ENERGY IN A FINITE WORLD

Executive Summary

Report by the Energy Systems Program Group of the International Institute for Applied Systems Analysis
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Executive Reports bring together the findings of research done at IIASA and elsewhere and summarize them for a wide readership. The views or opinions expressed in these reports do not necessarily reflect those of the National Member Organizations supporting the Institute or of the Institute itself.

This report is based on *Energy in a Finite World: Paths to a Sustainable Future*, Report by the Energy Systems Program Group of IIASA, Wolf Häfele, Program Leader, written by Jeanne Anderer with Alan McDonald and Nebojša Nakićenović. This latter report is a book for the general reader based on a more technical volume *Energy in a Finite World: A Global Systems Analysis*, also prepared by the IIASA Energy Systems Program Group. Both volumes were published in 1981 by the Ballinger Publishing Company, Cambridge, Massachusetts 02138, USA.

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FOREWORD

Two realities are clear:

- The difficulties associated with supplying and using energy are not temporary; they will continue, and we must learn to deal with them.
- The energy problem is inherently global; no nation is untouched, nor can any act in isolation.

Yet while the energy problem goes beyond the 20th century and transcends national borders, analyses tend to follow suit only selectively. Short-term pressures seldom permit the luxury of concentrating as much on the year 2020 as on 1985, or of being truly global in an analysis. Still, opportunities do arise.

This report summarizes the results of a seven-year study conducted at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. The work, which involved over 140 scientists from 20 countries, aimed to provide new and critical insights into the international long-term dimensions of the energy problem. Given this objective, the 50-year period from 1980 to 2030 was analyzed in detail, though parts of the study looked even further into the future. Geographically, all countries of the world were included – developed and developing, market and centrally planned economies.

The results are described in *Energy in a Finite World: Paths to a Sustainable Future* published in 1981 by the Ballinger Publishing Company, Cambridge, Massachusetts, USA; more detail is provided in a second volume also from Ballinger: *Energy in a Finite World: A Global Systems Analysis.*

The picture that emerges is one of a world facing, during the 1980–2030 period, what is anticipated to be the steepest ever increase in its population. At the same time, the developing regions of the world, in which most of this population growth will occur, will be trying to close the economic gap separating them from the developed regions. Despite the resultant strains on the world's physical resources, on its institutions, and on human ingenuity, the conclusion is that the physical resources and the human potential exist to provide the energy for a 2030 world that is more prosperous than the world of today while supporting a population double that of 1975. Moreover, if resources are developed judiciously and strategically, the world of 2030 could be at the threshold of a critical and ultimately necessary transition from a global energy system based on depletable fossil fuels to one based on nondepletable, sustainable resources.

But creating this opportunity will entail significant difficulties. From a global perspective, constraints become apparent that are difficult to discern from a national or even regional viewpoint. These need not be crippling, but they must be understood. To contribute to this understanding is the purpose of this report.

HOW THIS REPORT IS ORGANIZED

It is not necessary to read the five sections of this report in sequence, though each draws to some extent on those preceding it. It is, however, crucial to understand how they are related to one another.

SECTION 1 THE IIASA APPROACH

There are as many analytic approaches to the energy problem as there are opinions about it. Each has a limited focus and concomitant strengths and weaknesses. Thus, to interpret analytic results properly requires an understanding of the process, assumptions, and methods that produced them. Section 1 provides this understanding for the IIASA study.

SECTION 2 THE LESSON OF HISTORY: CONSTRAINED CREATIVITY

To begin a detailed study of the 50 years from 1980 to 2030 requires, first, an appreciation of the history that shaped the world's energy system prior to 1980 and, second, an equivalent appreciation of what the future *beyond* 2030 might possibly hold. Section 2 analyzes the past – at times going back more than 100 years – and examines how different energy sources and technologies have gradually replaced their obsolete competitors throughout history. The analysis is quantitative; it includes energy markets at all levels, from the global primary energy market to national markets within various economic sectors. The historical regularities it reveals are impressive and pervasive.

SECTION 3 ENERGY SUPPLY: EXPLORING THE LIMITS

This section looks into the future, going at times well beyond 2030. It explores the technological potential of each of the possible primary energy sources, including the fossil fuels, nuclear power, solar power, and other renewables. The purpose is twofold: to gain some insights into what a global energy system based on sustainable resources might eventually look like, and to determine the technical characteristics of each supply possibility that will, during the 1980–2030 period, determine its attractiveness in competition with the others.

SECTION 4 1980–2030: DEMAND, CONSERVATION, AND TWO SCENARIOS

The global energy supply over the next 50 years will not be exclusively fossil, exclusively nuclear, exclusively solar, or exclusively anything else. The supply mix that evolves will depend on the changing nature of energy demand, which will in turn depend on patterns of population growth, economic growth, technological improvement, and structural shifts within national economies. Based on the results of a set of computer models and on the analyses reported in Sections 2 and 3, this section describes two scenarios, each of which balances energy supply with demand for the 1980–2030 period.

SECTION 5 PATHS TO A SUSTAINABLE FUTURE

No numerical results can define a unique set of conclusions directly useful in establishing energy policies. Nonetheless they can be suggestive, and such suggestions are the focus of this section. Here we summarize the lessons emerging from the two scenarios and arrange the relevant analytic bits and pieces from the preceding sections to provide a glimpse of what some of the features of a sustainable global energy system might be. While it would be presumptuous to describe this section as presenting *the* solution to the energy problem, it nonetheless describes what we have seen while taking a long, hard look at the future from our restricted historical perspective. What it presents is not all that may await over our temporal horizon, but it is a part of it.

1
The IIASA Approach

It is a truism that everything affects everything else. More specific to the subject at hand are the observations that the evolution of energy demand depends on the supply options available, while the availability of different supply options is itself influenced by the level of energy demand. Moreover, both depend on environmental constraints, resource constraints, and the like. Where one chooses to start to impose order in all this need not be critical – what is more important is that, once a starting point has been chosen, the analysis proceed systematically and consistently. Thus, it is the purpose of this section to explain where we started and how we proceeded.

Geographically, we extended the analysis to include the entire globe. However, to have analyzed energy supply and demand for every country of the globe would have been impossible, while to have ignored international differences in resources and consumption patterns would have been to neglect the basic causes of international competition and dependence. As a compromise between these conflicting considerations of pragmatism and theory, the countries of the world were grouped into seven regions, chosen on the basis of national energy resources and economic structure, not necessarily on the basis of geographic proximity. The groupings are shown in Figure 1 and can be characterized briefly as follows.

Region I	North America (NA) has developed, market economies and is rich in resources
Region II	The Soviet Union and Eastern Europe (SU/EE) have

	developed, centrally planned economies and are rich in resources
Region III	Western Europe, Australia, Israel, Japan, New Zealand, and South Africa (WE/JANZ) have developed, market economies, but are poorer in resources than the other developed regions
Region IV	Latin America (LA) is a developing region with market economies and many resources
Region V	South and Southeast Asia, and sub-Sahara Africa excluding South Africa (Af/SEA) are developing regions with mostly market economies, but with relatively few resources (except for some notable exceptions, e.g., Nigeria and Indonesia)
Region VI	The Middle East and North Africa (ME/NAf) are a special case with their economies in transition and with rich oil and gas resources
Region VII	China and other Asian countries with centrally planned economies (C/CPA) are developing regions with only modest resources

Within this geographic framework, the period that was studied in detail was the next half century, from 1980 to 2030. That such an extended scope and period could be considered was because of the unusual opportunity offered by the International Institute for Applied Systems Analysis, which is insulated from many of the short-term pressures that often deprive corporate strategists or national administrators of the luxury of comprehensive, detailed, long-term analysis. But more importantly, we chose to concentrate on the next 50 years because of what we expected to find there: a transition from a global energy system based on depletable fossil fuels to a sustainable system based on nondepletable fuels. Such a transition must occur sometime, and for the following four reasons we expected the coming 50 years to provide an opportunity, though of course with no assurance that it would be exploited:

1. *Technological inertia.* The lifetimes of capital investments in key technologies in the current energy system, such as oil refineries and electricity generating plants, are on the order of 25–30 years. Thus, a period of 50 years corresponds to two generations

