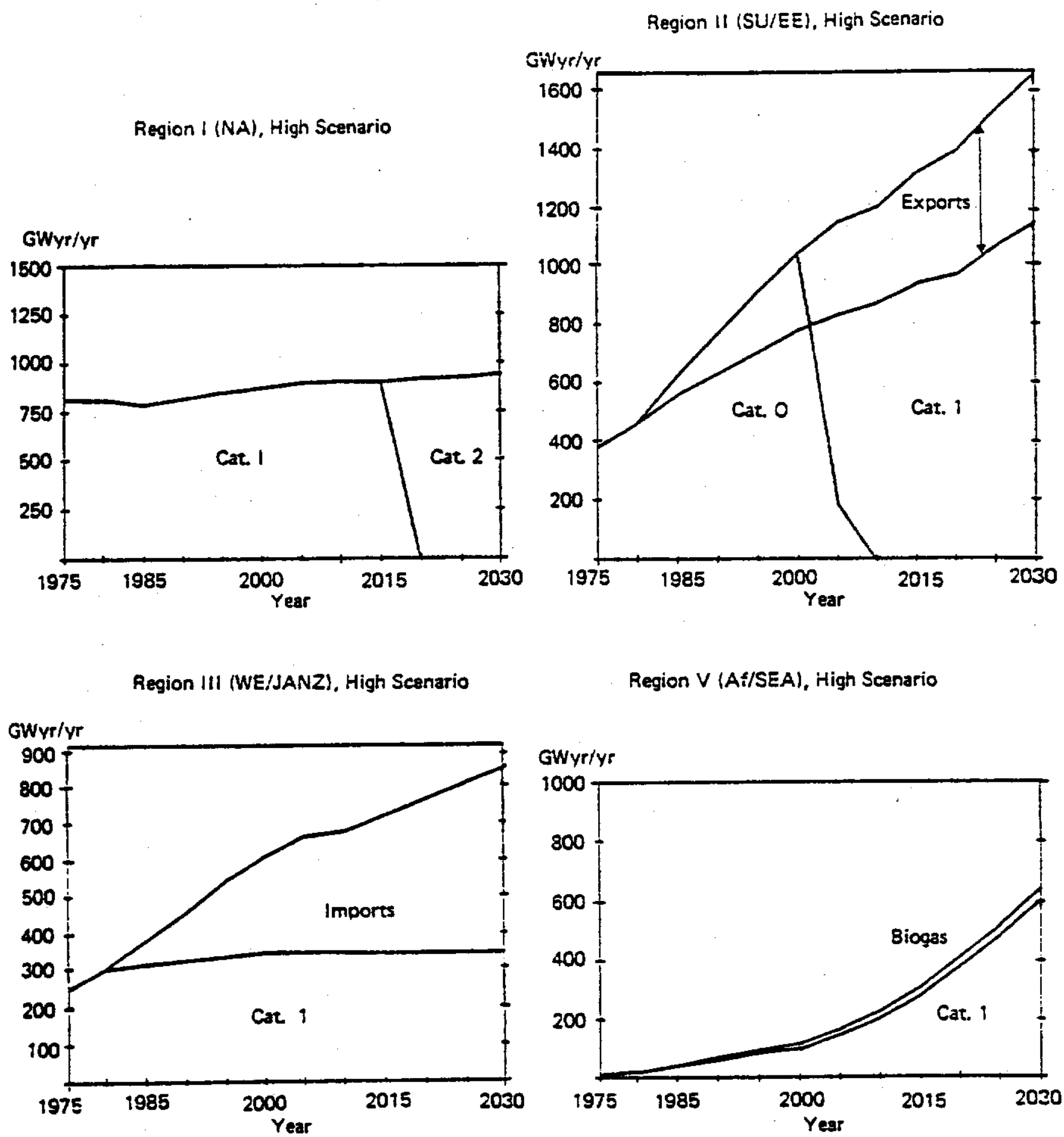
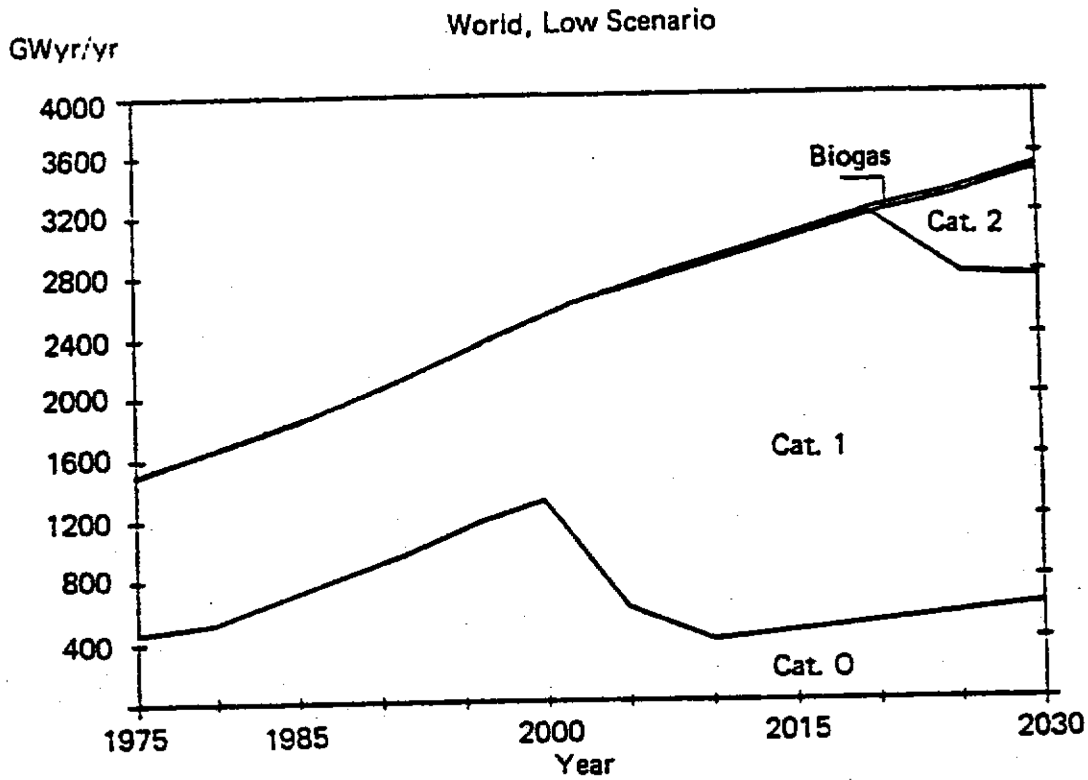



FIGURE 74 Global gas supply and demand, 1975-2030. (See Figure 66 for definitions of categories.)



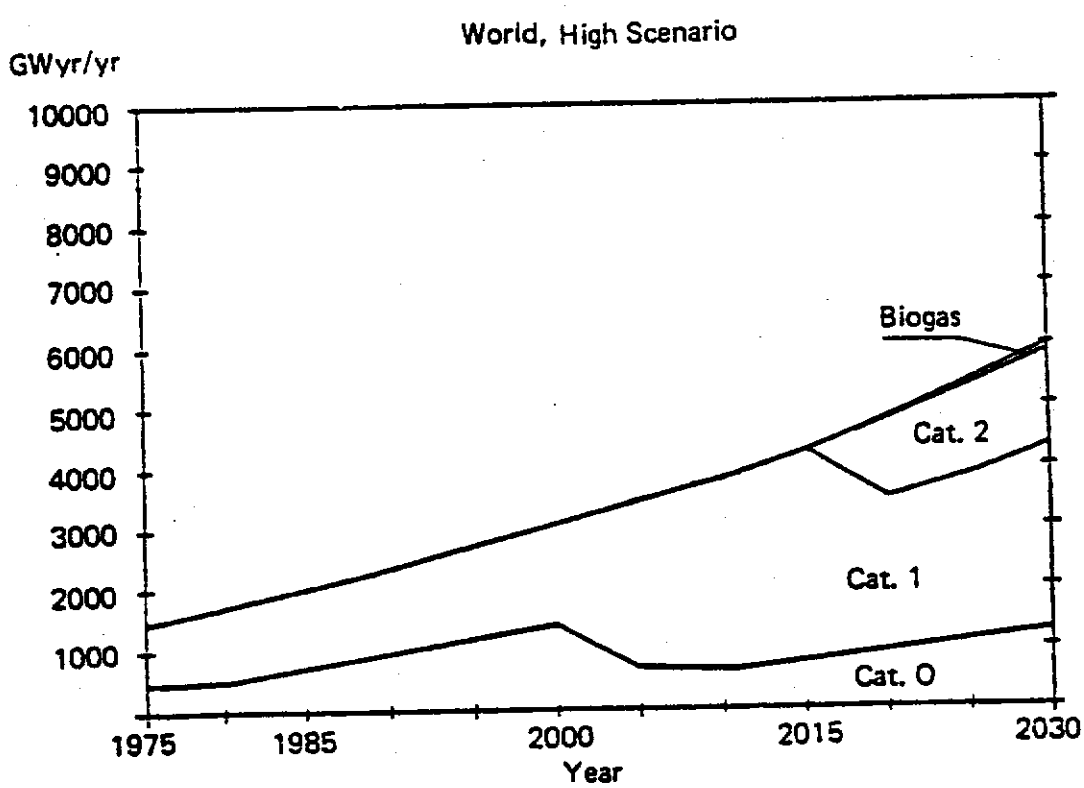




FIGURE 75 Global gas supply and demand, 1975-2030. (See Figure 66 for definitions of categories.)

Balancing Coal Demand and Supply

In both scenarios only the cheapest coal is used. This involves in the High scenario, 61% of the category 1 resource base and 40% in the Low scenario. Developed planned economies and North America avoid early depletion of their resources. The remaining developed countries, however, might use 83% of their resources, should no coal be imported. Of the developing regions, Latin America, the Middle East, and North Africa would not develop coal significantly, in view of their large hydrocarbon resources. According to the scenarios, China and the centrally planned economies of Asia are concerned with using much of their domestic coal resources for their own growth (in the High case almost all of their category 1 coal). The remaining developing countries, in contrast, should be able to keep within their regional resource limites.

Coal can be used directly as a solid or after conversion as liquids, gas, or electricity. The solid uses of coal were outlined in Chapter 3. Its role as a primary source of electricity will probably decline in the long-run future.

Our scenarios, as is indicated by Figure 76,have as a result very large future liquefication industries. Both the United States and the Soviet Union dispose of very large coal resources. For North America we assume a maximum 2.9 billion tons of coal per year (2.7TWyr/yr) possibly to be produced. This is an enormous amount, approximately twice the present world extraction rate or five times the US extraction in 1978. There are chances that it could be done; our scenarios indicate a strong need for success.

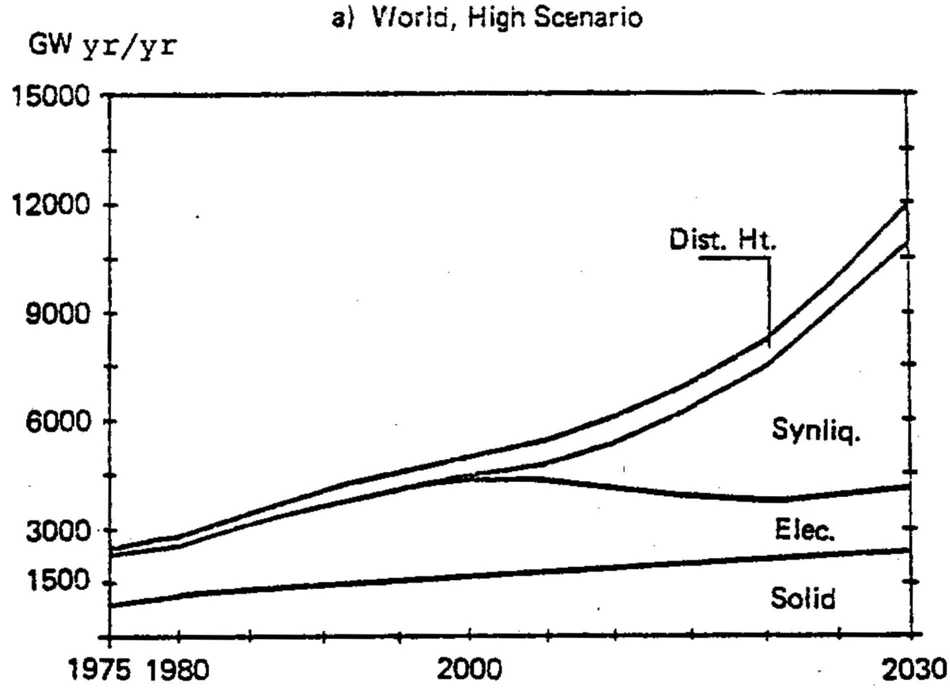
The same can be said for the Soviet Union, as well as for the other centrally planned developed countries, for which we have assumed a maximum yearly extraction of 3500 billion tons of coal.

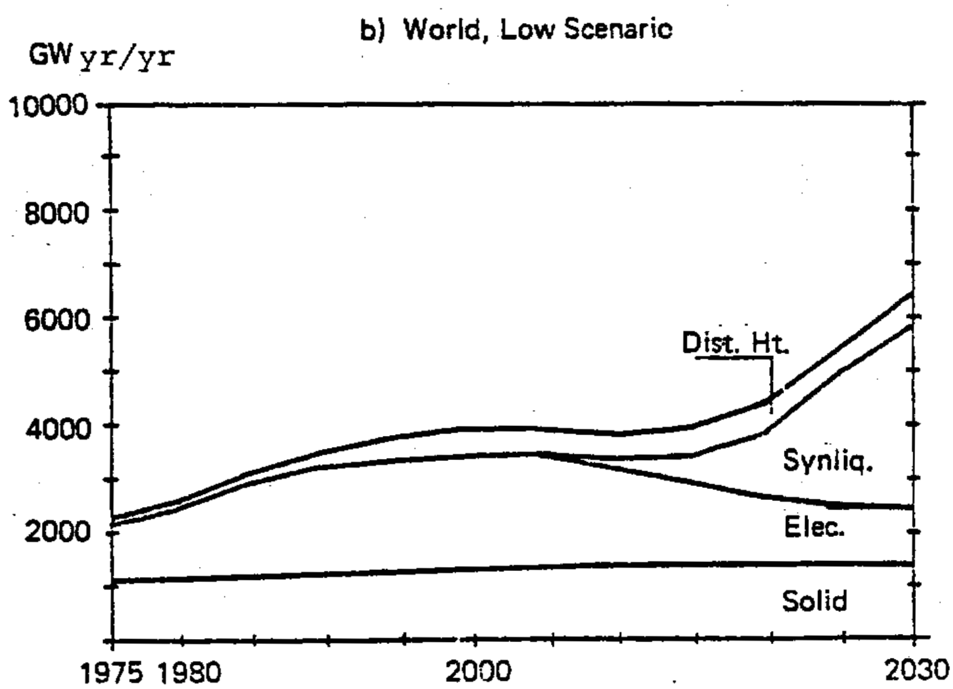
The two regions do not differ greatly with respect to the supply and demand balance, as Figure 77 illustrates. Electricity generation declines when in the High case the output ceiling is reached. An increasing shift to synthetic liquids can be observed. In contrast to North America, a significant amount of coal in Region II is used for district heating or in combined heat and power plants.