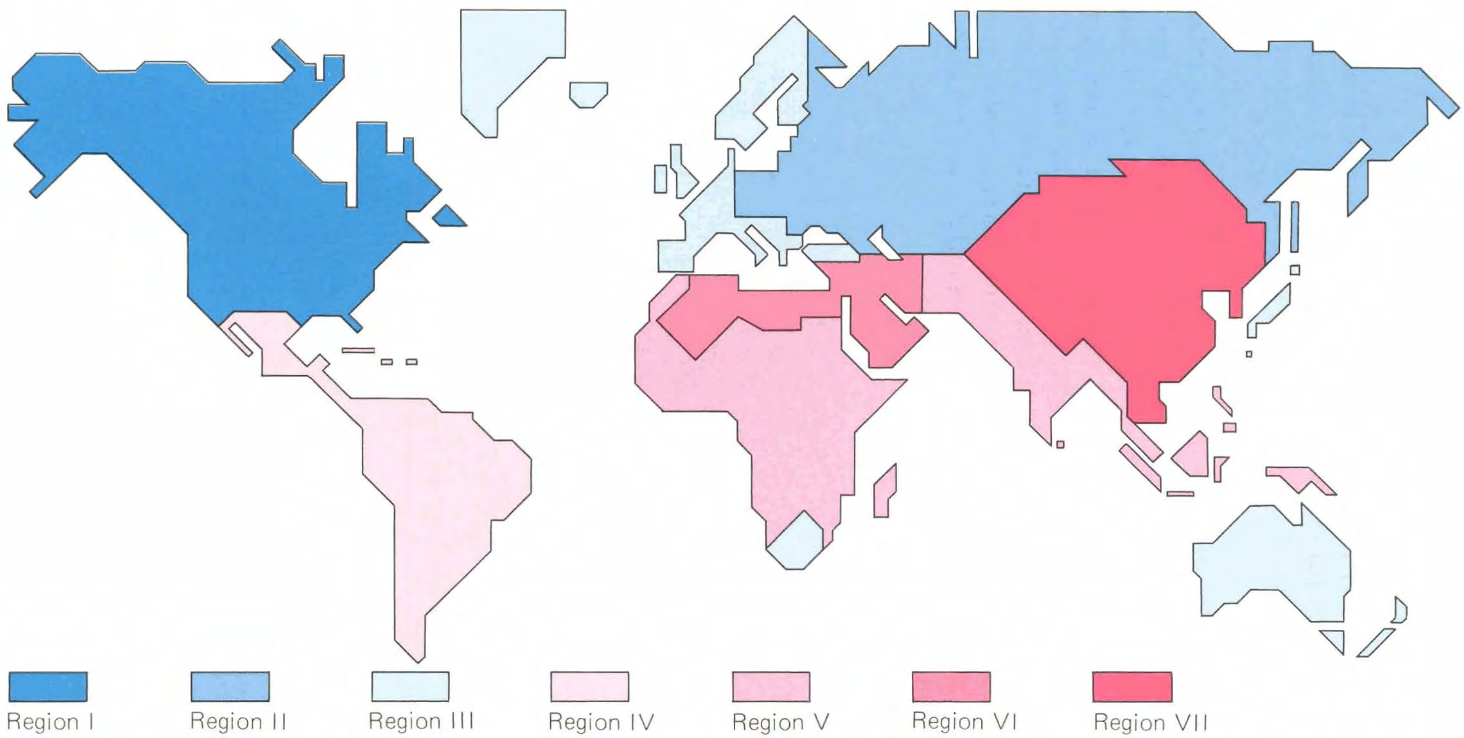


Figure 1. The seven regions defined.

and is not too short to rule out the possibility of major technological transitions during the study period.

2. *Social inertia.* Because 50 years also encompass two human generations, this period allows time for major social transitions, whether manifested in individual life-styles or in international relations.

3. *Market inertia.* To develop a technology, whether a small-scale solar water heater or a new coal-liquefaction process, and to have it penetrate the energy market successfully are two different things. From a global perspective, the substitution of one energy technology for another cannot occur overnight; it takes time – and, to judge from history, quite a bit of time. As the analysis in Section 2 of this report shows, to expect a transition to a sustainable worldwide energy system within a period substantially shorter than 50 years would be to ignore history flagrantly.

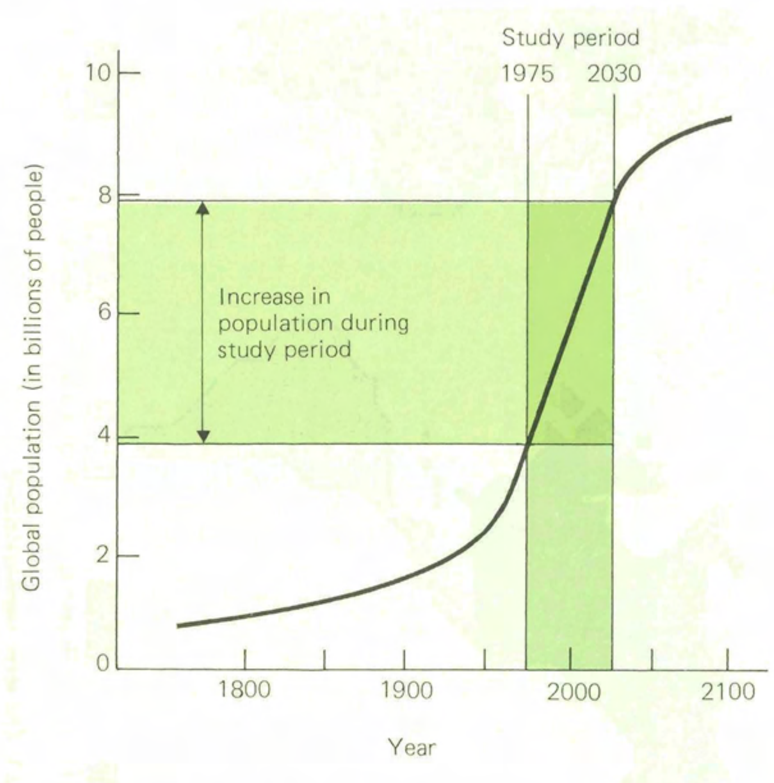


Figure 2. The population of the world, past and projected.

4. *Population growth.* As Figure 2 shows, the period from 1980 to 2030 coincides with what is anticipated to be the steepest ever increase in global population. The energy problem the world confronts during these next 50 years is thus unique, and any analysis based on a period of less than 50 years runs the risk of underestimating the pressures from population increases alone that will be placed on energy supplies.

For these reasons 50 years were thought to be sufficient to represent the severity of the energy problem facing the world, and to allow for the possibility of a transition to a sustainable energy system. However, as is discussed in Section 4, the transition turned out to be elusive. Within these 50 years and within the scope of our analysis, we found only the possibility of a less sweeping transition, one that would precede the transition we had expected. This preliminary transition can be characterized as one from clean, conventional fossil fuels, such as natural gas and oil, to dirtier, unconventional fossil fuels, such as heavy crudes, tar sands, and oil shales. But so straightforward a characterization is deceptive, as will become clear in Section 4. Time proved a more demanding constraint – a more scarce resource – than our intuition had anticipated.

Sections 2, 3, and 4 present three complementary perspectives on the world's energy problem. Each is instructive; none is definitive. All are long-term and globally comprehensive.

Section 2, using data covering the last 100 years as its basis, focuses on historical regularities in the world's energy system.

Section 3 concentrates on the opportunities of the future rather than the patterns of the past. Again the perspective often covers 100 years, but it is the coming 100 years, not the past 100.

Section 4 examines the period from 1980 to 2030 in detail, focusing on how the balance between the world's supply of energy and its demand for energy may evolve during this period. It uses two quantitative scenarios, as well as three variations arising from them (a nuclear moratorium case, an enhanced nuclear development case, and a very low demand case). It should be stressed that in writing scenarios we were in no sense attempting to make predictions. Rather, scenario writing was viewed as a way of organizing one's thinking and the available information; as used at IIASA its basis is fundamentally a rigorous insistence on internal consistency and global comprehensiveness.

The scenarios concentrate on the natural-science aspects of the energy problem, and the methods used are those of engineering and economics. Limiting the analytic focus and methods in this way necessarily means incorporating the following implicit assumptions:

- The future will be relatively free of surprises. We shall neither be confronted with catastrophic wars nor rescued by technological panaceas. The world's economic and physical regularities that are the subject of modern economics and engineering will not become transformed *unrecognizably*.

- However, the future will be blessed with a degree of international cooperation that can only be described as optimistic, though by no means impossible. Thus what the results suggest is not what *will* be done or what *should* be done, but what *can* be done with the world's endowments of energy resources, manpower, capital resources, and know-how, if we are successful in translating our increasing awareness and understanding of international dependencies into increasingly effective patterns of international cooperation. In particular, there will be a functioning world trade in oil, gas, and coal, allowing a flow of resources from the resource-rich to the resource-poor.

- Those social and political dimensions of the energy problem that are not explicitly included in the analysis will not severely limit the development of energy supplies during the next 50 years.

  The constraints addressed were restricted to those that are technical (e.g., the efficiency of electricity-generating plants), physical (e.g., the heating values of different coal deposits), or structural (e.g., limitations on the rate at which one energy source can be substituted for another in the global energy market). To some extent these constraints included well established concerns that could be described as basically political or social. But there is a much larger class of such social and political constraints that was left out of the analysis, and these must be kept in mind by anyone drawing conclusions from the results.

- Inflation effects are negligible. The analysis of competitive economics was carried out in terms of constant 1975 US dollars, and thus the monetary aspects of the energy problem, particularly those associated with inflation, were not taken into account.

To this list should be added the following two assumptions, which explicitly underlie the data used in the scenarios.

- A basic unifying characteristic of the demand and supply assumptions incorporated in the scenarios was that they reflect a future in which strong energy conservation programs in the industrialized countries are pursued in conjunction with aggressive exploration for additional energy resources.

- In both scenarios, economic growth rates were assumed to be moderate, declining over time, and consistently greater in the developing countries than in the developed countries.

These are the major assumptions to be kept in mind as one reads Section 4. On the one hand, they limit the sorts of conclusions that can be drawn from the numerical results; on the other hand, by restricting us to a manageable piece of the problem, they permit us to be thorough and rigorous in our analysis.

Finally, Section 5 returns to the motivating question: How may the world successfully negotiate a transition to a sustainable energy system? No definitive answers can be given. However, on the basis of the historical analysis in Section 2, the exploration of long-term supply options in Section 3, and the analysis of the next 50 years in Section 4, we can lay down the basic outlines of such a transition. How they will ultimately be filled in is a question that must be left to the future.

2
The Lesson of History: Constrained Creativity

One studies the past to improve his control of the future, for the better his understanding of the physical and social forces over which he has little control, the more productively he can utilize the forces over which he has more control.

An attempt to gain insights into ways in which the global energy system may be developed in the future must therefore begin with an examination of how it has developed in the past. The regularities revealed by such an exercise are stunning and sobering. They demonstrate that, while isolated, limited changes may sometimes occur relatively quickly, the system taken as a whole exhibits tremendous inertia; however, they also indicate the aspects of the global energy system that are most responsive to change.

To discern regularities hidden within worldwide energy consumption data, an analogy was drawn between

- different primary energy sources competing for shares of the world energy market, and

- other, more familiar instances of product competition (e.g., between brands of detergent competing for shares of the household detergent market or between steel production technologies competing for shares of the steel production market).

It was thus possible to apply much from existing analyses of product substitution dynamics to a better understanding of the workings of the global energy system. The process can be divided into three steps.

1. From the existing established mathematical models of product competition, we adapted a model to suit the case of energy markets, be they for forms of primary energy, forms of secondary energy, fuels for electricity generation, or whatever. (For definitions of terms see the Appendix.) This model was simply a set of equations relating the rate of change of the market share of any one competitor, its buildup rate, to the buildup rates of the others. The equations incorporated no assumptions about the actual historical market shares of different energy forms; but neither were the assumed relations among buildup rates arbitrary. They can more accurately be described as educated guesses – the question that remained was whether they were consistent with historical data.

2. The model was tested by applying it to 300 cases, covering 30 countries and energy subsystems and drawing on 60 data bases. The general result was that the assumed relations among buildup rates are indeed consistent with history.

3. Beyond confirming the reasonableness of the model's assumptions, the model's applications provided further insights that were used, first, to project the direction in which trends currently exhibited by the global energy system would lead. Second, they served to indicate where the global energy system is particularly responsive to adjustments, and where it is especially resistant to change.

Figure 3 shows the results of applying the model to the competition among different forms of primary energy for shares of the global energy market. The wavy lines represent historical data; the smooth lines represent the model's fit of the data, consistent with the assumed relations between the buildup rates of different primary energy sources. That the fit between the data and model results is so good for all four primary energy sources simultaneously (five if nuclear is counted) confirms the reasonableness of the model's assumptions for this example. The many other examples that were tested indicated that in fact the model's equations are generally applicable to energy systems, though the smaller the geographical area analyzed the larger the fluctuations of the data about the smooth lines produced by the model.

A remarkable aspect of Figure 3 is that the lines for natural gas and oil, and the rising part of the coal line, are approximately

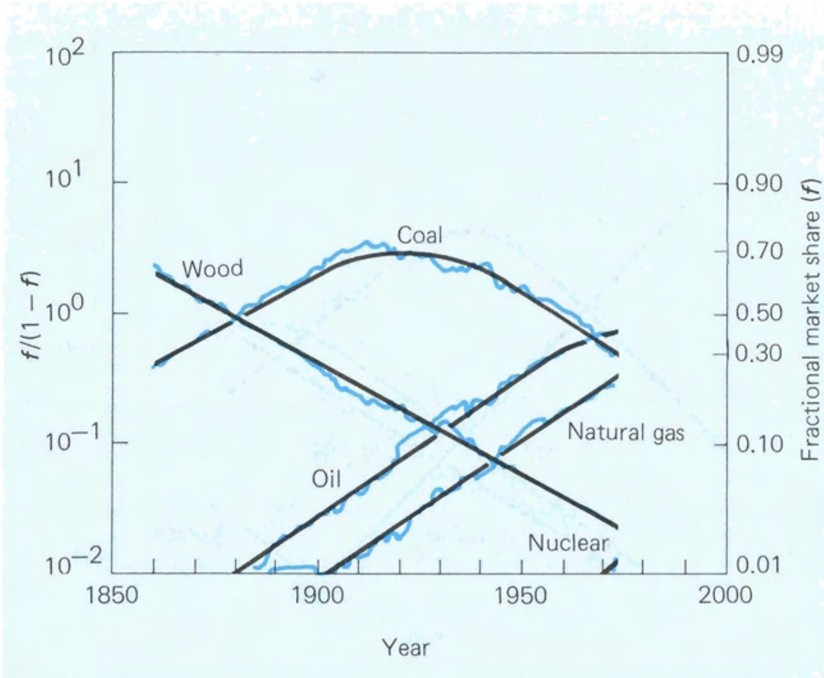


Figure 3. The history of global primary energy substitution. While f is the fractional market share of each technology, it is the transformation $f/(1-f)$ that is plotted against time, with the vertical scale being logarithmic, rather than linear. In this way results that would otherwise appear as S-shaped curves come out as straight lines, thus making them easier to comprehend and interpret. However, for the value of f that corresponds to a particular value of $f/(1-f)$ on the left-hand scale, see the scale at the right.

parallel. Identical slopes mean identical buildup rates. In other cases there is much less regularity across energy forms. Figures 4–6, for example, which apply the model to US data, show greater discrepancies among buildup rates.

The principal conclusion drawn from the applications of the model is that the behavior of an energy submarket can be accurately predicted by using just a few pieces of information:

- the times at which different energy technologies first achieve a critical minimum share of the market (around 2% or 3%), and

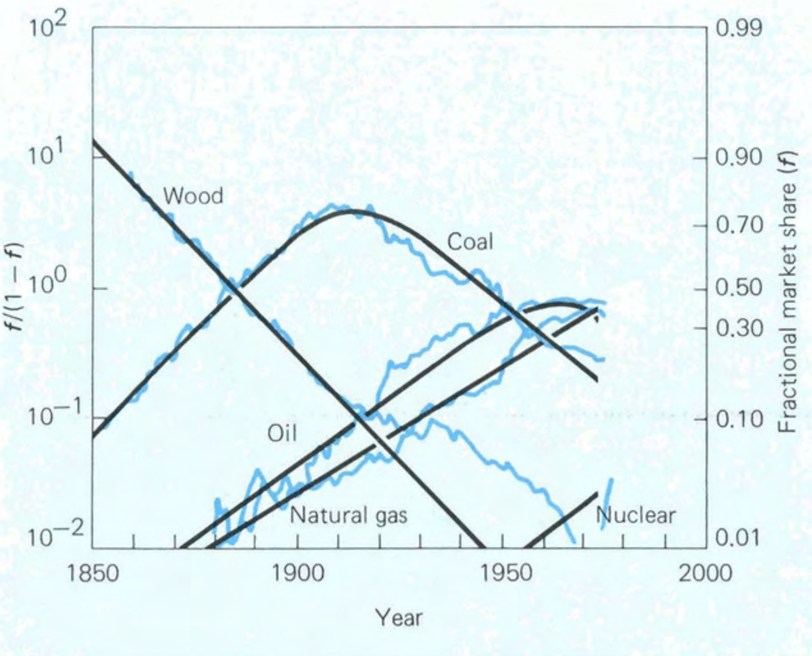


Figure 4. The history of primary energy substitution in the United States (f is the fractional market share of a technology).

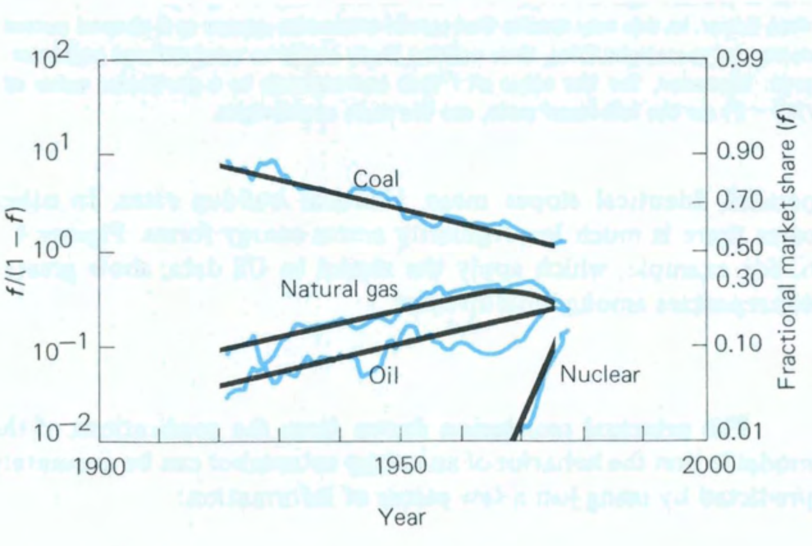


Figure 5. The history of the market shares of primary inputs to electricity in the United States (f is the fractional market share of a primary input).

- the buildup rate of each at the time it achieves this minimum market share.

Put another way, once an energy resource or technology has captured more than 2% or 3% of its market, the system takes over, and further penetration of this technology in the market can be neither speeded up nor slowed down by direct means; the technology's behavior can only be influenced by introducing a new competitor into the market.

Beyond such general conclusions are several more specific ones worth noting.

1. The regular substitution rates evident in the figures can be characterized by the notion of "takeover time" – the hypothetical time it would take a given energy form to increase its market share from 1% to 50%. For the global primary energy market the takeover times have been remarkably stable at a value of about 100 years.

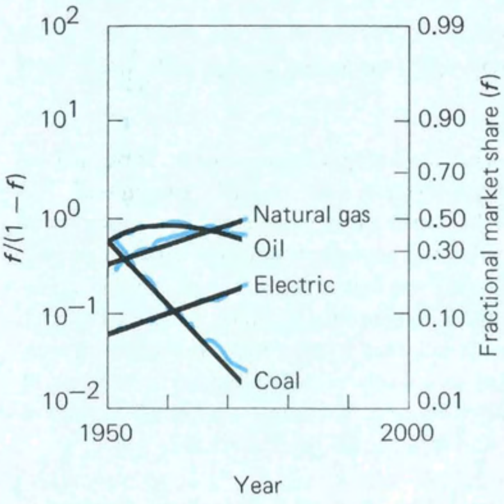


Figure 6. The history of energy substitution in the household/commercial sector in the United States (f is the fractional market share).

2. In the European countries of the Organisation for Economic Co-operation and Development (OECD), takeover times in the primary energy market have been much shorter – on the order of 30 years.

3. In the US primary energy market, takeover times have been long and stable at around 70–80 years.

4. In the US electricity submarket before the introduction of nuclear power, the takeover times associated with gas and oil were more than 100 years (Figure 5). This submarket seems to be characterized by decreasing takeover times.