Part of the coal produced in Region II is exported to the remaining developed world. For one, Region III must import coal to meet its liquid demand, in view of the limited amounts of oil available at home and from Region VI. Its domestic coal production though fairly large will be insufficient for adequate synthetic liquids production. Imports from Regions I and II might be either in the form of coal or as synthetic liquids, reaching about 1.5TWyr/yr in the High scenario.

In Region V (most of Asia and Africa) domestic coal production would have to climb by a factor of 11 in fifty years in the High scenario. Other than in the developed regions, the emphasis would be on the solid use of coal with a major share devoted to electricity generation (Figure 78).

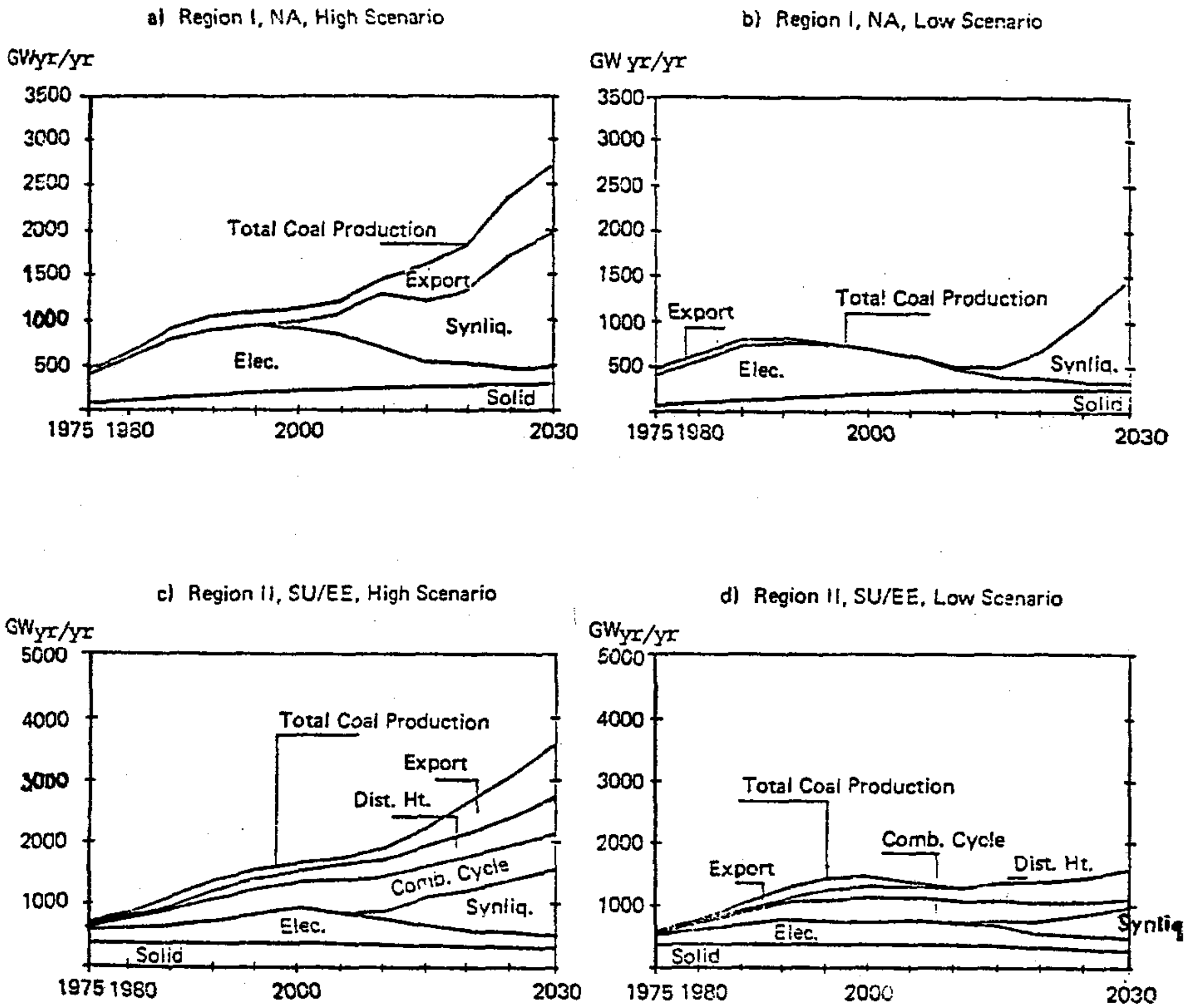
Worldwide about 6.7TWyr/yr, that is, 56% of the coal production, would under the conditions of the High scenario go into liquid production, providing 38% of the liquids demand.




Note: Synliq. represents synthetic liquid fuels produced from coal, here counted in primary coal input terms.

FIGURE 76 Coal supply and demand for the world, 1975-2030.




Note: Synliq. represents synthetic liquid fuels produced from coal, here counted in primary coal input terms.

FIGURE 77 Coal Supply and Demand for Regions I and II, 1975-2030

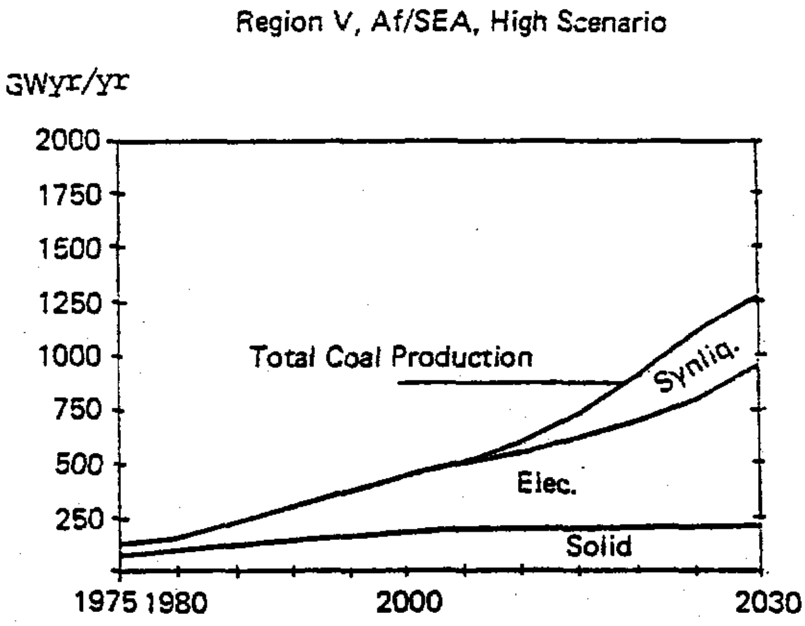



FIGURE 78 Coal Supply and Demand for Region V, 1975-2030

New conversion technologies, such as a methanol production from nuclear or solar hydrogen (see Chapter 3) might alleviate the problem slightly as would a further exploitation of gas resources (and conversion of gas into liquids).

Centralized Heat Supply

Particularly in the developed planned economies (Region II), steps have been taken to enhance the use of indigenous primary sources for the centralized production of heat or heat and power (cogeneration). Already today 70% of the low- and medium-temperature heat requirements of the region is supplied by district heat or cogeneration plants. Plans for vigorous expansion of facilities are plenty, with coal and gas being the main primary sources for district heating and with coal as well as a growing share of nuclear energy being used for cogeneration (Figure 79).

Other regions are projected in our scenarios to increase the use of centralized heat supplies, but on a scale not comparable to that of Region II. In Region III, for instance, in spite of a clearly higher use, the total centralized supply remains small, i.e., 138GWyr/yr by 2030 (or 3% of the total secondary demand).

Electricity Generation

Today, in the developed regions, electricity is generated from coal, oil and gas, hydroelectricity, and nuclear energy. In Europe and Japan the role of fossil fuels is somewhat less, and that of hydro power is larger. In developing regions hydroelectricity is the primary source, with coal as well as oil and gas equally sharing the remainder.

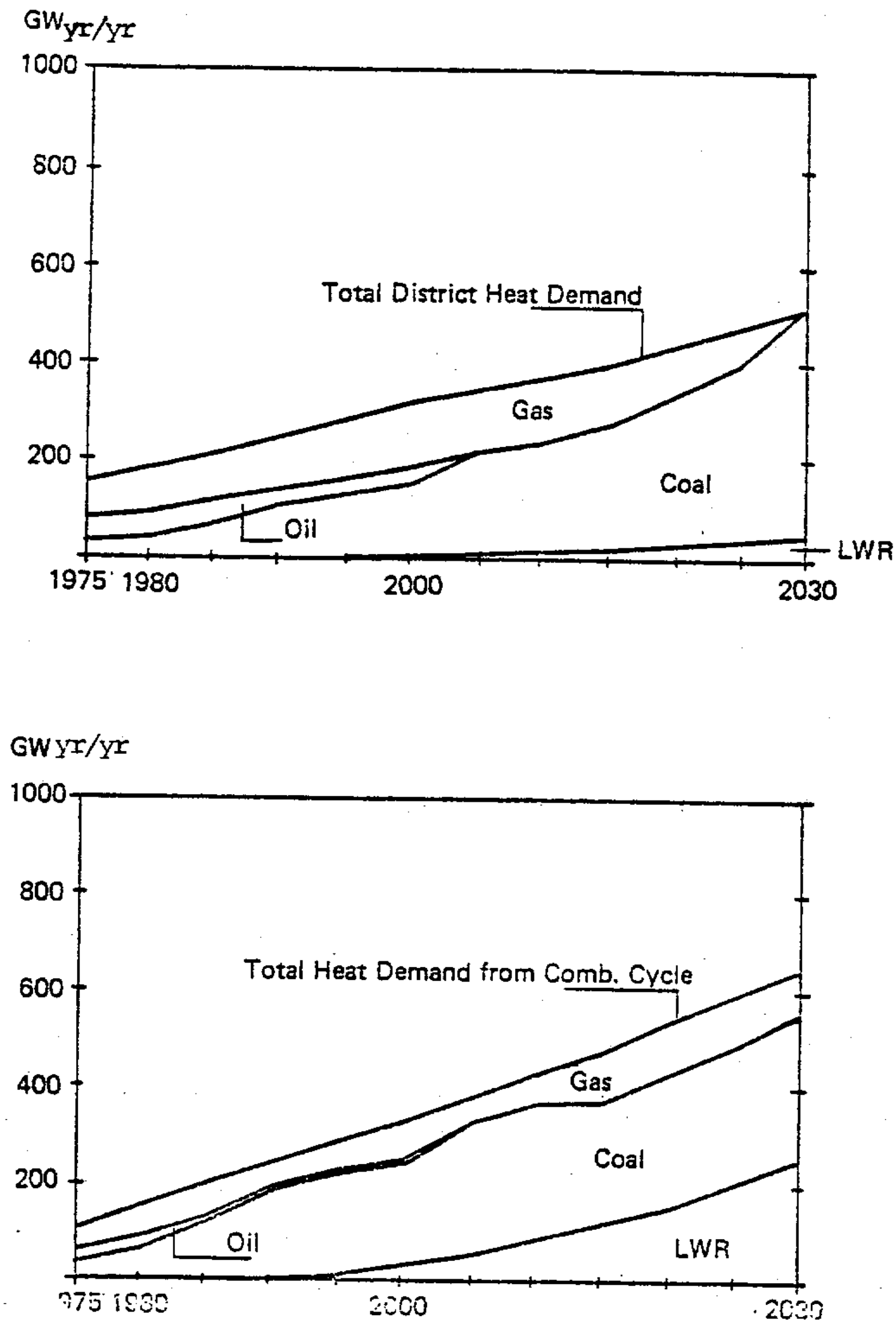



FIGURE 79 Centralized heat supply in Region II (SU/EE), High scenario.

The picture will be quite different by 2030, as Figure 80 indicates. Nuclear energy will have largely taken over electricity generation in the developed regions (Region I: 81%, Region II: 60%, Region III: 76-85%) and make significant contributions in the developing regions. The great potential of hydropower in the developing regions still has to be exploited (see Figure 81). It could supply a substantial and growing increment of electricity generation. Different regions can therefore be expected to take highly divergent energy paths.

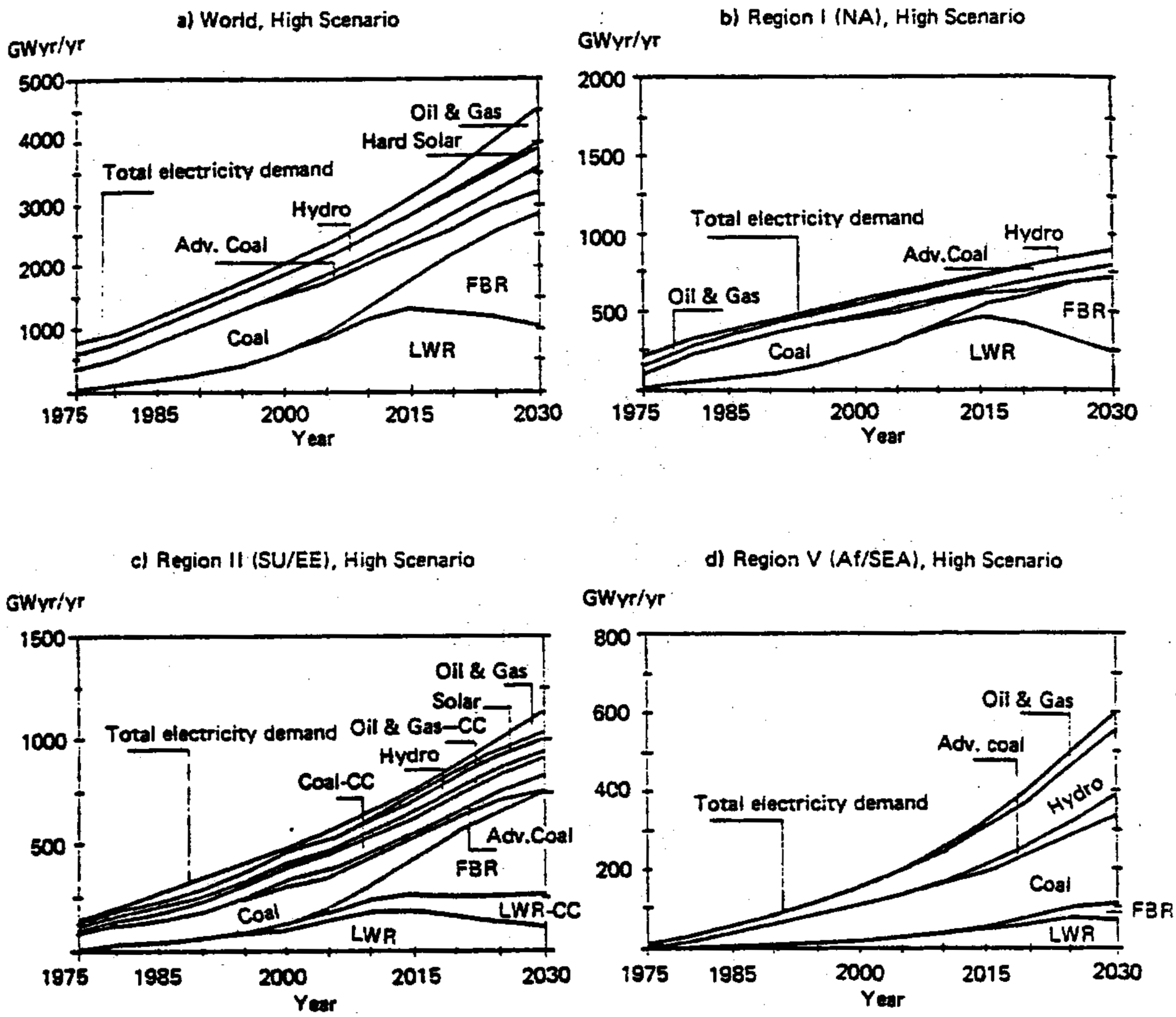



FIGURE 80 Electricity generation, 1975-2030, High scenario globally and by region, I, II, V.

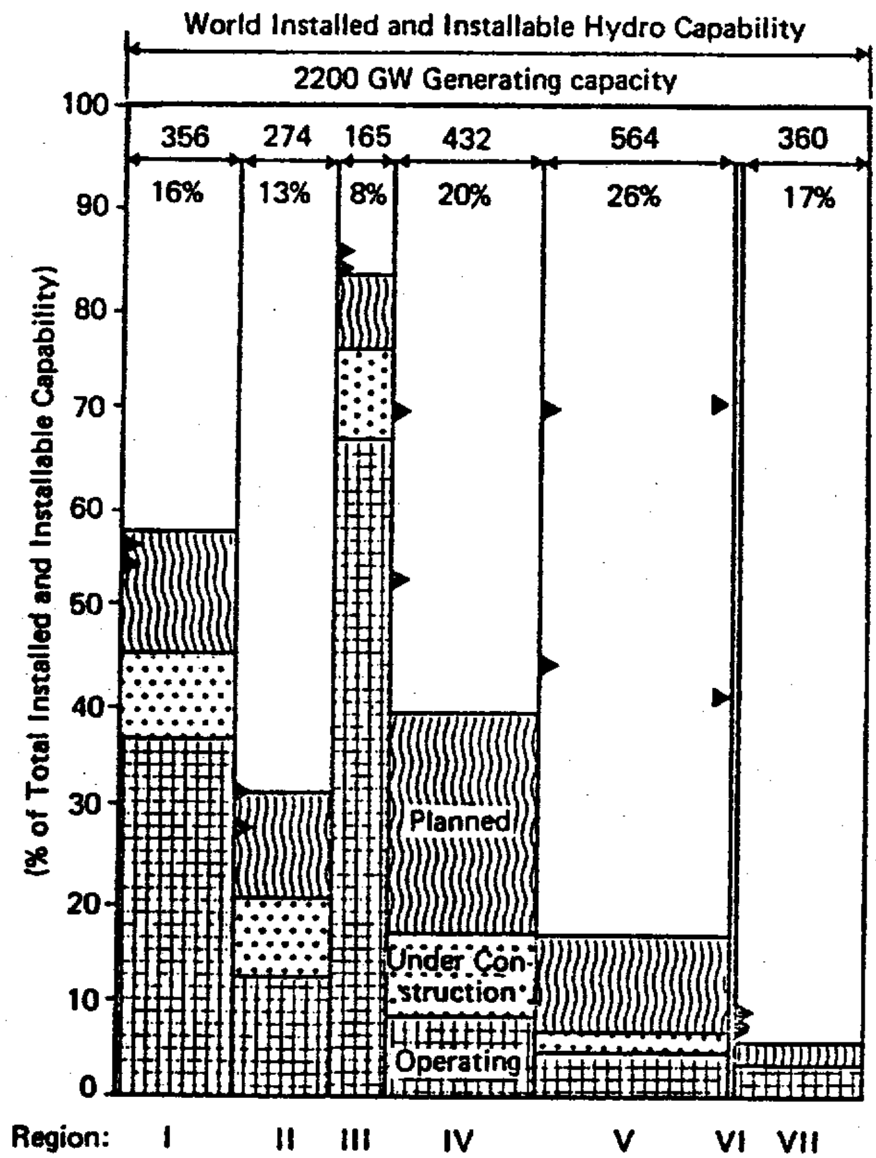



Figure 81 Global hydroelectric resources, total installed and installable capability, world regions. Top arrow in each regional column is the assumed maximum realizable by MESSAGE. Bottom arrow is the actual realized by MESSAGE in 2030, both High and Low scenarios; area of column proportional to total potential installable capacity.

Total secondary electricity demand grows to 3000 GW(e) of capacity in 2030 in the Low scenario and 47,000 GW(e) in the High scenario. This compares, for instance, with a potential nuclear capacity of 10TW(e) (see Chapter 3). Most of the electricity is optimally used and applied for special purposes.

Renewable Resources

The theoretical and practical potentials of renewables have been considered in some detail (see Chapter 3). Use of these continually available sources has been limited so far by their unfavorable economic and harvesting conditions, which might change in the future. As was mentioned, large-scale hydroelectricity holds an important share in our scenario projections. In some favorable locations, small-scale wind and hydropower might profitably be applied. Our scenarios project that these sources could meet up to 80% of the agricultural electricity needs and 30% to 60% of the electricity demand of small towns and villages in developing regions. The contribution for all developing regions would be 6-8% of their electricity demand.

In Region V, biomass might contribute 272-303GWyr/yr in the form of charcoal from natural forests, 0-153GWyr/yr as charcoal from plantations, and 35-40GWyr/yr, as biogas from agricultural and animal wastes if an aggressive policy were pursued. In Region IV, only charcoal from natural forests is assumed to contribute significant levels of 206-317GWyr/yr. In each region, approximately one third of the potential regenerative capacity of the forest area would have to be harvested to that end. Eleven to 43% of the wastes in Region V would be converted into biogas.

FOSSIL FUEL USE AND $CO_2$ PRODUCTION

Fossil fuel use remains high in both scenarios. Of the total fossil resources recoverable at costs less than US$12/boe (estimated at 464TWyr), the High scenario consumes 317TWyr and the Low scenario 264TW/yr (Table 57).

Exploitation of such large amounts of fossil fuels is bound to lead to substantial releases of $CO_2$ to the atmosphere and to possibly significant impacts on the world's climate.

A model simulating the global carbon cycle has been developed by Niehaus (1976) of the joint IAEA/IIASA Risk Project. This model permits relating increases in $CO_2$ concentrations to the warming up of the atmosphere. Combining this model with a method developed by Augustsson and Ramanathan (1977) for estimating changes in global average temperature due to increasing $CO_2$ concentration in the atmosphere, one obtains an overall temperature rise in the lower troposphere of 1.9°C if the atmospheric $CO_2$ content is doubled (from 300 to 600 ppm); the effect is larger by a factor of 3 to 5 in polar regions.

Both tools have been applied to our scenarios (Figure 82). It appears that, by the year 2030, the atmospheric $CO_2$ would have increased to about 430 and 500 ppm, respectively, and *the temperature changes involved be on the order of 0.8°C and 1.1°C above 1967 levels, with all other climatic parameters held constant.*

TABLE 57 Cumulative Uses of Fossil Fuels, 1975 to 2030, High and Low Scenarios

| | Total Resource Available[2] (TWyr | High Scenario Total Consumed (TWyr | High Scenario Remaining Resource[4] (years) | Low Scenario (TWyr | Low Scenario Remaining Resource[4] (years) |
|---|---|---|---|---|---|
| **Oil** | | | | | |
| Cat. 1+2 | 464 | 317 | 22 | 264 | 40 |
| Cat. 3 | 373 | 4 | 54 | 0 | 74 |
| **Natural Gas** | | | | | |
| Cat. 1+2 | 408 | 199 | 35 | 145 | 76 |
| Cat. 3 | 130 | 0 | 22 | 0 | 38 |
| **Coal**[3] | | | | | |
| Cat. 1 | 560 | 341 | 18 | 224 | 52 |
| Cat. 2 | 1019 | 0 | 85 | 0 | 158 |

1 For definition of terms and categories, see Figure 66.
2 Total resources, including to be discovered, as of 1975.
3 Coal use includes coal converted to synthetic liquids and gas.
4 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.

What does this imply? For the time being it is not possible to say much in detail about the climatic impacts that may result. Shifts in climatic zones or in the rainfall patterns are conceivable. But the climatic system is a changing one as we know from several rapid changes on the order of $2^{o}$-$4^{o}C$ that have occurred over the past 20,000 years in central Europe (Flohn 1979). If the presently estimated "green house" effects are accurate we may note a "signal" stronger than the usual variations still before the turn of the century. If then this warning were taken seriously and fossil fuel consumption were reduced drastically, the atmospheric $CO_2$ concentration would go on rising for another 40 years or so.

These are disturbing aspects necessitating intensive research. For the implications could be enormous and the lead times are long.

ALTERNATIVE CASES

A main focus in the energy debate is nuclear energy. Our scenarios indicate that the potential role of nuclear energy in the world's

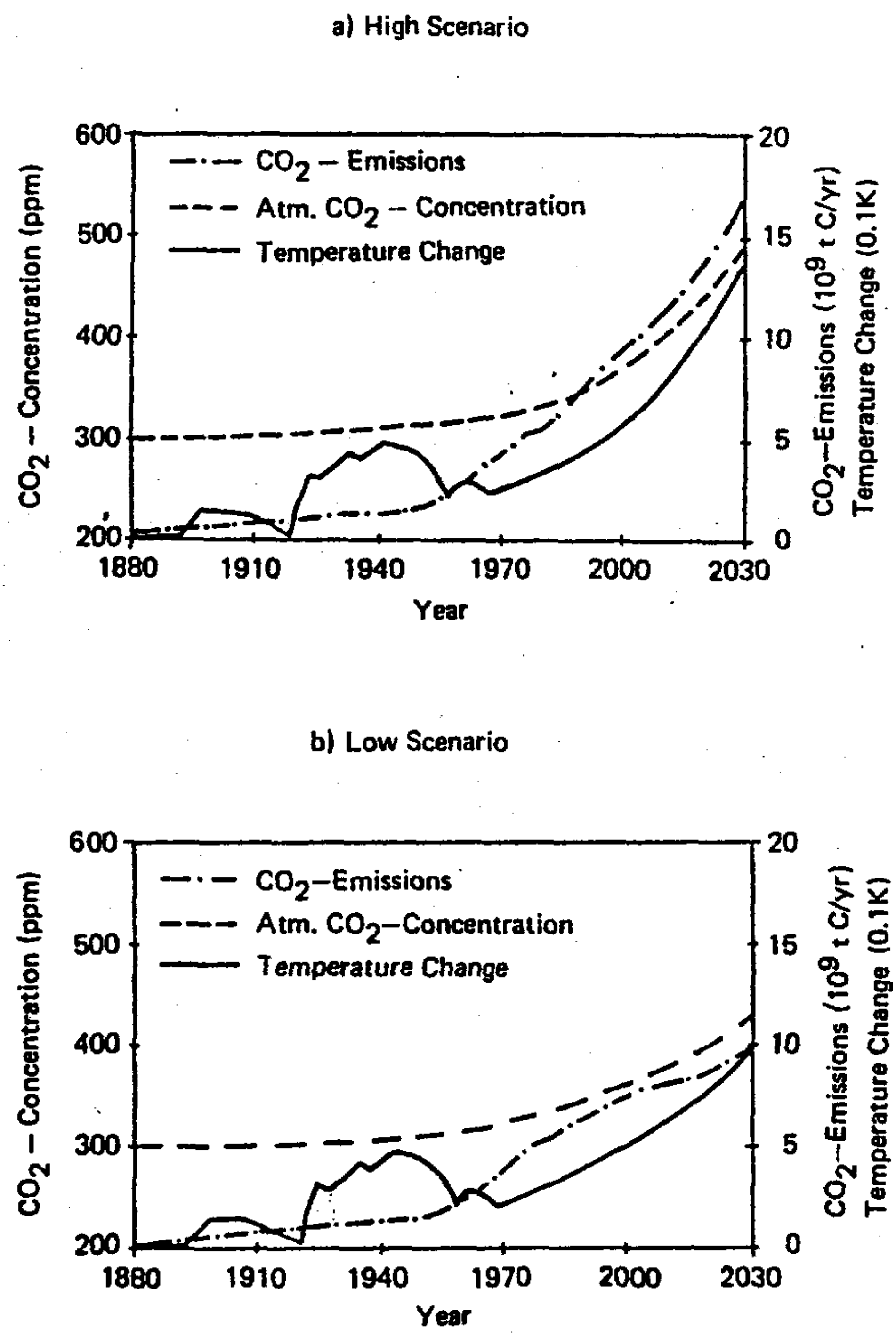



FIGURE 82 $CO_2$ emissions, atmospheric $CO_2$ concentration and temperature change, High and Low Scenarios.

future supply is an important one. In order to better understand the role of nuclear energy we have expanded our analysis to include two alternative cases, a Nuclear Moratorium case, and a scenario of accelerated growth of nuclear power called Enhanced Nuclear case.

The *Nuclear Moratorium case* was quantified on the basis of the Low scenario by the supply constraint that no new nuclear power capacities would be introduced after 1979. In contrast, fossil exploitation limits would be higher, and solar power buildup would set in earlier.