5. In general, energy systems are ponderous, but smaller energy systems are less ponderous than big ones.

INTERPRETATIONS

The "system" that we describe as "taking over" the market fate of energy technologies is hardly monolithic or passive. It is just the opposite – varied and dynamic. It comprises political battles, regulatory decisions, bureaucratic administrations, corporate strategic planning, investment decisions, legal maneuverings, fluctuating consumer habits, and, in the global case analyzed here, two world wars and a worldwide depression. Why such a heterogeneous collection of forces should display the macroscopic regularities that it does is not even addressed, much less explained, by the model. One could speculate, but that is not the point. Rather the purpose is to caution against ignoring a class of regularities that have proved so persistent.

At first blush this all may seem discouragingly pessimistic. Is our ability to improve the world's energy system quickly really so limited? The answer is indeed "Yes" – but such an answer is no justification for pessimism. An analogy that should be made is with the attempt to land a man on the moon. There, what was essential was a sophisticated appreciation of the laws of gravitation (according to which things fall *down*), which were seemingly so contradictory to the objective (sending spacecraft *up*). That appreciation ultimately provided the understanding of orbital mechanics required for success. The trick was knowing when to fire the spacecraft's rocket and when to let the system take over.

From a slightly different perspective, it would be inaccurate to presume that, were we to leave it "unattended," the world's energy system would continue to show the regularities that have characterized it to date. The slow substitution of new energy sources for older ones – of coal for wood or oil for coal – happened only because of much careful thinking and constructive activity throughout the system, all directed toward optimizing local situations. To suggest that this effort could be discontinued, that future energy investments could be made haphazardly, without dangerously damaging the world's ability to provide itself energy, would be to miss the point entirely. We should not overestimate our capabilities, but neither should we underestimate them.

What happens if our substitution model is used to project a future? We use the phrase, "*a* future," rather than "*the* future" because any projections the model makes depend critically on when new, emerging technologies are assumed to reach the critical minimum market share and on the values assumed for the corresponding initial buildup rates.

As an example, consider the case with the following assumptions:

1. The critical date for nuclear power is taken as 1970 (1% of the global primary energy market). Its assumed initial buildup rate is at the upper end of the range defined by established energy sources, even though such values are below the actual nuclear power buildup rate of the previous decade.

2. The critical date for solar power is taken as 2000 (again 1% of the global market). The initial buildup rate is the same as that used for nuclear power.

The results, which are shown in Figure 7, indicate market shares in 2030 of approximately 7% for solar power, 40% for nuclear power, and 45% for natural gas. Oil's market share is the same as that of solar power (7%), and coal, at 2%, controls even less of the market. Thus, under the assumptions of this example, by 2030 nuclear power would not be the principal primary energy source at the global level, solar power's contribution would be still well below that hoped for by its proponents, natural gas, the dominant energy source, would have entered its period of declining importance, and coal, in contrast to the projections of so many analyses, including that described in Section 4 of this report, would be fast becoming globally negligible.

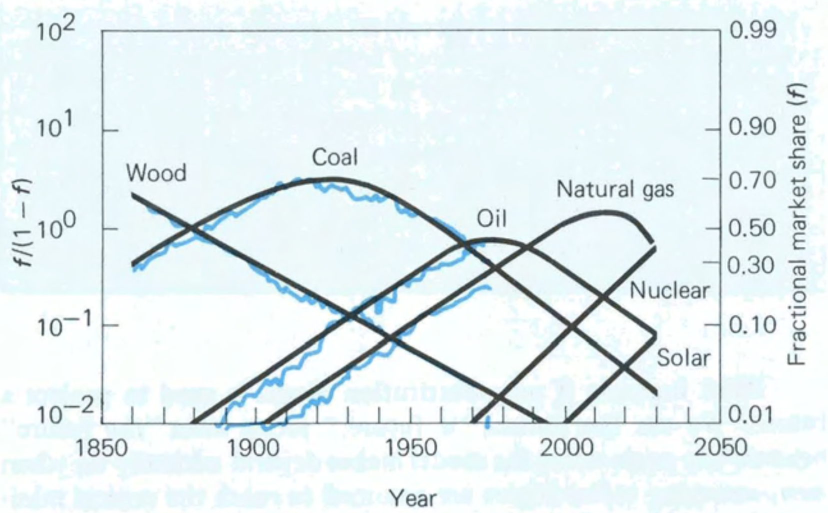


Figure 7. An example using the history of global primary energy substitution from 1860 to 1975 to project the market shares through 2030 (f is the fractional market share of a technology).

This is only one set of results that can be generated with the substitution model, and as such it should be taken with a few grains of salt. Perhaps it is inappropriate to include new uses of coal – for producing synthetic liquids, for example – in the same category as the historic uses. The same might be said for comparable emerging uses of wood (under its current alias of biomass). Finally, the analysis dealt only with market shares – never with the actual magnitudes. Thus, a solar contribution of 7% in a 2030 world using 22.4 TWyr/yr (as projected in the low scenario of Section 4) would equal 1.6 TWyr/yr. This is the equivalent of 22 million barrels of oil per day, hardly a small undertaking when seen in absolute terms. (For definitions of units see the Appendix.)

In this section we took a very long-term, macroscopic view of the global energy system to emphasize historic regularities. Thus, the future that is suggested is one very much colored by the trends of history. In contrast, the next two sections focus on the opportunities of the present rather than the patterns of the past. The next section explores, under the most optimistic of assumptions, the promises of different energy sources, while Section 4, taking a more down-to-earth perspective, describes two technically feasible scenarios in which the world's energy supply is balanced with the growing energy demands of the next 50 years. However, the qualitative and quantitative lessons learned in this section are not ignored; they will reappear often.

3
Energy Supply: Exploring the Limits

The intent of this section is to be imaginative, to be exploratory, to stretch our thinking. The method is to ask, for each of the different possible energy sources, what its ultimate technical potential would be if only resource constraints and limitations on technological buildup rates (see Section 2) were considered. Problems of environmental impacts, safety questions, or mismatches between supply and demand patterns are initially assumed essentially solvable, and the constraints of competitive economics are left for Section 4.

The conclusion is that the world's energy resources are tremendous, although taking advantage of this abundance can be neither quick nor cheap. Exploring the implications of expanding any one energy source to the unprecedented scale necessary to supply the needs of a rapidly growing population defines vividly the associated safety and environmental questions. The purpose here is neither to determine an ideal level of use for each energy source nor to define acceptable levels of environmental impacts. It is rather to give a clearer picture of the options ultimately available – both their good and bad sides.

The presentation borrows the categories most often used in discussions of energy supply:

- fossil fuels, including coal, oil, and gas
- nuclear power, including fission and fusion
- centralized, high-technology solar power
- decentralized, but not necessarily low-technology, solar power in conjunction with other renewables

Considerations of fossil fuels usually begin with estimates of reserves and resources, and the IIASA study was no exception. Where it differed from past studies was in its concentration on unconventional resources – on deep off-shore oil, on oil available only with tertiary recovery methods, on gas in tight formations or geopressure zones, on off-shore coal deposits, on tar sands and oil shales – in short, on fossil resources much more expensive in terms of money, environmental impacts, and possible social effects than the world is traditionally used to.

Table 1 summarizes the resultant estimates of global fossil resources. The numbers in the first column, which represent the conventional fossil resources, add up to slightly more than 1000 TWyr, which corresponds well with conventional wisdom concerning global fossil resources. (For definitions of units see the Appendix.) But in the last column, where the unconventional, expensive resources are also included, it turns out that the total is almost 3000 TWyr, three times higher.

TABLE 1 Estimates of global fossil fuel resources measured in terawatt-years (TWyr). The price categories are specified in barrels of oil equivalent (boe) for oil and gas and in tons of coal equivalent (tce) for coal.

Resource	Category 1	Category 2	Category 3	Total
Coal	560	1019	–	1579
Oil	264	200	373	837
Gas	267	141	130	538
Total	1091	1360	503	2954

For oil and gas: Category 1, $12/boe or less
Category 2, $12–$20/boe
Category 3, $20–$25/boe

For coal: Category 1, $25/tce or less
Category 2, $25–$50/tce

It is by now no surprise that coal proves to be by far the most abundant of the fossil resources. But its dominance raises two problems. The first concerns how coal is to be used to satisfy the most pressing component of the demand for fossil fuels – the liquid fuel component – and the second concerns the distribution of coal resources around the world.

In looking at the first problem, it became apparent that the coal liquefaction schemes currently being developed all rely on autothermal processes; that is, of the three basic ingredients involved in producing liquid hydrocarbons from coal – carbon, hydrogen, and heat – all three come from the coal. The alternative is an allothermal process, where the hydrogen and the heat come not from the coal but from some other source. Clearly the most important immediate effect of such an approach would be a decrease in the amount of coal needed to produce a given amount of liquid fuel. Only one-fourth to one-third of the coal required by autothermal processes is needed for the allothermal schemes. But almost as importantly, the carbon dioxide released to the atmosphere is reduced to one-fourth to one-third of the level associated with autothermal methods.

In the near term, and at the national level, these differences between autothermal and allothermal coal liquefaction are not crucial. But, as will become clear in Section 4, the world is likely to be relying on coal – particularly for the production of liquid fuels – to an increasing extent for at least the next half century. In this light, extending by a factor of three to four the portion of the world's coal resources that is devoted to producing liquid fuels becomes a more urgent priority.

The second point to be made about coal concerns its geographical distribution. As Table 2 shows, three countries will dominate the world coal market: China, the USA, and the USSR. The principal implications of this are clear – if coal is to replace oil as the world's principal fossil fuel

- the technical infrastructure required to move vast quantities of coal or coal products from the resource-rich to the resource-poor countries must be developed, and

- the associated institutional infrastructure must be developed, for, although the current patterns of the world's balance of payments problems may shift, the problems will by no means vanish simply as a result of a global shift to coal.

For the case of nuclear power the summary also begins with resource estimates. But here there is an additional element, which arises because of the variety of nuclear technologies – which range from existing light water reactors (LWRs) through fission fast breeder reactors (FBRs) to fusion technologies – and the fact that the amount of energy that can be extracted from the earth's nuclear

TABLE 2 The distribution of global coal resources in billions of tons of coal equivalent (10^9 tce).