The moratorium is considered to affect most strongly the developed regions, where the reference scenarios envisage the highest nuclear shares. There coal extraction is allowed to rise to the High scenario levels. Solar energy would meet the balance, expanding at a maximum rate that is discussed in Chapter 3, by providing about 6% of the world's energy supply by 2030.

How does the resulting energy use compare with that of the Low scenario (Table 58)? Electricity generation would have to depend mostly on coal for baseload and intermediate load, and solar power could provide peak load. But so mugh coal would be needed for electricity that *less* would be available for liquefaction in the Moratorium case (33%) than in the Low scenario (39%). Here natural gas could give some relief. With an only slightly bigger share (as it is demand constrained), and provided there exists a reasonable conversion process (which has yet to be developed), natural gas could significantly contribute to meeting the demand for liquids.

TABLE 58 Primary Energy, Nuclear Moratorium Case and Low Scenario, 2030 (% 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 |

The nuclear moratorium case shows that with a low energy demand, primary energy needs until 2030 might be met without the use of nuclear energy. It also means, however, that the concomitant high use of fossil fuels would leave an uncomfortably low resource base for the times thereafter. Whereas, the transition to non-resource constrained systems cannot be avoided eventually it will be the more difficult the later the world prepares for it.

The *Enhanced Nuclear case*, based on the High scenario, imposes tighter limits on fossil fuel production and assumes an earlier introduction of the nuclear breeder than the High scenario. With such a more rapid, maximum nuclear energy buildup as is outlined in Chapter 3. More energy would become available for the production of liquid fuels and more depletable and nonrenewable reserves could be earmarked for specific non-energy purposes.

Coal consumption would be lowered by 2 TWyr/yr--a considerable reduction. More important, it would allow the main coal importing Region III to loosen its dependence on the finite coal supplies of others. Nuclear energy expands only modestly in terms of market shares (from 23% in the High scenario to 29%; see also Table 59. Absolutely speaking, 1000GW(e) of additional capacity would be required, a certainly challenging effort, even if the analysis of Chapter 3 indicates that it could be done.

TABLE 59 Primary Energy, Enhanced Nuclear Case and High Scenario, 2030 (% 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 |

Fossil resource depletion as compared to the two scenarios would be somewhat less severe but still considerable. For instance, coal resources would be stretched by just 6 years in Category 1 and by 8 years in Category 2. An essential shift would occur in the liquids sector, where instead of 39% synthetic fuels and 61% oil the break up would be 31% synthetics, 55% crude oil, and 14% methanol of nuclear origin.

In summary, the Enhanced Nuclear case would take away some of the pressure on the fossil resource base invoking at the same time a large effort which would, on the supply side, have to overcome substantial infrastructural, institutional, and psychological constraints. Another prerequisite for its feasibility is that methanol-producing technology be commercialized in time.

The full impact of this case would be felt in the period after 2030. Provision of 14% of liquid demand from nuclear or solar energy would signal a first move in the direction of "endowments;" it would speed up the development towards an energy system where technologies "unlimited" by natural resource availability serve as the cornerstones of the world's energy supply.

## ECONOMIC IMPACTS OF THE STRATEGIES

The new energy supply systems will be characterized by an increasing capital intensity. In parallel, the capital costs of many other natural resources will enlarge. More capital will also be needed for improvements in agricultural production, the cleaning of the environment, expansion and improvement of all infrastructures, investments in new economic activities, etc.

If the energy industry is to be presented as one of many competing for the capital available it is necessary first of all to seek to grasp the order of magnitude involved in the switching to a new energy form. This is attempted below, but the figures presented must be taken with a pinch of salt. For uncertainties in projecting costs and prices are enormous, and the usefulness of these figures lies in their qualitative nature rather than in their quantitative face value.

The High and the Low scenarios were analyzed by using the IMPACT model described above. Both scenarios appear to require very large capital investments indeed: for direct energy investments in the Low case US$ (1975) 7 billion ($10^{12}$) for 1975-2000 and US$ 20 trillion for 2000-2030, representing 2.9% and 3.8% of the cumulative world gross product (GWP) during the two periods, and US$ 9 trillion, US$ 33 trillion, 3.1% and 3.9%, respectively, according to the High scenario.

The corresponding annual investment rates are given in Figure 83. With US$ 135 billion (or 2.2% of the GWP) needed in 1975, these annual investments would increase to a level of US$ 840 billion and US$ 1400 billion by 2030, in the Low and High scenarios, respectively. The monetary requirements of the world's energy system, here described in terawatts, are on the scale of teradollars. The share of gross world product this requires appears much less disconcerting than the scenario result that of the global energy investments necessary the developing regions would have to account for 32%-38% in 2000 and 40%-44% in 2030.

With cheap hydrocarbons being exhausted first investments for the harvesting of lower quality resources will grow faster than energy consumption. Significant structural changes in the industrial energy supply system will occur at the same time, and the distribution of such investments will be adjusted accordingly (Table 60). With the investments in synthetic fuels production and in nuclear plants and supporting facilities growing rapidly, total electricity-generation investment, measured in percent of total energy investment, will drop. Investment for renewable small-scale technologies will grow from 6% to 12%.

The two strategies require indirect investments as is shown in Figure 84, both in absolute terms and in percent of direct investments. Present indirect investments total US$ 22 billion/yr. They would increase to US$ 90 billion in the Low scenario and US$ 150 billion/yr in the High scenario. Indirect investments would peak between 2010 and 2020, preceding a maximum of direct investments 10 to 20 years later. In the developing regions, including Region VII, 35%-50% would be spent on the development of engineering and chemical industries. Most of the indirect investments in the developed regions (30%-35%) would go into ferrous metallurgy.

Table 61 summarizes total investments, both direct and indirect, 1980-2030. They could amount to US$ 30 trillion in the Low and US$ 46.5 trillion in the High scenarios, representing 3.9% and 4.1% of the gross world product. Investments in the energy system grow faster than GWP.

Developed and developing regions differ substantially. In the developing regions, which invested 2% of their GDP for energy

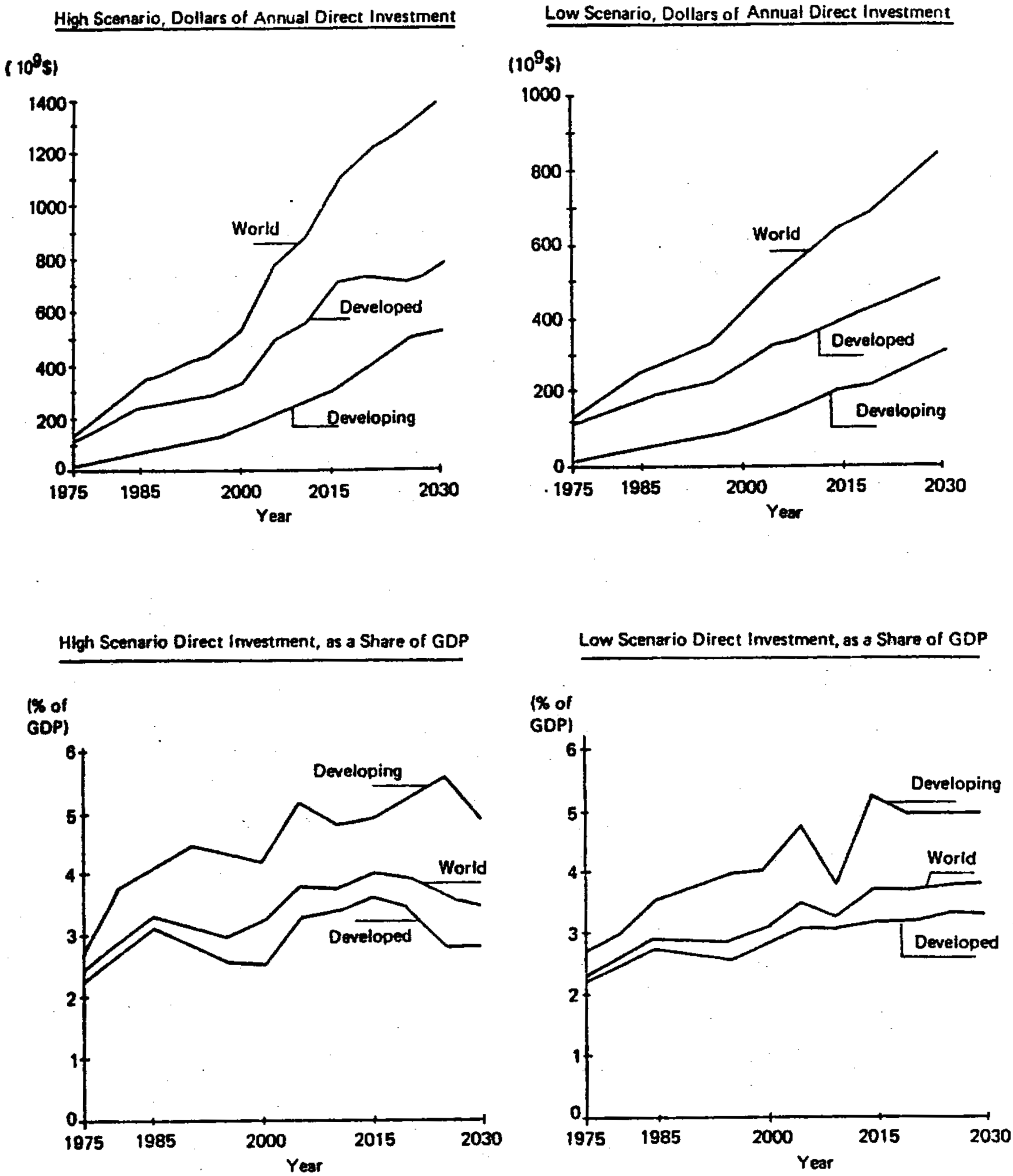



FIGURE 83 Direct annual investment requirements for energy supply systems for the two scenarios. These figures include requirements for energy supply and transportation facilities; they do not include investments in final energy consumption and investments in energy conservation.

TABLE 60 The structure of direct global energy investment, High scenario (in %).

| | 1980 | 2000 | 2020 |
|---|---|---|---|
| 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 | 6 | 12 | 12 |
| Total (%) | 100 | 100 | 100 |
| Total ($10^9$\$/year) | 238 | 580 | 1330 |

Note: "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.

purposes in 1975, investments in the energy system would reach a maximum of 6.1% of GDP in the Low scenario and 6.7% in the High. Region V has a slightly lower maximum investment level than the remaining developing regions, but will have to struggle with severe balance of payment problems due to its high oil imports (see also Figure 85).

The investment shares of developed regions are smoother and generally lower in contrast. Region III investments in the energy sector would not exceed 3% of GDP (the other regions might go up to 5%). This is due to the continuing high imports into the region. Maintenance of this import volume, as it grows from US$ 80 billion in 1980 to US$ 220 billion in 2030, will demand a substantial expansion of the export industry, which in turn requires investments that are not considered here.

In the *Nuclear Moratorium case* two main forces counteract. There is the switch away from a nuclear buildup and towards

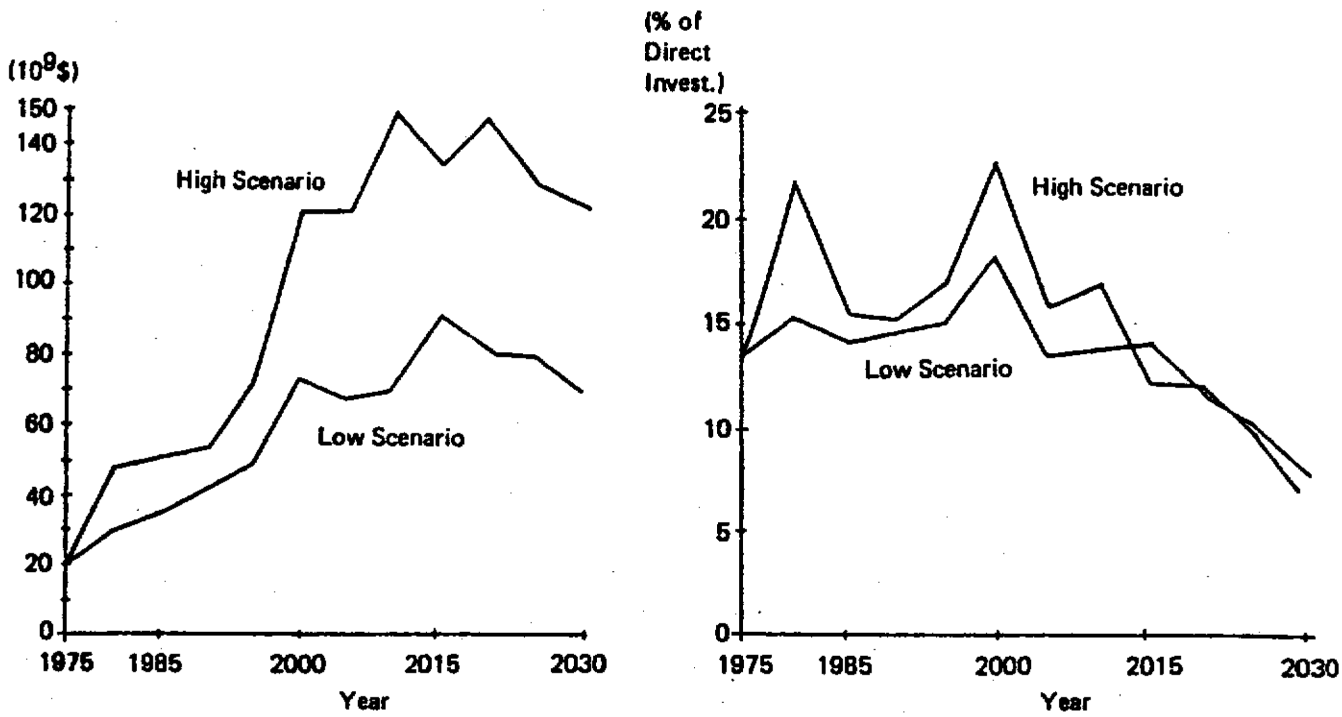



FIGURE 84 Global indirect investment. These figures include capital requirements for additional development of metallurgy, engineering, chemical, and other industries associated with implementation of the energy supply scenarios.