Greater than 10^{12} tce (1000×10^9 tce)		Between 10^{11} and 10^{12} tce (100 and 1000×10^9 tce)		Between 10^{10} and 10^{11} tce (10 and 100×10^9 tce)		Between 10^9 and 10^{10} tce (1 and 10×10^9 tce)	
USSR	4860	Australia	262	India	57	GDR	9.4
US	2570	FRG	247	South Africa	57	Japan	8.5
China	1438	UK	163	Czechoslovakia	17.5	Colombia	8.3
		Poland	126	Yugoslavia	10.9	Zimbabwe	7.1
		Canada	115	Brazil	10	Mexico	5.5
		Botswana	100			Swaziland	5.0
						Chile	4.6
						Indonesia	3.7
						Hungary	3.5
						Turkey	3.3
						Netherlands	2.9
						France	2.3
						Spain	2.3
						North Korea	2.0
						Romania	1.8
						Bangladesh	1.6
						Venezuela	1.6
						Peru	1.0

resources depends critically on whether introducing these technologies is coordinated so that they complement each other as productively as possible.

For fission reactors the resource in question is natural uranium. The estimate we arrived at for the amount ultimately available globally at prices under \$130/kg (1978 US\$) was 24.5 million tons. How much energy can be produced from this amount depends on how the uranium is used.

If it is used solely to fuel LWRs and if spent fuel is not recycled, the conclusion is that the resource could be exhausted by 2030. This estimate is based on a reference case, which assumes that additional LWRs are introduced at the highest rate still consistent with, on the one hand, the findings outlined in Section 2 and, on the other, an independent assessment of the projected capabilities of the worldwide nuclear industry. This reference case led us to a nuclear power production level of 17 TWyr/yr (thermal) in 2030 and, as just mentioned, the exhaustion of the world's high-grade natural uranium resources by the same date.

The immediate question is, "How may the lifetime of nuclear fission power be extended?" There are three possible approaches.

The first involves mining the earth's vast deposits of low-grade uranium ore – deposits that were not included in the 24.5 million ton estimate made above. The disadvantage is that the low-grade ores – ranging from uranium concentrations of 500 parts per million (ppm) down to 30 ppm – would be much more expensive, both financially and environmentally, than the higher-grade ores. For example, Table 3 compares the land requirements, manpower requirements, and the amount of material that must be handled in order to support LWRs fueled by 70 ppm uranium ore, with those same requirements for LWRs fueled by high-grade ore (2000 ppm of uranium). From the requirements for coal-powered electricity

TABLE 3 The requirements for operating a one-gigawatt (electric) power plant.

	Land 30-year total (km^2)	Mining personnel (man-yr/yr)	Material handling involved, 30-year total (10^6 tons)
LWR (2000 ppm ore)	3	50	45
Coal	10–20	500	321
LWR (70 ppm ore)	33	300	360

shown in the table one can see that the mining requirements for the case of low-grade ore exceed those for coal.

The second approach stretches the lifetime of the high-grade uranium resources by assuming both improved efficiencies in LWRs and recycling of the nuclear fuel. But in extending our reference case along these lines, the 24.5 million tons of high-grade ores could not be made to last much more than 10–20 years beyond 2030, even on the basis of optimistic assumptions. Afterward, the only option is again the low-grade, expensive resources.

The third possibility is to introduce breeder reactors – the family of fission reactors capable of using the more than 99% of natural uranium that cannot be used directly in LWRs. Considerations of breeder reactors usually envision a system based on LWRs of current design and an increasing proportion of breeder reactors that gradually replace the LWRs, eventually doing so altogether. The problem with this approach is that the world is already behind schedule; breeder reactors have not been and are not being developed and introduced at the necessary speed. But if the introduction of breeders is pursued in conjunction with enhanced LWR efficiencies, it turns out that the full potential of the breeders can ultimately be exploited. The approach that is necessary in order to reach the required improvements in LWR efficiencies assumes the gradual introduction of the uranium isotope known as uranium-233 as a fuel for LWRs. The source of this uranium-233 is presumed to be

INTERPRETATIONS

The 300,000 TWyr associated here with nuclear fission power is larger by a factor of 100 than the total resources of both conventional and unconventional fossil fuels (Table 1). More particularly, it is large enough to justify contemplating a sustainable global energy system based on nuclear power. But in doing so, it is crucial to remember that these 300,000 TWyr only become available if the world's uranium resources are used, not to fuel burner reactors, but to build up a system of both burner and breeder reactors – a system through which the energy supply of the future could become effectively independent of any resource considerations. Such a system we label "sustainable," and the use of existing resources to create such a system we label "investive." The alternatives to investive uses of resources are the current "consumptive" uses that characterize both existing LWRs and, necessarily, the fossil fuels.

thorium-232 converted in the breeder reactors; the result is a system capable of extracting a total of 300,000 TWyr of energy from the 24.5 million tons of high-grade uranium resources (see box).

The two other obvious bases for a sustainable energy system are nuclear fusion and solar power. The commercial introduction of nuclear fusion at a global level, is, we feel, more than 50 years away; rather than speculate that far into the future here, we will simply state the energy potential of fusion and leave it at that. Deuterium–tritium reactors could tap a resource equal to approximately 300,000 TWyr, the same as that made available by fission reactors. Introducing deuterium–deuterium reactors would enhance this estimate by a factor of 1000, leading to a total fusion potential of 300,000,000 TWyr.

Solar power is a more immediate possibility than fusion power, and therefore deserves more elaboration. We shall distinguish between "hard" uses of solar energy and "soft" uses; the label hard solar refers to applications involving large centralized technologies, while soft solar refers to decentralized uses on a smaller scale.

The potential of hard solar is tremendous. The average energy input to the earth from the sun is 178,000 TWyr/yr of thermal energy; even after accounting for the filtering effect of the atmosphere, the usable sunlight shining in locations suitable for hard solar technologies is sufficient to provide energy equal to hundreds of terawatt-years each year. Considering the possibility of solar plants located in space outside the earth's atmosphere increases the calculated solar potential even more. Thus, as in the case of nuclear power, solar energy can be imagined as the basis for a sustainable energy system – with the energy supply of the future independent of resource considerations forever.

But in identifying this potential, and especially in concluding that the necessary usable land area suitable for hard solar technologies exists, two qualifications must be mentioned.

1. As in the case of fossil fuels, the world's solar resource is unevenly distributed among countries. In particular, much of the area most suitable for solar power plant sites lies in Northern Africa and the Middle East, areas already rich in oil and gas. A crucial dimension of exploiting the solar potential is therefore to develop both the technical and institutional infrastructures for transporting solar-generated electricity or fuels from the sun-rich regions to those that are sun-poor.

2. Related to the large land requirement necessitated by the diffuseness of the solar resource is a comparably large requirement for materials; whether based on some configuration of mirrors, pipes, and valves supported by concrete structures or on some arrangement of photovoltaic cells, the equipment required to collect incoming solar energy is necessarily extensive. Moreover, while land availability does not appear to be a problem, material availability may be. For orientation, a program designed to build up over the next 100 years a hard solar capacity of 35 TWyr/yr could require each year an amount of concrete roughly equal to that produced worldwide in 1975. It is an intimidating result, but what must be remembered is that *using material resources to build up a global solar energy system would be another example of the investive use of existing resources.* As would be the case with nuclear power, the return on the investment would be a future energy supply essentially independent of resource constraints.

The definition of solar power is often extended to include energy derived from biomass, hydropower, the wind, and ocean currents, waves, and temperature gradients. However these sources are labeled, an examination of their potential is a critical part of any assessment of the earth's energy resources, and here they are considered together with geothermal energy, tidal energy, and decentralized uses of direct solar insolation – i.e., soft solar power. Table 4 lists the technical potential estimated for each (the term technical potential again indicates that constraints associated with the environment and competitive economics are not taken into

TABLE 4 The technical potential of renewables and soft solar power.

Source	Technical potential (TWyr/yr)
Biomass	6
Hydroelectricity	3
Wind	3
Geothermal	2
Ocean thermal energy conversion	1
Tides, ocean currents, and waves	0.045
Soft solar power	2.2
Total	17.2

account). The total shown in Table 4 is 17.2 TWyr/yr, which is more than twice the global primary energy use in 1975. Still, it is well below the ultimate potential of either nuclear power or hard solar power, and is hardly sufficient to justify the possibility of a sustainable energy system based solely on this collection of energy sources.

But the numbers in Table 4 are by no means insignificant. Most importantly, to consider using these resources at the maximum levels indicated in the table would be to contemplate undertaking active ecological management on an awesome scale. Exploiting the 6 TWyr/yr listed for biomass, for example, would correspond to managing 30 million km^2 of forests, more than twice the land area devoted to agriculture worldwide in 1975. It would mean managing the habitats of thousands of species, and it would mean dealing with more familiar problems on an unprecedented scale – problems of soil erosion, managing water systems, and the decreasing resistance of cultured plants to pests. In short, it would mean operating a worldwide herbarium.

The general conclusion to be drawn from the exploration of supply limits summarized in this section is that nuclear fission, nuclear fusion, hard solar power, or some combination of the three can provide the basis for a sustainable global energy system. The fossil fuels, soft solar technologies, hydroelectricity, biomass, and all the other energy forms considered here can play only a supplementary role, though by no means an insignificant one.

But this conclusion is based on looking well into the future. And to identify where the world could end up in perhaps another 100 years is very different from determining the direction in which it is headed now. This is the subject of the next section: What might we expect during the next 50 years? Only after this question has been answered can we address, in Section 5, what a transition from the world's current energy system to a sustainable energy system might actually look like.

4
1980-2030: Demand, Conservation, and Two Scenarios

In Section 2 we examined the gross dynamics of the global energy system over the past 100 years. There we focused on the competition between different primary energy sources for shares of the world's energy market. The details of the human choices, the technological advances, and the economic shifts and forces that are buried within the macroscopic regularities were not addressed explicitly.