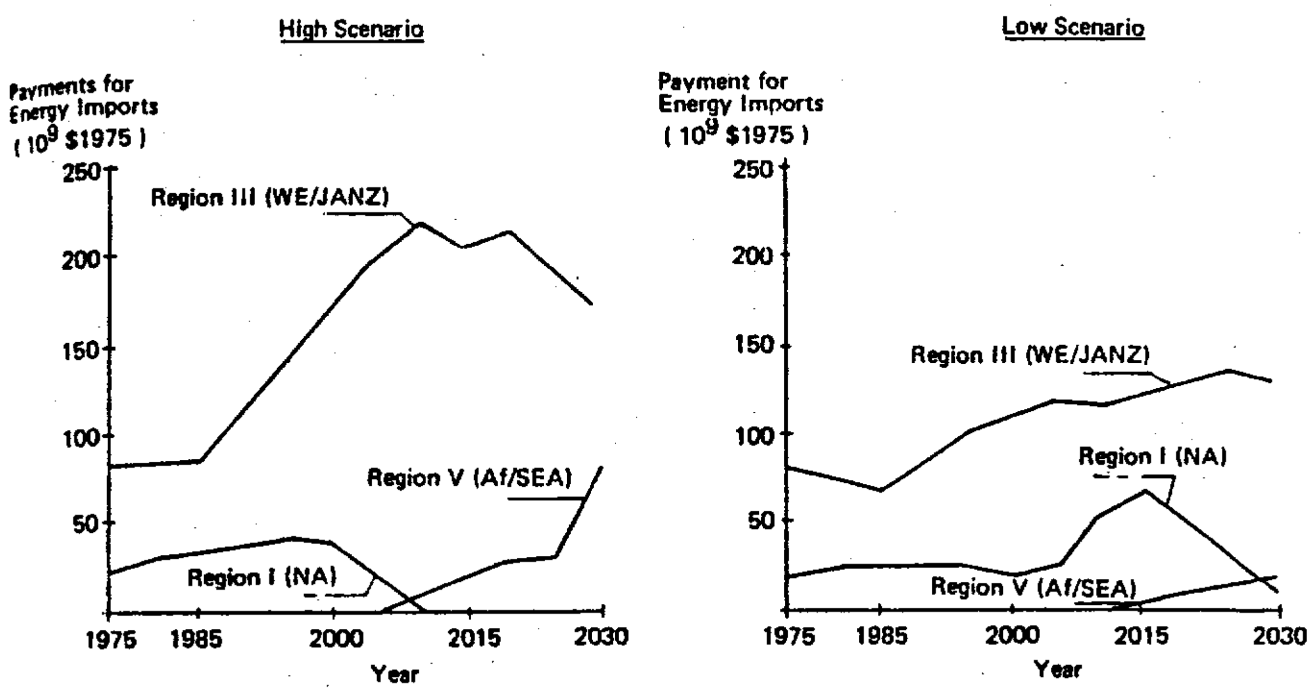



FIGURE 85 Costs of energy imports for the High and Low scenarios.

TABLE 61 Total (Direct and Indirect) Cumulative Energy Investment Requirements, 1980-2030.

| Period | Developed Regions[a] | | Developing Regions[b] | | World | |
|---|---|---|---|---|---|---|
| | High Scenario | Low Scenario | High Scenario | Low Scenario | High Scenario | Low Scenario |
| 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).

more coal, which will make the system less capital intensive. But the investment requirement will rise with the necessarily larger additions of expensive oil and gas. As a result, the nuclear moratorium case is less capital intensive over the next 20 years but requires substantial additional investments after 2000.

Altogether, cumulative direct investment is higher by US$ 4.6 trillion (by about 19%) than in the Low scenario. The largest share (US$ 3.3 trillion) must come from the developed regions. Worldwide indirect investments surpass those in the Low scenario by 24%, i.e., about US$ 0.9 trillion. Total direct and indirect investments would be 17% higher than in the Low scenario. Table 62 compares the investment data for both cases.

In contrast to the High scenario, the *Enhanced Nuclear case* would require direct investments that are larger by 8% in the developed regions and greater by 10% in the developing regions (excluding the oil producers in the Middle East and in North Africa). Worldwide, some US$ 3.4 trillion would be required, most of which after 2015, concurrently with a rapid large-scale introduction of the breeder. Indirect investments would be *lower*, both in absolute and relative terms, than in the High scenario. Table 63 highlights this comparison. In the

TABLE 62 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).

TABLE 63 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).

Enhanced case, the sum of direct and indirect investments would be only 6.5% and 8% higher in the developed and developing regions, respectively. The annual GWP needed for related investments would at most be 7.4%, compared with 6.4% in the High scenario.

## IMPACTS ON OTHER RESOURCES

Capital requirements is one dimension of the requirements and impacts of energy strategies. Another class of impacts, as important as the first, includes the requirements in terms of basic resources, that is, manpower, materials, energy, land, and water, or--to use the acronym coined by M. Grenon--the WELMM impacts of energy strategies. As we look at energy possibilities over the next fifty years, this class of impacts becomes especially important for two reasons. First, the natural resources (such as water, land, or materials) that are required by the various energy conversion and processing technologies will become ever more strained. Second, as lower quality, more expensive fossil fuels in particular are developed, both the natural and social resources needed to provide an additional unit of energy will increase. That is, energy will become more WELMM intensive.

The principal tools of the WELMM analysis are two data bases, a Facility Data Base and a Resource Data Base. The Facility Data Base, the more important in the case of the analysis described here, contains data in the form of resource requirements (water, energy, land, materials, and manpower) for various typical energy facilities. For most energy facilities such as coal unit trains, pipelines, tankers, conversion plants, or power plants it is not overly difficult to define a standard reference facility size to use in resource accounting. An exception arises in the case of coal mines as will be discussed below. For each facility the data are further divided into two sub-categories, a *construction* file describing the resource requirements associated with facility construction, and an *operation* file containing the impacts of operating the facility.

The data included were derived from four different types of sources. 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 were used, although they are generally more restricted in their scope and content. The third source of information was from questionnaires distributed to companies, research institutions, and public organizations. Some data were derived from an extensive literature search. To integrate all these data, each was assigned a quality rating according to Hittman's (1974) classification scheme, thus allowing us to account for differences in data reliability. The specific data management systems used to analyze and synthesize the data were the INGRES system developed at the University of California at Berkeley in the USA and the ENERTREE system developed at IIASA (Medow (1979)) which links the data base and the application programs.

In the case of coal mines, it is practically impossible to reduce the large number of coal mines to a few representative examples. Here the approach has been to develop *for each important coal basin* a few representative mines. The data sources here were primarily the literature (particularly environmental impact statements) and questionnaire responses.

The approach of the Resources Data Base was to begin with a given natural deposit and examine the region around it that would be affected by possible exploitation. However, this data base was only developed for the case of unconventional oil resources, and did not contribute to the analysis of WELMM impacts for other primary resources. Again the principal data sources were the open literature and questionnaire responses.

The IMPACT model could then use the WELMM data base, incorporating these various components in order to compute the order of magnitude of the resource requirements associated with the two scenarios. This was the approach followed for Regions III, IV, V, VI, and VII. For two regions, North America (Region I) and the developed planned economies (Region II), we employed the results of similar studies obtained by Bechtel Corporation (1978; Gallagher et al. 1978) and the Siberian Power Institute (Kononov and Makarov 1975).

*Manpower* for operation and construction of the global energy system would grow by 0.4%/yr until 2000 and by 0.7%/yr thereafter in the Low scenario and 1%/yr and 2.3%/yr in the High scenario. In 2030 some 13 million people (High) and 4.4 million people (Low) more than today would be engaged in the energy sector. Indirect manpower requirements would grow at 1.2%/yr in the High and 0.3%/yr in the Low scenarios. Figure 86 captures the dynamics of that development.

The Nuclear Moratorium case would by 2030 require 14% *more* labor than in the Low scenario, and the Enhanced Nuclear case would require 13% *less* manpower than in the High scenario.

The total labor force requirement (26 million to 42.5 million people) does not appear too serious a problem. However, the quality of the work force enlisted (Table 64) might be a criterion more difficult to meet; in the developing regions, for example, in the High scenario, some 9-10 million skilled workers, technicians, and engineers will be needed in 2030 in the energy sector alone.

Figure 87 summarizes the scenario *material and equipment requirements*. In the High case, material requirements (direct and indirect) would increase by a factor of 5.9, 1975-2030. The Low case would necessitate 30-40% less materials than the High. In both the material needed for chemical products would zoom up rapidly. The need for equipment will be even greater still, namely 7-12 times larger in 2030 than what is needed today for primary energy extraction facilities. The Nuclear Moratorium case increases material and equipment requirements in 2030 by 25% over the Low scenario. Twelve percent could be saved in the Enhanced Nuclear case as compared to 14% in the High scenario.

Figure 88 shows that the shares of materials and equipment in total world production would increase only slightly, except in the Nuclear Moratorium case. Apart from that, material and equipment requirements do not appear insurmountable.

The *energy* needed to produce these amounts of equipment and materials can be seen as constituting the indirect energy requirements of the strategies. In the High scenario, 1.85TWyr/yr (4.6% of demand) and in the Low scenario 1.1TWyr/yr (4.2% of

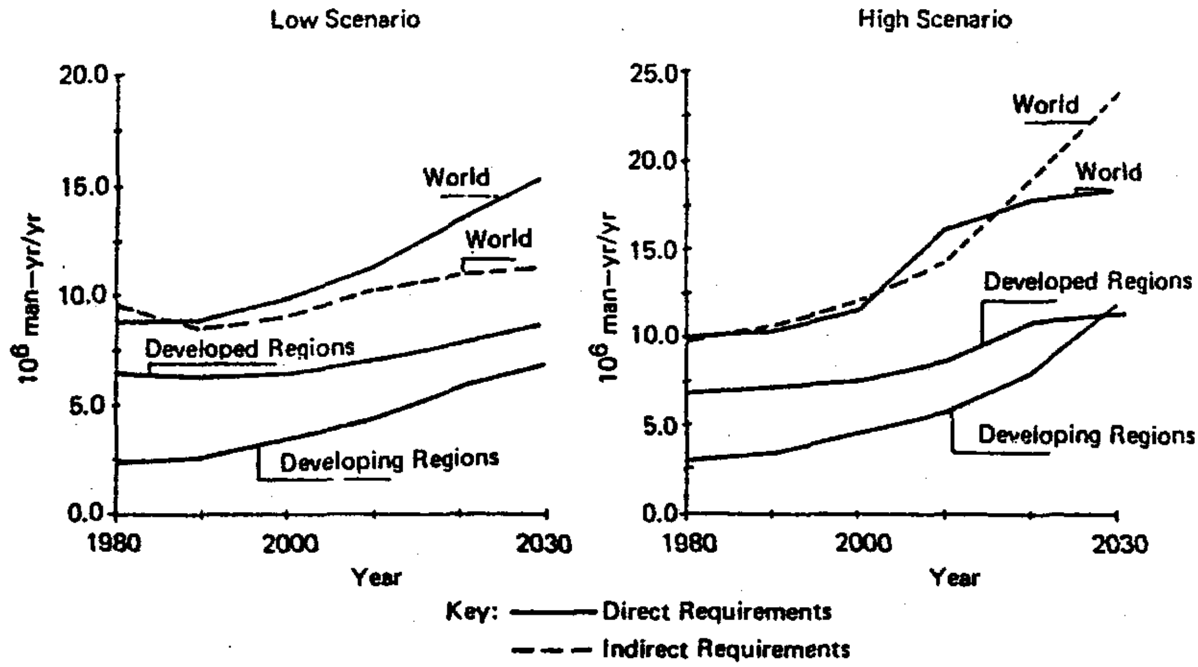



FIGURE 86 Total manpower requirements.

TABLE 64 Structure of Direct Energy Manpower Requirements for the High Scenario, 2030 (%)

| | 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).

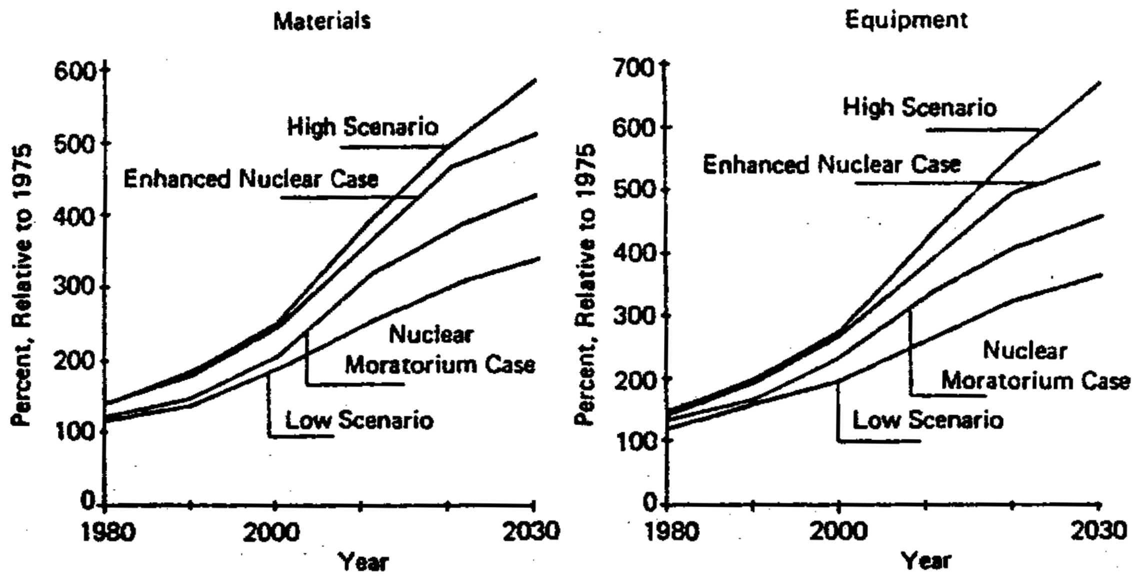



FIGURE 87 Aggregated global materials and equipment requirements for the scenarios and alternative cases.

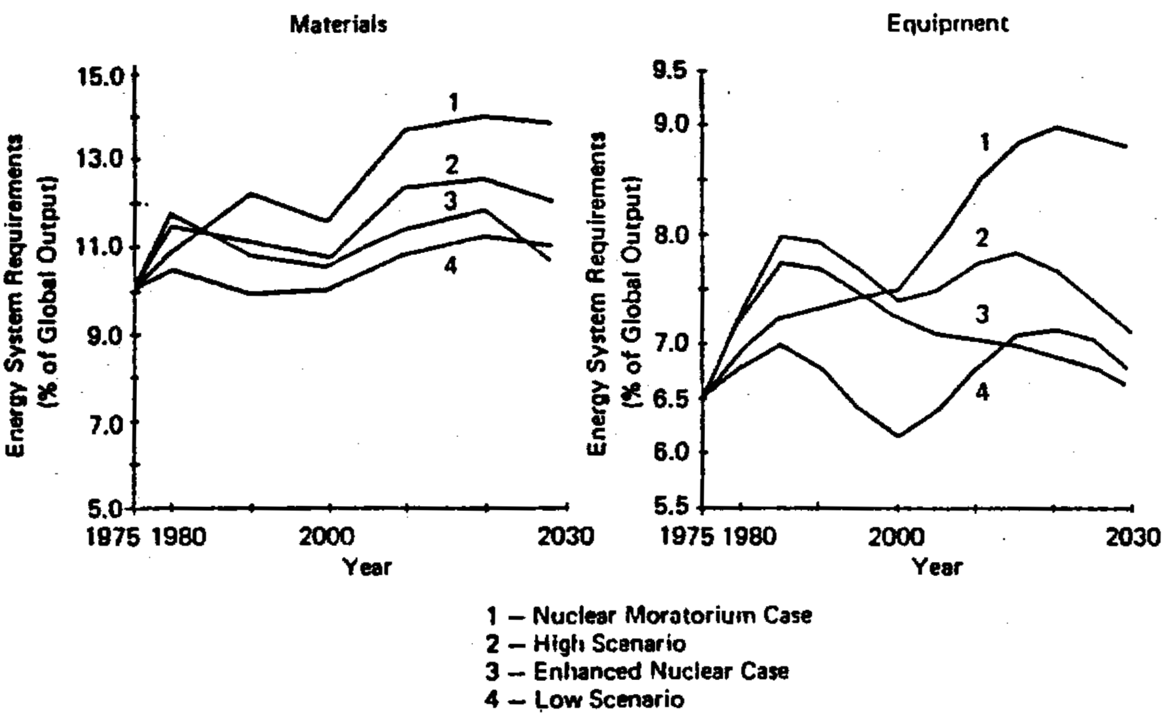



FIGURE 88 Energy supply system requirements as share of global output of materials and equipment.

demand) would be needed in 2030. The Nuclear Moratorium case adds 0.4TWyr/yr to the Low scenario 2030 figure; the Enhanced Nuclear case reduces the High scenario demand by 0.25TWyr/yr.

Table 65 illustrates the differences between the various strategies with respect to *land and water requirements*. The High and the Low scenarios would require in 2030 500,000km$^2$ and 330,000km$^2$ respectively and, in addition about 400,000km$^2$ to 750,000km$^2$ for nonexclusive energy use (e.g. power transmission). The Nuclear Moratorium case requires 25% more land for exclusive uses than the Low scenario, and the Enhanced Nuclear case 6% less than the High scenario.

TABLE 65 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).

About 80% of the water demand would originate in the developed regions, where this requirement might become a very severe constraint indeed. This situation is somewhat better in the Nuclear Moratorium case but less so in the Enhanced Nuclear case: nuclear power plants require 30% more water than fossil fired plants.

## A FINAL COMPARISON OF THE STRATEGIES

Enough capital and basic resources would be available for the world to take the Low scenario path. In doing so it would shift the problems to the second half of the 21st century, however. The High scenario, in contrast, presupposes a significantly higher economic activity and exhausts resources more quickly. Difficulties in providing enough capital might arise in 2005-2020. The Enhanced Nuclear case on the other hand, would be slightly more capital intensive than the High scenario, but would somewhat relieve the pressure on resources (except for water demand). In terms of materials and equipment requirements it would have an edge over *all* other cases. In contrast, the Nuclear Moratorium alternative is, relatively speaking, the most intensive case in terms of capital, labor, and material.

In all the cases considered, the requirements for capital, labor, and materials rise much faster in the developing regions than in the developed regions. These requirements taken together, will increase from 20-25% at the present time to 40-50% by the year 2030. Thus, availability of capital, skilled manpower, and investment goods are likely to become constraining factors worldwide. Balance of payment problems that are due to substantial import requirements for equipment and resources might aggravate the situation.

# 6 SYNTHESIS

## SUMMARY IN TEN POINTS

The main objective of our work under this contract has been to develop and apply a method appropriate for comparing alternative energy options. In view of the changing energy systems of most of the nations and their growing interdependence, a global approach to a "comparison of energy options" has been mandatory. This approach was bound to lead to a long-term study period of some 50 years--for only over the long run can the consequences of alternative global energy strategies be adequately conceptualized and assessed.

The first few chapters of this report were concerned with energy demand, energy supply technologies and related resources--or options for short--and the constraints upon their deployment. These were the elements presumed to determine in one way or another the process of striking a balance of energy demand and supply over time. The tools we used to identify "optimal" solutions to this balancing problem over a time horizon of half a century were discussed under the heading of energy strategies.

We used this kit of basically a set of distinct computer models to quantify two global scenarios, called Low and High, specifying two different conceivable evolutions of seven comprehensive world regions. Each region is characterized by demographic and technoeconomic parameters. The fact that not just one but two reference cases of different economic growth were explored is indicative of the big uncertainties involved and of the "decisions yet to be made" that any meaningful attempt at quantifying the future must account for. One of the most important methodological achievements of this study was a rather extensive separation and disentanglement of the various types of uncertainties entering any long-term projections.

For reasons of uncertainty, not even all of the technically identified constraints could be incorporated in the process of designing "optimal" energy supply-demand balances. Strictly speaking, the supply scenarios are the results of cost optimizations within estimated deployment limitations (e.g., buildup rates). Some of these limitations, such as those imposed by economic interaction, were explored and, to some extent, were made internally consistent through an iterative procedure. Other limitations or constraints, particularly social, institutional, and political factors, entered the analysis in the form of assumptions or were treated as potential problems. An example of the latter is the climatological impact of a buildup of atmospheric carbon dioxide, which as such was not considered in the allocation of fossil energy production capacity in the supply scenarios.

This chapter is meant to give a synthesis of the results. To this end we should first of all look at the most crucial assumptions and acknowledge the "new" problems that the scenarios have brought forward.

In a broader sense, the scenarios are conceptualizations rather than projections of the future. They are neither the likely nor the inevitable paths of evolution. Rather they depend on the realization of certain, difficult to achieve conditions outside the energy domain. They imply informed and rational decisions of the energy sector that are taken on a worldwide basis. These scenarios can therefore not be separated from the process of describing real world behavior by formalized computer models.

Ten observations are given below which briefly summarize the results we obtained comparing alternative energy options. These observations also illustrate both the possibilities and the limitations of the analytical method that has been developed under this contract.

- *A balance between global energy demand and supply within a time frame of the next five decades is possible, but the energy problem is likely to influence decisively the world's economic development.*

Table 66 gives the per-capita economic growth rates for the High scenario and the Low scenario, 1975-2030. These scenario pathways of economic development largely fall short of current aspirations and plans, in particular of those for the developing regions of the world. The growth rates in Table 66 were obtained after several iterations involving downward revisions of initial projections as a response to excessive pressure on the energy supply potential. For higher economic growth paths, the demand for a rapid buildup of new energy supply capacities would have exceeded reasonable limitations, even under very optimistic assumptions about energy conservation.

- *In fact, energy conservation appears to be a permanent necessity. But energy conservation is limited by energy's function of serving as an indispensable production factor in the development of general economic productivity.*

Improvements in technical energy efficiency have a long history in the developed countries. There has been impressive progress along this line since the first industrial revolution

TABLE 66 1975 Per Capita GDP, Historical and Projected Real Growth Rates for Two Scnenarios 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 1975-2000 | High Scenario 2000-2030 | Low Scenario 1975-2000 | Low Scenario 2000-2030 |
|---|---|---|---|---|---|---|
| I (NA) | 1.9 | 7,046 | 2.9 | 1.8 | 1.7 | 0.7 |
| II (SU/EE) | 6.7 | 2,562 | 3.6 | 3.2 | 3.1 | 1.9 |
| III (WE/JANZ) | 4.0 | 4,259 | 3.0 | 1.8 | 1.7 | 0.9 |
| IV (LA) | 2.9 | 1,066 | 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 | 1,429 | 3.8 | 2.8 | 2.4 | 1.2 |
| VII (C/CPA) | 5.1 | 352 | 2.8 | 2.4 | 1.6 | 1.4 |

NOTE: All growth rates are average annual growth rates (rounded) over the time period shown; actual projections have decreasing growth rates.

(Figure 89). For some technologies with rather high efficiencies further progress will have to come slowly; but overall the prospects for additional technological improvement are substantial. Figure 89 suggests that technological progress adaptable to economic conditions is a time consuming process.

However, the technical potential for energy conservation must be considered separately from what could be called the "energy efficiency" of an economy. Economic development in this context is the result of deploying an increasing number of technical devices per head of population, which in turn requires more energy to run this equipment. Consequently, a substantial "decoupling" of energy growth from economic growth due to technological progress will be confined to those economies already availing themselves of a high per-capita level of productive technical equipment. In these cases only may savings in the operation of existing capital stock outweigh the incremental energy demands that must be met in order to operate such additions to the productive capital stock. Figure 90 is a historical representation and quantification of this process for the seven world regions considered.

Figure 90 contains the projected energy intensities (Low scenario) for the seven world regions as a function of the development level, given as economic productivity in terms of GDP per capita. The projections are optimistic in two respects. In highly developed regions saturation in energy-intensive equipment and improvement in technical efficiency combine into a significant decoupling of energy growth and overall economic growth. For the less developed regions the economic viability of energy efficient advanced basic technologies is taken for granted; hence much less energy is postulated as being invested in the early development of the developing countries than in the first few decades in the developed nations.

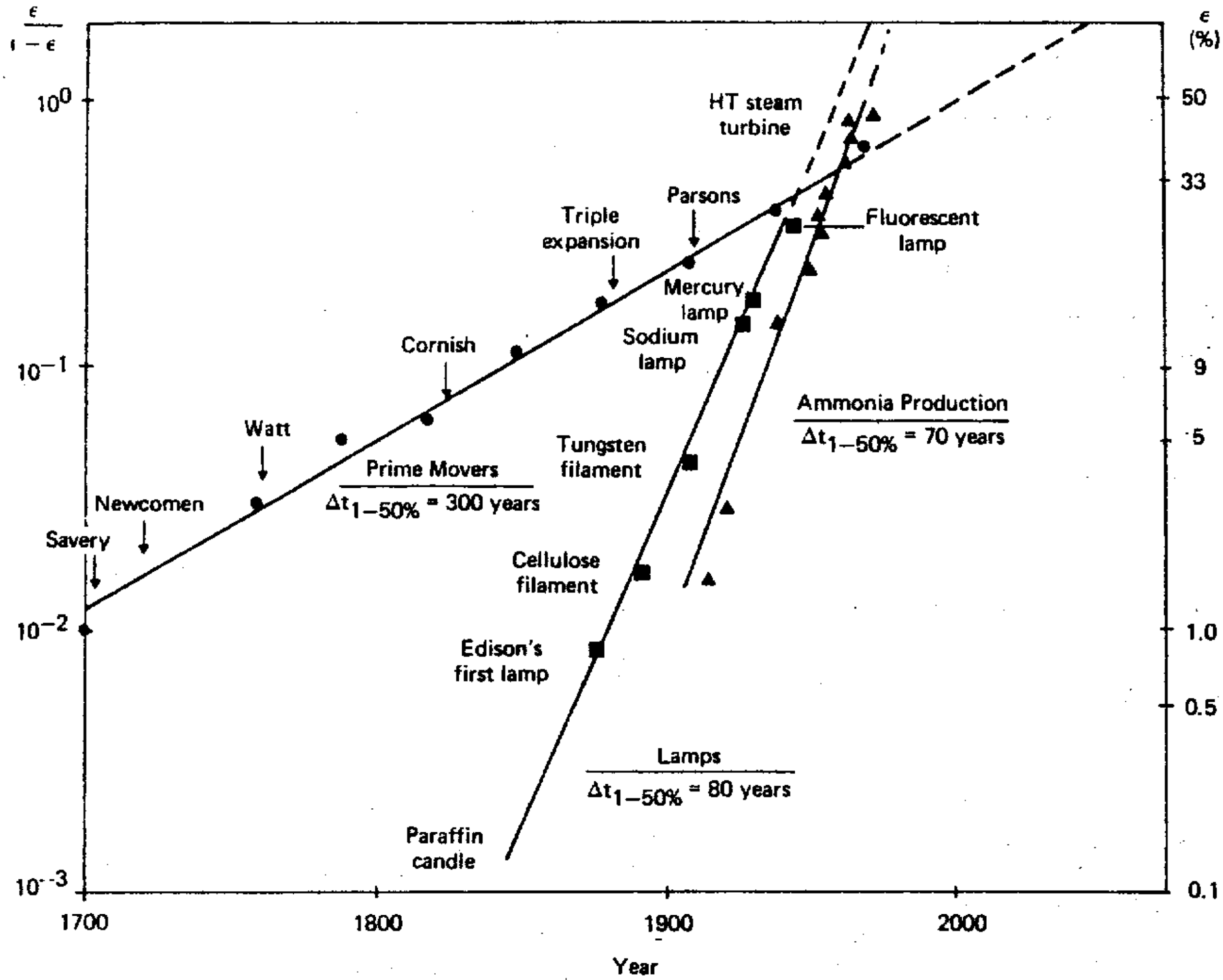



FIGURE 89 Historical trends in efficiency ($\Delta t_{1-50\%}$ is the time necessary to evolve from 1% to 50% efficiency; ε is second law efficiency).

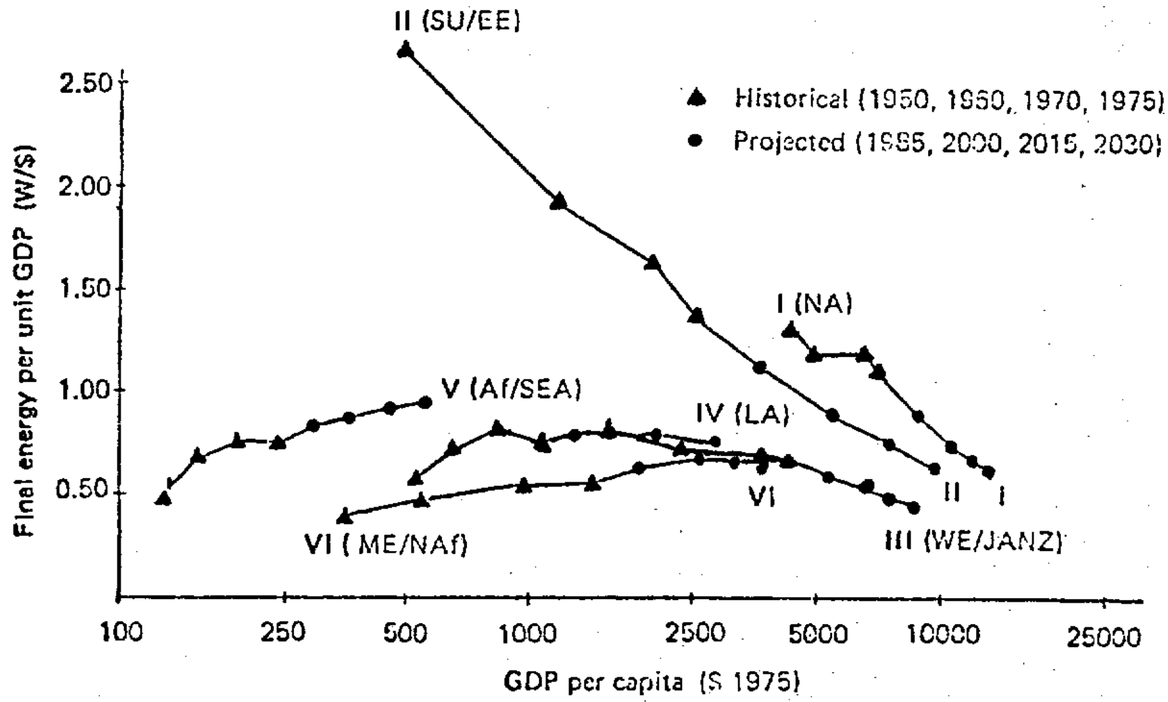



FIGURE 90 Energy intensity in different world regions, Low scenario.