In Section 3 we explored the technical limits of different primary energy sources over the next half century and beyond. The focus was on resource potentials and engineering possibilities. Again the details of energy demand patterns were afforded less attention, and the competition between different sources – the central consideration of Section 2 – was not dealt with explicitly.

This section explores in detail future energy demand and the competition among different energy sources contributing to meeting this demand. We extend the analysis only as far as 2030.

The quantitative results are expressed in two reference scenarios and three supplementary cases that are variations of the reference scenarios. The principal tool used in building the scenarios and alternative cases was the set of computer models outlined briefly on page 37.

The two scenarios are labeled the "high scenario" and the "low scenario." The former assumes relatively higher economic growth rates throughout the world, and the latter assumes relatively lower worldwide economic growth. The high scenario leads to a level of global primary energy consumption in 2030 equal to 35.7 TWyr/yr, which amounts to slightly more than four times the 1975 level of

8.2 TWyr/yr, while the low scenario yields a global primary energy consumption in 2030 of 22.4 TWyr/yr, a little less than three times the 1975 level. (See the Appendix for energy unit conversion factors and for definitions of the levels of energy use.)

The two scenarios are not meant to describe extremes in either direction, but rather to cover a middle ground. Neither are they intended as predictions; instead, the objective was to detail the engineering and economic consequences that follow from two different sets of reasonable assumptions. Nonetheless the results of the exercise suggest powerful trends within our current global energy system, and it is worth listing these before describing the scenarios.

- In the developed regions of the world there is a tremendous potential for energy conservation from efficiency improvements and expanding the economic sectors that are less energy intensive, such as the service sector. For these regions the average growth rate for final energy from 1975 to 2030 is only 1.7% per year in the high scenario and 1.1% per year in the low scenario. These values compare to a 1950–1975 average of 3.8% per year.

- In the developing regions expanding populations, increasing urbanization, and continuing development needs limit the prospects for energy savings. As a result, throughout the 1975–2030 period primary energy growth rates in these regions are predominantly higher than the gross domestic product (GDP) growth rates, although the differences tend to decrease with time. In contrast, in the developed regions the primary energy growth rates are always below the GDP growth rates.

- The production and consumption of oil in both scenarios go up, not down, compared with 1975. Although oil's share of the primary energy market decreases from 1975 to 2030 (from 47% to 19% in the high scenario and from 47% to 22% in the low scenario), the absolute amounts of oil used go up (from 3.83 TWyr/yr in 1975 to 6.83 TWyr/yr in 2030 in the high scenario and from 3.83 TWyr/yr in 1975 to 5.02 TWyr/yr in 2030 in the low scenario).

- Despite such increases, and even with vigorous conservation measures in the industrialized regions, increasing needs for liquid fuels throughout the world may, over the next five decades, exceed the capabilities of the global energy supply system. In the high scenario primary liquid fuel demand increases from 3.83 TWyr/yr in 1975 to 11.1 TWyr/yr in 2030. In the low scenario the increase is from 3.83 TWyr/yr in 1975 to 7.22 TWyr/yr in 2030.

These 2030 demand levels exceed 2030 oil production levels by 63% and 44% for the high and low scenarios, respectively.

- The gap between liquids demand and oil supply is closed by liquefying tremendous quantities of coal. For the high scenario, 6.7 TWyr/yr of coal are liquefied in 2030; for the low scenario the figure is 3.4 TWyr/yr. For both cases this amounts to liquefying more than half the coal mined in 2030. For orientation, the high-scenario value of 6.7 TWyr/yr of coal is equivalent to 4.3 TWyr/yr of crude oil, which nearly equals the total world crude oil production of 1978.

- What oil is produced will come increasingly from unconventional sources – tar sands, oil shales, heavy crudes, and enhanced recovery techniques. In the high scenario the shift is such that by 2030 the majority of the oil produced is, in fact, unconventional oil.

The forces driving energy demand can be divided into four categories:

- population growth
- economic growth
- technological progress
- structural changes within economies.

Population growth. The assumptions about population growth were presented in their aggregate form in Figure 2; Table 5 disag-

TABLE 5 Global population projections (in millions of people) by region.

Region	Base year 1975	Projection 2000	Projection 2030
I (NA)	237	284	315
II (SU/EE)	363	436	480
III (WE/JANZ)	560	680	767
IV (LA)	319	575	797
V (Af/SEA)	1422	2528	3550
VI (ME/NAf)	133	247	353
VII (C/CPA)	912	1330	1714
World	3946	6080	7976

gregates them by region. We see that 90% of the projected population growth between 1975 and 2030 occurs in the developing Regions IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA). The population assumptions for both scenarios are identical.

Economic growth. Figure 8 shows the average 1975–2030 gross domestic product (GDP) growth rates assumed for each of the seven different regions for the two scenarios. These averages, however, mask an important characteristic of both scenarios – that in all regions of the world, the rate of economic growth continually decreases. The more detailed data are given in Table 6 along with historic growth rates for the periods 1950–1960 and 1960–1975. Except for the case of Region II (SU/EE) in comparison with Region VII (C/CPA), the growth rates in the developing regions consistently exceed those in the developed regions, although never by much. That the gap is not larger reflects a recognition that, for the next several decades at least, the developing countries will still be tied to the economies of the rest of the world through trade and other institutional relations.

Unlike the population assumptions presented earlier, the economic growth rates of Table 6 do not represent initial assumptions that remained unchanged throughout the subsequent analysis. They are rather the result of several revisions designed to ensure their consistency with the evolution of energy demand and supply that is calculated to follow from them.

Technological progress and structural changes within economies. For these two categories, which include the sorts of technical and social changes usually labeled conservation, it is more difficult to summarize all the scenario assumptions in a few graphs or tables. As an indication of the extent to which energy conservation assumptions are reflected in the two scenarios, Figures 9 and 10 therefore present some of the aggregate results of the scenarios.

Figure 11 is a schematic representation of the IIASA set of energy models as they were used in constructing the scenarios.

The analysis began with assumptions belonging to each of the four categories just mentioned: population growth, economic growth, technological progress, and structural changes within economies. An Energy Demand Model then calculated for each of the seven regions the resultant evolution of *final* energy demand from 1980 to 2030.

The projected final energy demands were translated into pro-

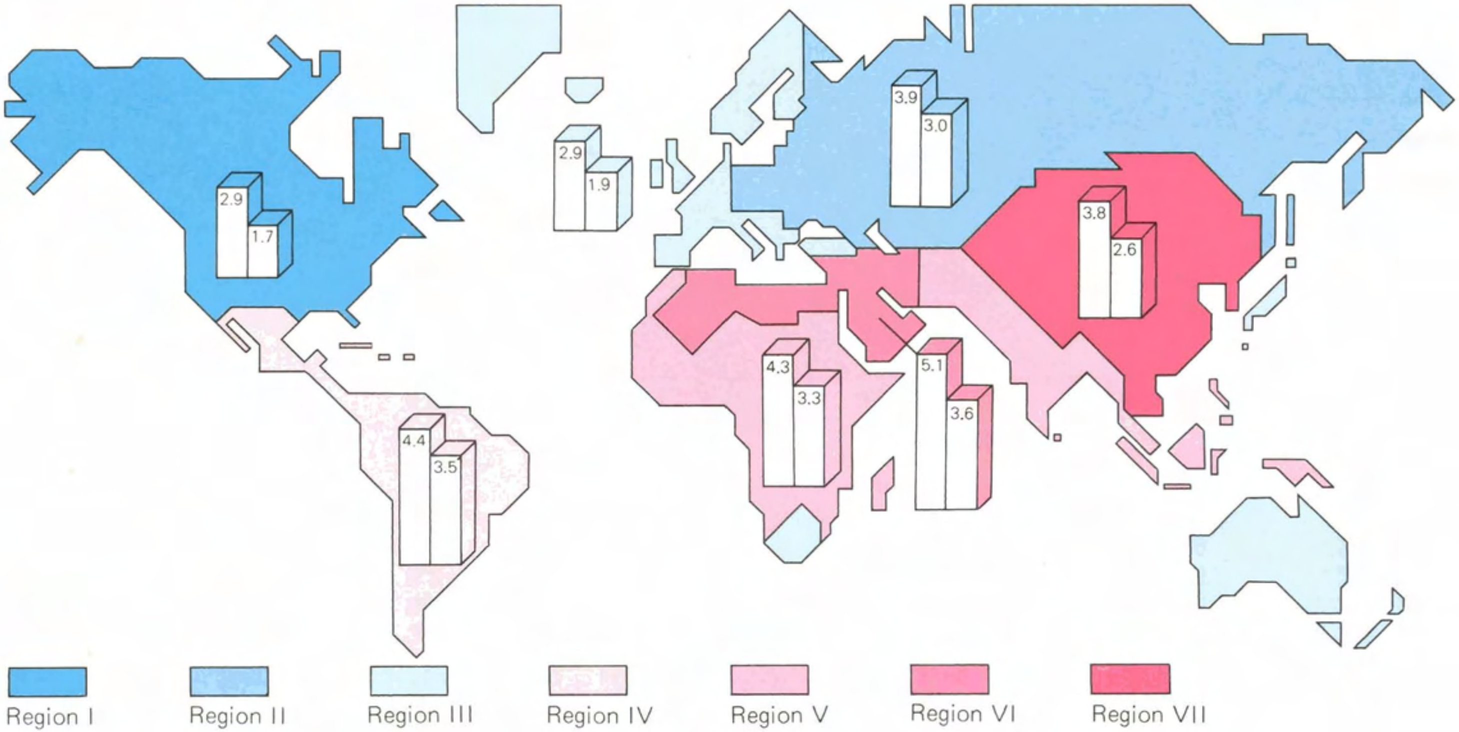


Figure 8. The assumptions about average growth rates of gross domestic product (GDP) for the IIASA high (left bar in each region) and low (right bar in each region) scenarios. The figures shown indicate percentage growth per year averaged for the period 1975–2030 for each of the seven regions.