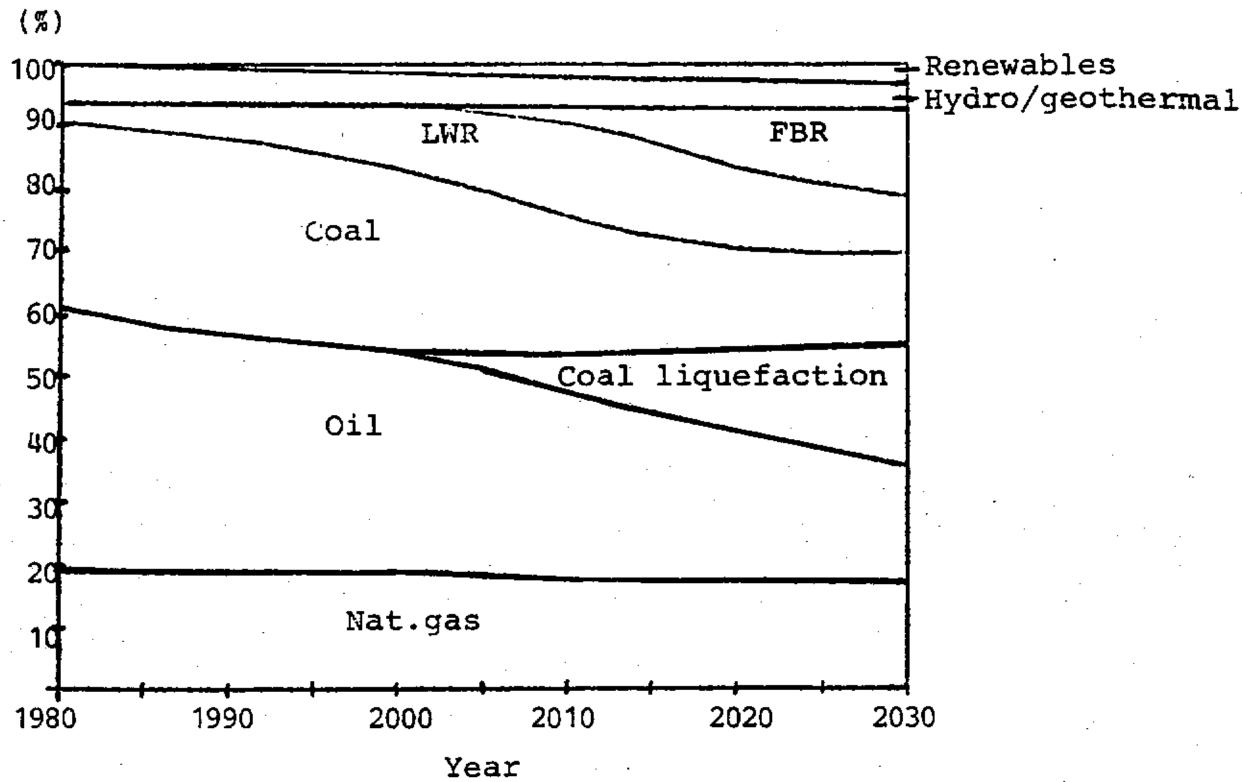



FIGURE 91 Primary energy (or equivalent) supply, world; High scenario, 1980-2030.

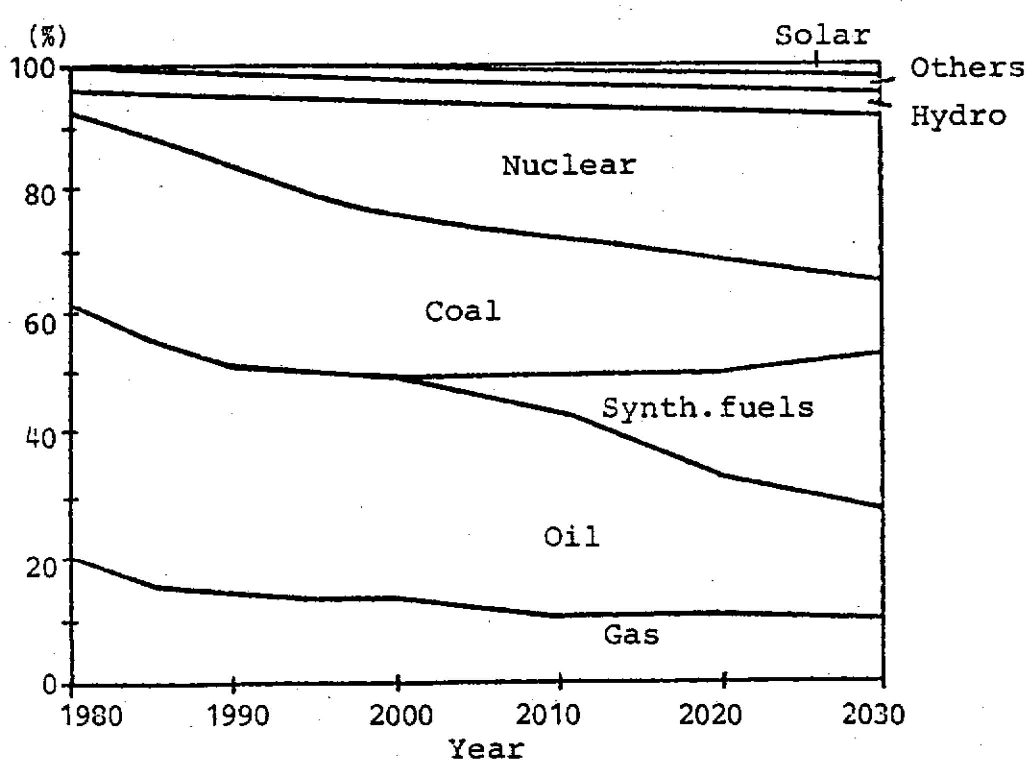



FIGURE 92 Primary energy (or equivalent) supply, world; Low scenario, 1980-2030.

- *The overall global energy demand in the two reference scenarios presupposes an essentially unrestricted access to all the world's energy resources.*

In the same way that the availability of advanced production--and energy conservation technologies for that matter--is postulated for all the world regions, the supply scenarios are based on the unrestricted availability of supply technologies. With the exception of classical oil resources largely controlled by Middle East/North African oil exporting policy, energy production from all other sources for meeting the calculated pattern of final energy is allocated according to "cost prices Figures 91 and 92 give the respective shares of primary energies for the High and the Low scenarios.

Our considerations in projecting regional economic development and consequently energy demand were based on the fundamental interdependence of the principles governing general trade." and the exchange and transfer of technology with the principles governing energy trade and exchange. The balance between demand and supply that we attempted to strike in the scenarios rests on that basic interdependence. It by and large excludes restrictions on the production of energy resources that are due to increases in the economic value of the resources over time.

- *Although the resource base is limited it is crucial to vigorously develop an additional fossil energy supply capacity.*

The physical size of the future energy problem is captured by Table 67 reproducing the--cost-oriented--scenario allocations of the various fossil and nonfossil energy sources in terawatts. There is a marked contrast between these supply scenarios and the recent changes and trends in world energy markets. According to the scenarios, the contributions from all the sources, including oil, will have to be expanded during the next five decades. The rate of growth of each source that this larger supply capacity would require appears prohibitive. And what if this balanced pressure as quantified in Table 67 were assumed not to materialize and the distribution of the sources were rearranged? Then, by using somewhat different cost estimates, for example, or by allowing for certain national resource conservation policies, even higher burdens would be put on some of them. But, in fact, there is no option in the sense that some sources could be chosen and others be discarded completely.

- *Among the various energy sources, fossil resources will play the main part in meeting the global energy demand over the next 50 years. Their extensive use is confined to this intermediate period however.*

Both the exceptionally optimistic estimates for ultimately recoverable resources of oil, gas, and coal and the cumulative consumption of these resources in the High and the Low scenarios are given in Table 68. The resources in cost categories 1,2 and 3 total as much as 3000 TWyr, which is about 3 times higher than the (presently known and indicated) economically viable fossil

TABLE 67 Two Supply Scenarios, Global Primary Energy by Source, 1975-2030 (TW)

| Primary Source[a] | 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 | 4.95 | 11.98 | 3.93 | 6.45 |
| LWR | 0.12 | 1.70 | 3.21 | 1.27 | 1.89 |
| FBR | 0 | 0.04 | 4.88 | 0.02 | 3.28 |
| Hydro | 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 is counted in coal figures.

[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.

TABLE 68 Cumulative Uses of Fossil Fuels, 1975 to 2030, High and Low Scenarios

| | Total Resource Available[a] (TWyr) | High Scenario Total Consumed (TWyr) | High Scenario Remaining Resource (years)[d] | Low Scenario Total Consumed (TWyr) | Low Scenario Remaining Resource (years)[d] |
|---|---|---|---|---|---|
| Oil | | | | | |
| Cat. 1+2[b] | 464 | 317 | 22 | 264 | 40 |
| Cat. 3 | 373 | 4 | 54 | 0 | 74 |
| Natural Gas | | | | | |
| Cat. 1+2 | 408 | 199 | 35 | 145 | 76 |
| Cat. 3 | 130 | 0 | 22 | 0 | 38 |
| Coal[c] | | | | | |
| Cat. 1 | 560 | 341 | 18 | 224 | 52 |
| Cat. 2 | 1019 | 0 | 85 | 0 | 158 |

[a]Total resources, including to be discovered, as of 1975.

[b]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$/ton
cat. 2: 25-50$/ton.

[c]Coal use includes coal converted to synthetic liquids and gas. For coal, only a part of the ultimate resource (~15%) has been included, because 1) the figures are already very large for the time horizon of 2030; and 2) there are too many uncertainties on the very long term coal resources and production technologies.

[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.

reserves. Cost categories 2 and 3 encompass "unconventional" energy forms; unconventional by type, location, or production technology. In spite of a significant contribution by nonfossil sources (Figures 91 and 92), conventional fossil reserves will practically be used up by 2030 in the supply scenarios. Only coal of category 1 will have another 18 or 52 years for meeting the specific demand after 2030. The exhaustion times of all the unconventional fossil resources at the end of the study period are so low--at least in the High scenario--that a much speedier change in the energy infrastructure will be needed for them after that cutoff point.

It is appropriate to say that energy strategies for implementing a supply systems in a way described in Figures 91 and 92 would not solve the long-term basic energy problem by 2030. These strategies largely shift the transition to nonfossil energy sources to the next generations. For them it would be more difficult to make this transition, as the scenarios use up the better part of the easily accessible fossil resources. Thus the essential safety margin needed to compensate for unexpected difficulties would be significantly lower after 2030.

- *During the next 50 years nuclear energy largely contributes by stretching the availability of fossil energy. In electricity production it substitutes for low-grade fossil energy, in particular coal.*

The baseload electricity for the conservation societies assumed in the High and the Low scenarios requires a nuclear contribution to the global energy balance of 20% (thermal heat equivalent) already shortly after the year 2010. If nuclear energy from fission is to be maintained as a potential long-term energy source thereafter, fission breeders must be introduced early. The resource situation of natural uranium would foreclose a wider substitution of fossil energy for conventional nuclear energy production beyond 2010 or 2020--a time when fusion will not yet be able to supply energy on a relevant world scale.

Since the nuclear option is able to provide a broader non-depletable future energy base by the breeding of fissile material--which is contingent upon the establishment of a nuclear fuel cycle--nuclear strategies have to be oriented towards long-term goals. Any comparison of the fossil and the nuclear options therefore is particularly difficult and ambiguous--a dilemma that we also faced and could not really solve with the methodology of this study.

- *Excepting direct conversion of incident solar radiation one finds that all other renewable energy sources provide a rather limited supply potential. Their valuable but small contribution to the global energy balance by 2030 is 10-15%.*

The amounts of power natural systems dissipate in the form of biomass, wind, warm or cold ocean currents, or continental run-offs are very large considering man's energy needs. Practically all of these natural power flows constitute patterns of nature, however. Thus for reasons of system stability only limited fractions thereof might be diverted for man's purposes--disregarding the fact that man's hold on or reach for these systems can at best be limited (in the case of atmospheric motion only the power flows in the thin boundary layer between the atmosphere and the land or the sea can be tapped). Last but not least, natural power flows are stochastic processes; and man's energy needs more often than not originate from the partial absence or failure of natural phenomena on which we normally live. Instead there is the need to convert, store, and transport energy that is derived from rather dilute sources. Table 69 puts all these factors together summarizing the technically and practically realizable potentials of renewable energy sources. Measured in oil equivalent, the practically realizable potential of renewables is about 1.5 times the world's present energy consumption level. The term "practically realizable" refers to an all-out effort neglecting economic constraints. Exploiting these sources at what appears a reasonable level would cover a limited fraction of the global energy supply and demand balance. The scenarios indicate that some 20-30% of the practially realizable potential would be absorbed by 2030.

Large-scale direct uses of solar radiation, that is most likely centralized electricity and hydrogen production from desert areas, come into focus only after our cutoff point. Note that the methodology developed is not suitable for assessing whether the long-term solar option would be a partner or a competitor to nuclear energy.

- *Over the next 50 years, primary energy sources will hold relative shares that are nearly identical in the High and the Low economic growth scenarios.*

This outcome reflects the low flexibility of a large techno-economic system striving for efficient resource allocation. It is important to recall that the near identity of Figures 91 and 92 is clearly not maintained for each subregion on the globe. Both the timing and the relative size of the contributions of new energy sources vary between regions in the High and the Low cases. Moreover, interregional energy trade and thus the burden of adequate energy supply are distributed differently among the two scenarios.

On a global scale, however, it becomes obvious that energy conservation by cutting back economic growth does not buy time for decisions necessary for the buildup of an intermediary fossil supply solution.

- *The buildup and maintenance of new energy supply capacities presupposes a solution to the problem of capital formation and transfer.*

All the alternatives to present energy production from classical resources are capital intensive and greatly raise the share of energy-related investments in national capital formation. The faster these expensive energy technologies have to be built up, the bigger is the burden on a given economy. Figures 93 and 94 relate the direct and indirect annual investments for energy

TABLE 69 Comparison of Technical and Realizable Potentials.

| Source | Technical Potential (TWyr/yr) | Realizable Potential (TWyr/yr) | Constraint | 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% 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<br>0.005 | 0 | Computational | Amount available insignificant compared with uncertainties of other estimates. |
| Total | ±15 | 9.6 | | |

[a]Not included in Table 22. For general discussion see this chapter's section on the Solar Option.

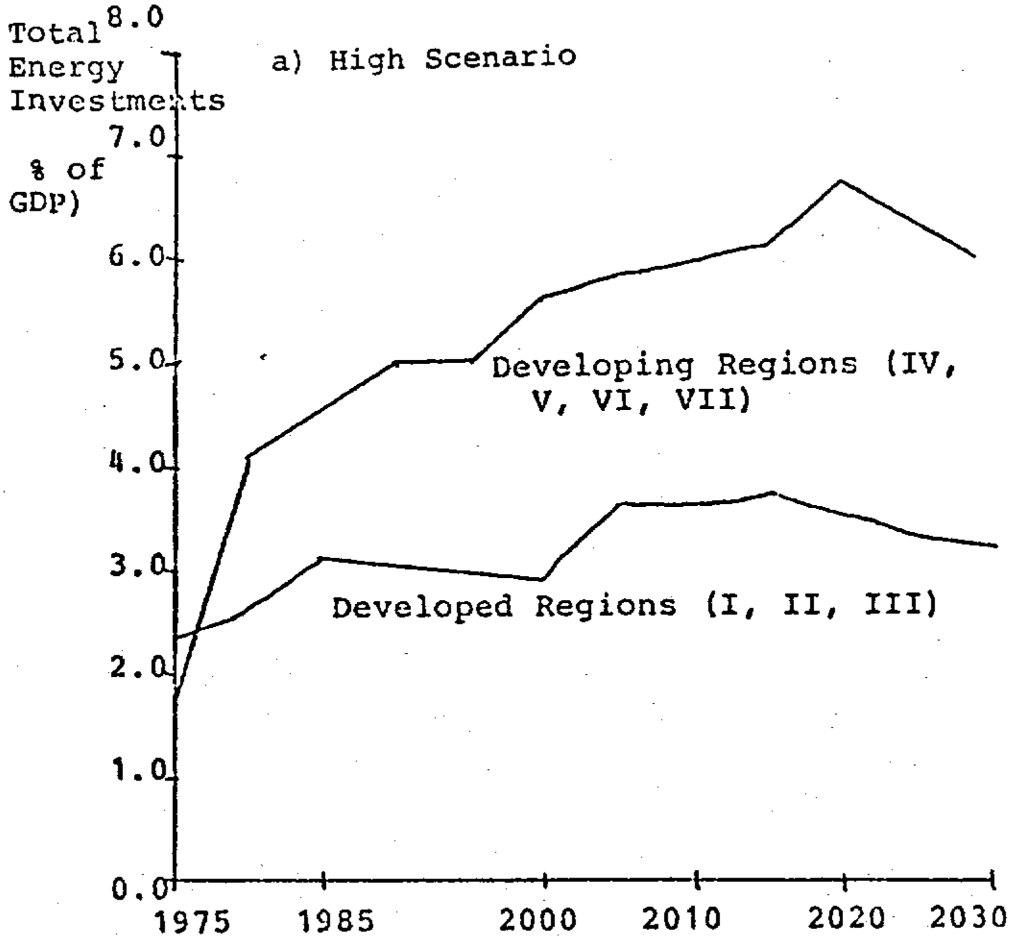



FIGURE 93 Total (direct plus indirect) energy investment as a share of GDP.

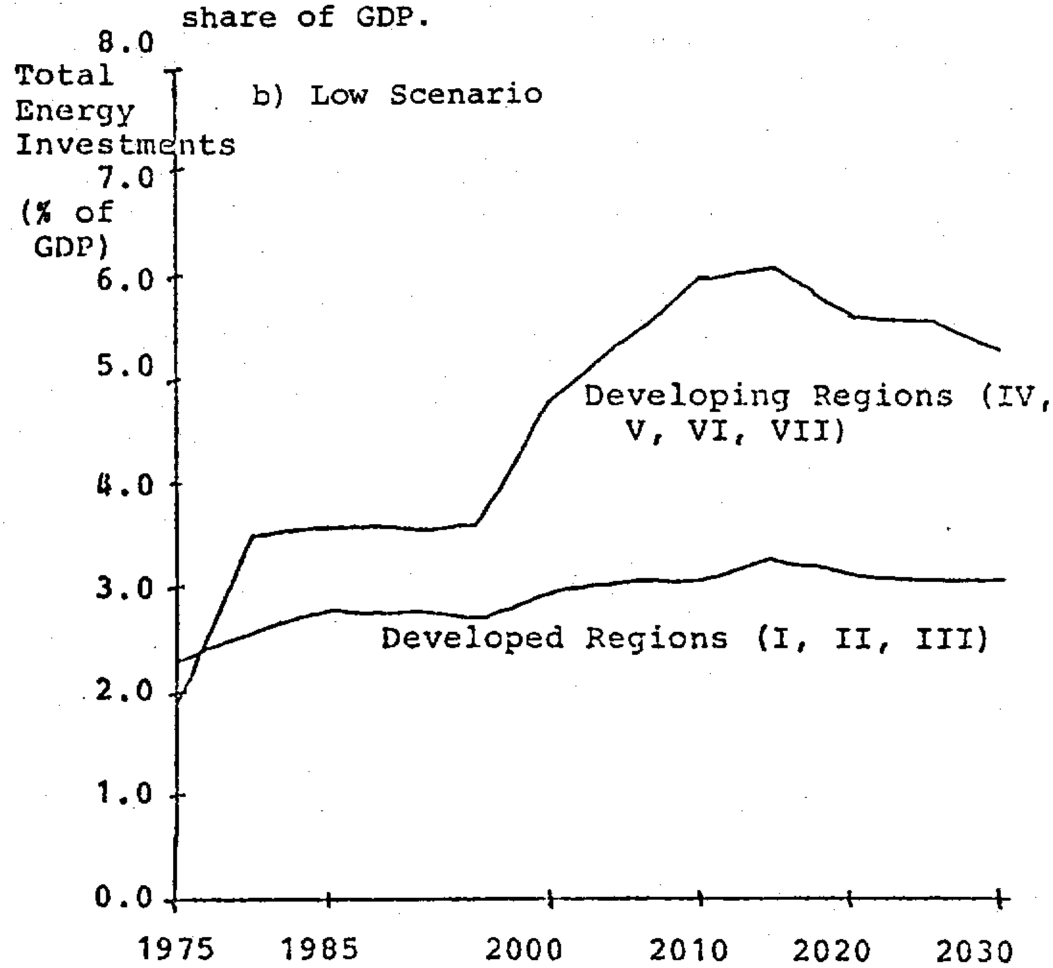



FIGURE 94 Total (direct plus indirect) energy investment as a share of GDP.

to the economic outputs in the two groups of regions. Thus energy investments will have to grow quickly particularly in the developing regions. Nevertheless, the fractions of GNP required for a timely buildup of new energy supply capacity still appear feasible, in particular for the developed countries. However, the process of aggregating and averaging the information over developed and developing regions hides a much higher spread that exist for each region. In fact, extreme capital investments must be expected on the national levels due to the unequal distribution of fossil resources: most of the global energy capital derived from the supply scenarios will have to cross borders, flowing to countries with unconventional fossil resources. This result points to an unprecedented problem of international monetary control.

Over and above the funding aspects of new energy supply technologies there are the implications of investing into energy conservation. Like the renewable energy sources or like nuclear power, energy conservation suffers from a front loading of capital--the more so the bigger the conservation effort. Our demand scenarios imply a considerable amount of conservation (see the comments on Figure 90 above) by the postulate of an ever increasing sophistication of the general economic infrastructure. A balanced strategy in this context then is one where the costs of energy saving equipment eventually do not exceed the costs of incremental additions of new supplies. While this condition cannot be verified with the methodology of the present analysis, one can conclude that the capital requirements for the conservation efforts not included in Figures 93 and 94 will be of the same order as those calculated for the energy supply. This might well double the capital problem of the developed regions towards the end of the 50-year horizon. These questions of capital formation and transfer cannot be answered by a methodology geared mainly to the comparison of alternative energy options.

- *Any solution to the world's energy problem entails significant impacts on the global environment. Recognition of the limits of stability of environmental systems or their active stabilization are postulated. Such adaptations or stabilization efforts are not inherent in the global demand-supply scenarios considered.*

A critical global feature of an intermediate fossil energy phase is the carbon dioxide buildup. The increases in atmospheric $CO_2$ concentration monitored for the past 20 years are attributed mainly to the combustion of fossil fuels. We should take this buildup as an early sign of warning, although the reliability of the explanatory models presently available is not yet well established. As regards the possible climatic consequences of our scenarios, it is for these reasons that the calculated increases in atmospheric carbon dioxide concentration and the related temperature change for the High and the Low supply scenarios (Figures 95 and 96) indicate a risk rather than predict a likely consequence of growing fossil fuel consumption.

a) High Scenario

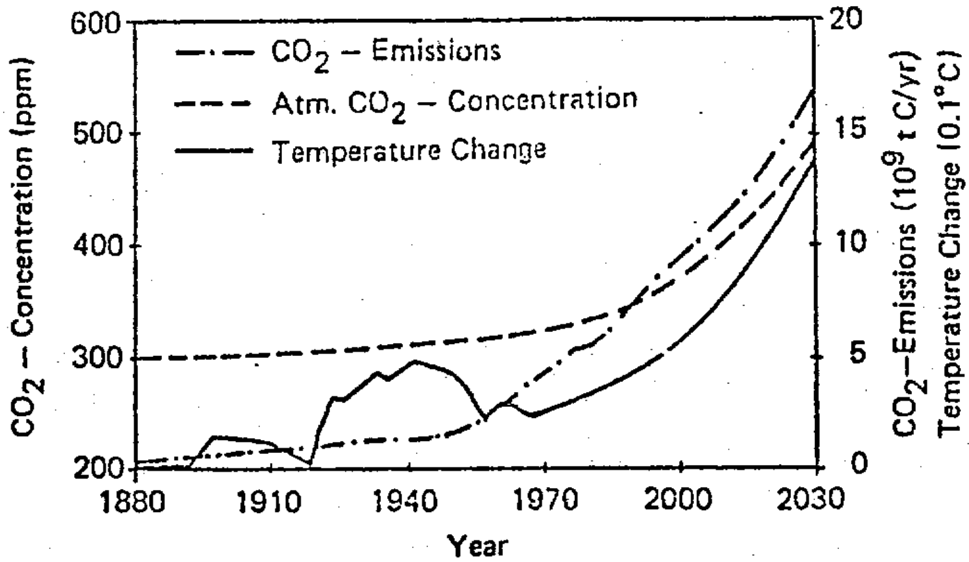



FIGURE 95 $CO_2$ emissions, atmospheric $CO_2$ concentration and temperature change.

b) Low Scenario

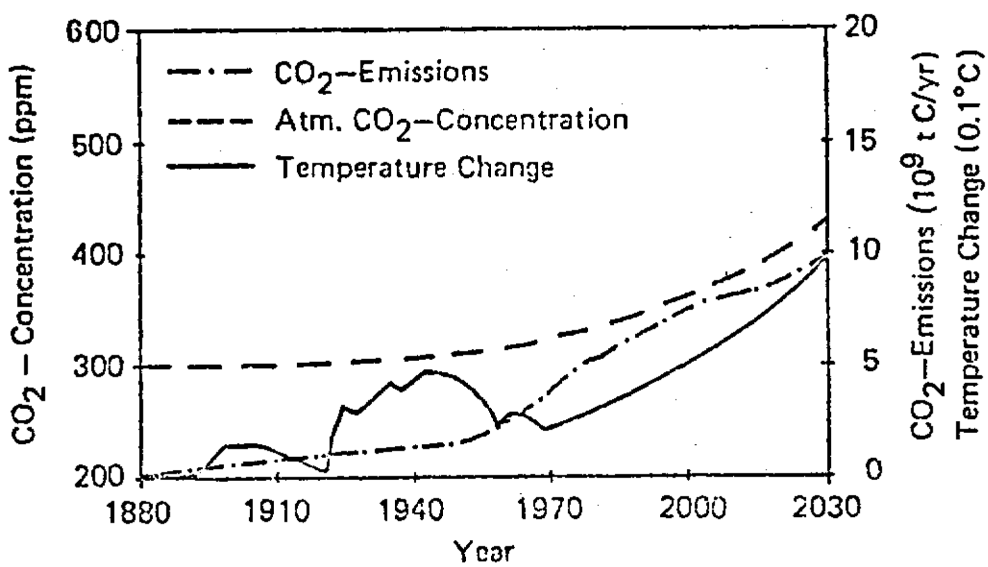



FIGURE 96 $CO_2$ emissions, atmospheric $CO_2$ concentration and temperature change.

A comparable uncertainty about the actual levels of risk and their acceptability exists for the contributions of the nuclear option in the scenarios and, no doubt, also for the rather modest scenario allocations of renewable energy sources. A yield of 4-6 TWyr/yr from biomass, wind, hydropower, and local small-scale solar heat translates into average yield densities of about 0.1 watt per square meter of inhabitable land. This rate, which is close to estimated average sustainable yield densities of natural forests, implies an all-out effort in ecological terms. Rigorous exploitation of a major fraction of all biomass or of the global continental run-offs, or of wind, wherever to be found and used reasonably, would mean to transform nature into a world "garden." What consequences such a recourse to renewables will have and how viable it will be, in the face of competing land use requirements, for example, cannot be assessed so far.

These ten points taken together clearly transpose the global energy problem from the energy "subsystem" into other areas that interact with it. It is in these other areas that the validity of the assumptions structuring our scenarios must be evaluated.

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