TABLE 6 Historical and projected growth rates of GDP for the IIASA high and low scenarios (percent/year).

Region	Historical		Scenario projection							
	1950–1960	1960–1975	1975–1985		1985–2000		2000–2015		2015–2030	
			High	Low	High	Low	High	Low	High	Low
I (NA)	3.3	3.4	4.3	3.1	3.3	2.0	2.4	1.1	2.0	1.0
II (SU/EE)	10.4	6.5	5.0	4.5	4.0	3.5	3.5	2.5	3.5	2.0
III (WE/JANZ)	5.0	5.2	4.3	3.2	3.4	2.1	2.5	1.5	2.0	1.2
IV (LA)	5.0	6.1	6.2	4.7	4.9	3.6	3.7	3.0	3.3	3.0
V (Af/SEA)	3.9	5.5	5.8	4.8	4.8	3.6	3.8	2.8	3.4	2.4
VI (ME/NAf)	7.0	9.8	7.2	5.6	5.9	4.6	4.2	2.7	3.8	2.1
VII (C/CPA)	8.0	6.1	5.0	3.3	4.0	3.0	3.5	2.5	3.0	2.0
World	5.0	5.0	4.7	3.6	3.8	2.7	3.0	1.9	2.7	1.7

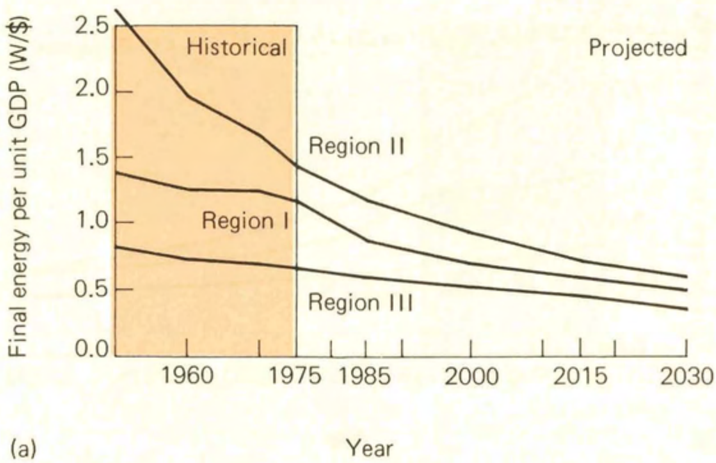
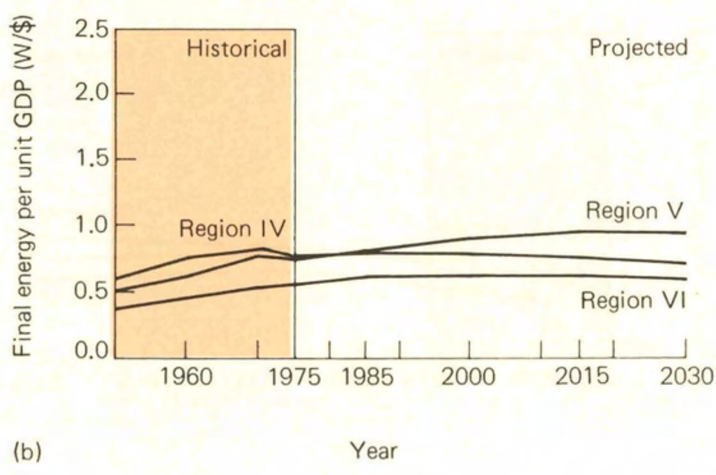


Figure 9. Final energy per unit of gross domestic product for the high scenario in (a) developed, and (b) developing regions.



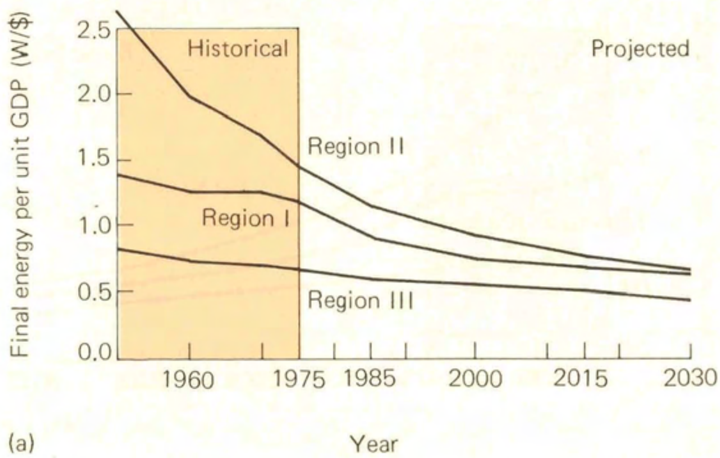
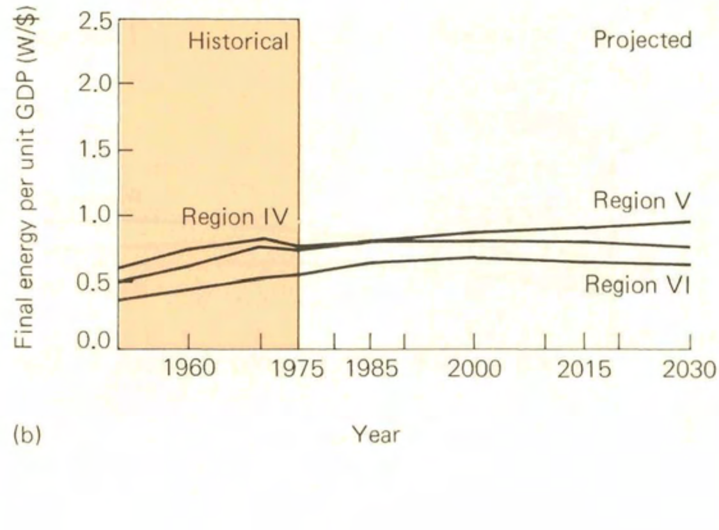


Figure 10. Final energy per unit of gross domestic product for the low scenario in (a) developed, and (b) developing regions.



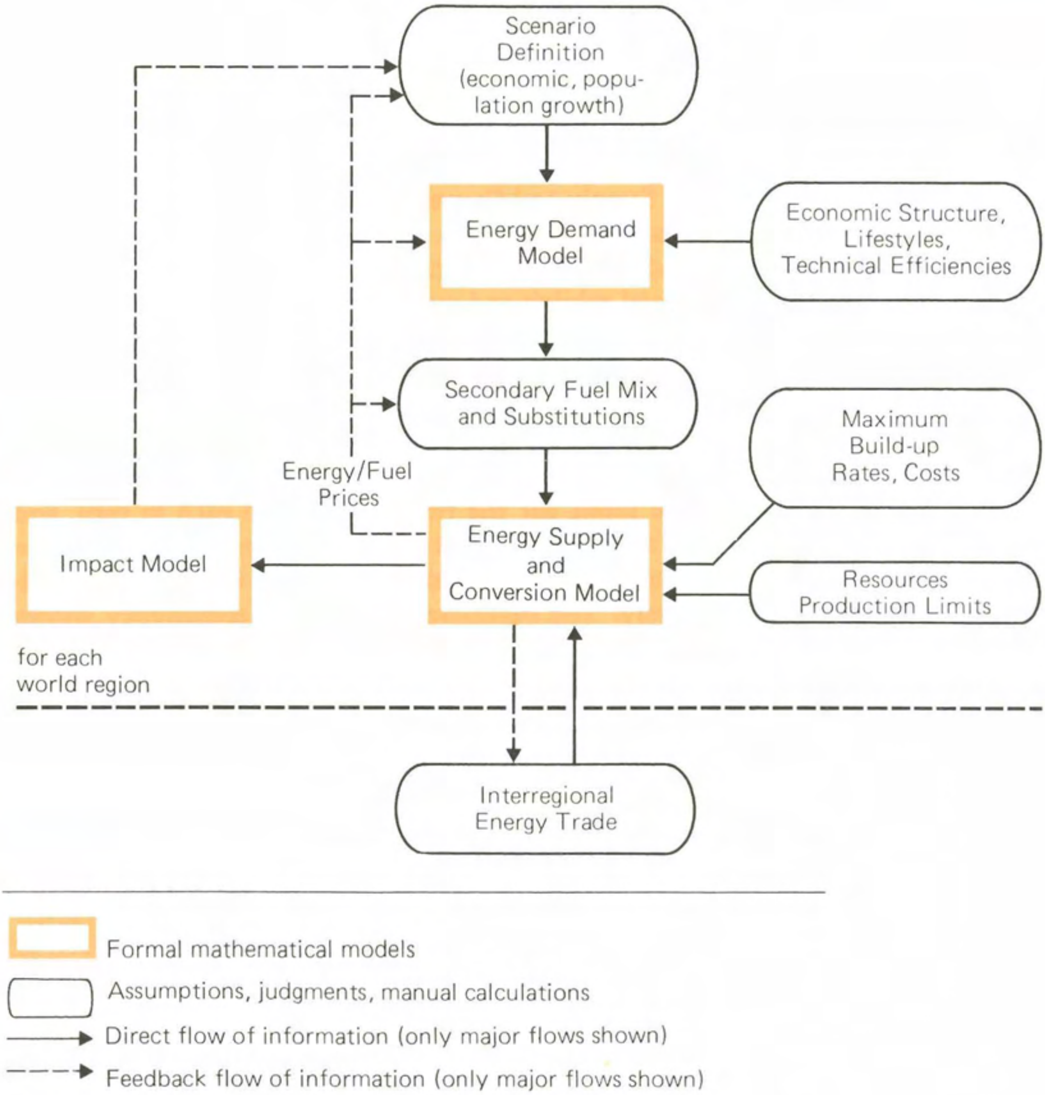


Figure 11. A simplified representation of the IIASA set of energy models used in constructing the scenarios.

jected *secondary* energy demands, which were then input to an Energy Supply and Conversion Model. Other inputs to this model were, first, assumptions constraining energy supply and conversion possibilities (see Figure 11) and, second, the results of a procedure analyzing the patterns and prices of oil imports and exports among the seven regions.

The Energy Supply and Conversion Model calculated the primary fuel supplies and conversion facilities needed to meet the projected secondary energy demands at lowest cost and within the specified constraints.

Associated with providing the resources and facilities indicated by the Energy Supply and Conversion Model, there are necessarily direct and indirect requirements for capital, materials, manpower, equipment, land, water, and additional energy. In particular, capacities within crucial mining and manufacturing industries have to be expanded. These related industrial capacities, as well as the direct and indirect requirements listed above, were calculated for each scenario using a model labeled simply Impact.

This short summary is necessarily slightly misleading in that it presents the models linearly and suggests that the analysis simply began with the input for the first model, used each in turn, and ended up with some final results from the last model. In reality, as is usually the case with such sets of models, they were used in parallel and iteratively. The objective was internal consistency within each scenario, which in turn required several iterations of the model set. The major consistency checks between models are suggested by the dotted lines in Figure 11.

The resultant final energy consumption per capita in each region of the world is shown in Table 7 for both the high and low scenarios. Table 8 shows the corresponding primary energy requirements. Whether expressed in terms of final energy consumption or primary energy requirements, the results of both scenarios indicate a noticeable reduction in the gap between the energy budgets of the developed regions and those of the developing regions. The reduction is greater in the high scenario, where, because of overall higher economic growth rates, the developing regions are able to catch up more than they do in the low scenario. Still, in both scenarios, the advances achieved in 2000 and 2030 by the developing countries lie well below their currently expressed aspirations. For example, even in the high scenario, the 2030 per capita final energy consumption in Region IV (LA) remains below the 1975 level in Region II (SU/EE). And Region V (Af/SEA) has by 2030 only just passed where Region IV (LA) was in 1975.

As shown in Table 9, energy consumption *growth rates* decrease throughout the scenarios for all regions, though once again there is a noticeable difference between developed and developing

TABLE 7 Per capita final energy consumption (kWyr/yr) calculated from the scenarios.

Region	Base year 1975	High scenario 2000	High scenario 2030	Low scenario 2000	Low scenario 2030
I (NA)	7.89	9.25	11.63	7.95	8.37
II (SU/EE)	3.52	5.47	8.57	4.98	6.15
III (WE/JANZ)	2.84	4.46	5.70	3.52	3.90
IV (LA)	0.80	1.75	3.31	1.28	2.08
V (Af/SEA)	0.18	0.42	0.89	0.32	0.53
VI (ME/NAf)	0.80	2.34	4.64	1.76	2.46
VII (C/CPA)	0.43	0.93	1.87	0.64	0.93
World	1.46	1.96	2.86	1.58	1.83

TABLE 8 Primary energy requirements by region (TWyr/yr) calculated from the scenarios.

Region	Base year 1975	High scenario 2000	High scenario 2030	Low scenario 2000	Low scenario 2030
I (NA)	2.65	3.89	6.02	3.31	4.37
II (SU/EE)	1.84	3.69	7.33	3.31	5.00
III (WE/JANZ)	2.26	4.29	7.14	3.39	4.54
IV (LA)	0.34	1.34	3.68	0.97	2.31
V (Af/SEA)	0.33	1.43	4.65	1.07	2.66
VI (ME/NAf)	0.13	0.77	2.38	0.56	1.23
VII (C/CPA)	0.46	1.44	4.45	0.98	2.29
Total[a]	8.21[b]	16.84	35.65	13.59	22.39

[a] Columns may not sum to totals because of rounding.
[b] Includes 0.21 TWyr/yr of bunkers – fuel used in international shipments of fuel.

regions. Part of the difference is due to the lower economic growth rates assumed for the developed regions, but part of it is simply because regions that use more energy today have more opportunities to conserve.

The resultant contributions of each primary energy source toward meeting the projected demand levels are shown in Table 10. For both scenarios the level of use increases for each source of primary energy. Most importantly, this includes the fossil sources – coal, gas, and especially oil. For, although the share of primary

TABLE 9 Final energy growth rates for 1950–1975 and projections to 2030 (percent/year) calculated from the scenarios.

Region	Historical 1950–1975	High scenario 1975–2000	High scenario 2000–2030	Low scenario 1975–2000	Low scenario 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

TABLE 10 Global primary energy by source (TWyr/yr) for the high and low scenarios.

Primary source	Base year 1975	High scenario 2000	High scenario 2030	Low scenario 2000	Low scenario 2030
Oil	3.83	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar	0	0.10	0.49	0.09	0.30
Other[a]	0	0.22	0.81	0.17	0.52
Total[b]	8.21	16.84	35.65	13.59	22.39

[a] "Other" includes biogas, geothermal, and commerical wood use.
[b] Columns may not sum to totals because of rounding.

energy requirements that is met by oil decreases in both scenarios (Figure 12), the absolute amount of oil used increases.

However, the oil used in 2030 is very different from that used today. Figure 13 shows how the scenarios project that the future primary liquids demand of the regions with noncentrally planned economies will be met. Except for oil from Region VI (ME/NAf), none of the oil used after 2010 comes from currently known reserves of conventional oil. And by 2030 the portion of the primary

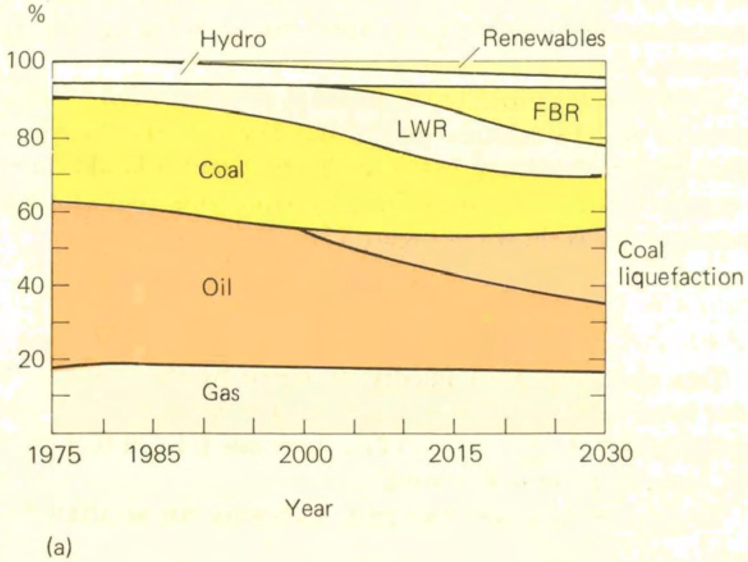
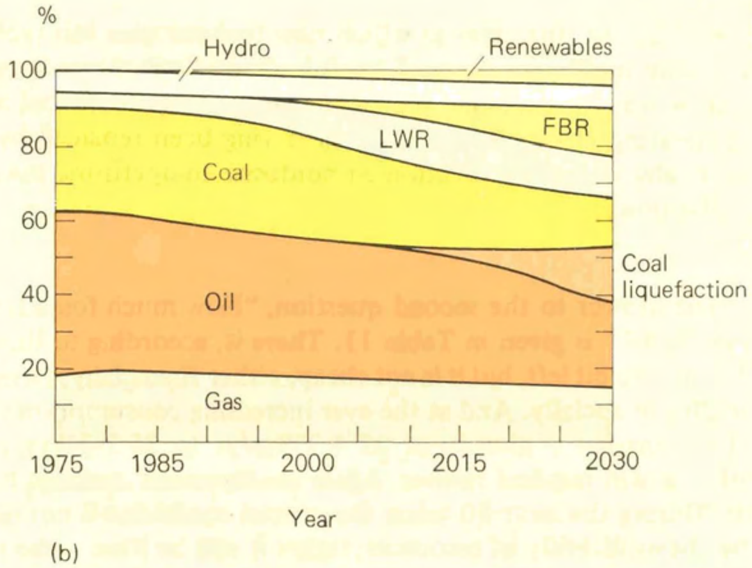


Figure 12. The global primary energy shares by source for (a) the high scenario, (b) the low scenario.



liquids demand that is met by conventional oil reserves, including those yet to be discovered, is small. For the world as a whole, Figure 14 describes essentially the same story, though using slightly different terms.

Even with the projected increases in oil production of all sorts, Figures 13 and 14 indicate that in the 21st century the scenarios project an increasing gap between the demand for liquid fuels and the supply of oil. The gap is filled by liquefying coal at a rapidly increasing rate, as shown in Figure 15.

Two questions are immediately raised by these results. Why do the fossil fuels continue to dominate the world's energy system so persistently? And, given this fact, how much fossil fuel is left in 2030, according to the scenarios?

To the first question, two partial answers can be offered:

- First, there is the steadily increasing demand for liquid fuels, although both scenarios assume that in the future they will increasingly be reserved for essential needs (such as transportation and chemical feedstocks). In a sense, the demand for liquid fuels constitutes the key problem within the energy problem.

- Second, the rates at which new technologies can replace older, more inefficient users of fossil fuels are limited (see Section 2). Figure 15, for example, indicates that even by 2030 coal used for generating electricity is far from having been replaced by its theoretically unlimited (Section 3) nonfossil competitors, nuclear and solar power.

The answer to the second question, "How much fossil fuel is left in 2030?" is given in Table 11. There is, according to the scenarios, quite a bit left, but it is not cheap, either financially, environmentally, or socially. And at the ever increasing consumption rates of the scenarios – already at 22.4 TWyr/yr to 35.7 TWyr/yr in 2030 – it will not last forever. Again the scenarios' message is the same. During the next 50 years the crucial constraint is not likely to be the availability of resources; rather it will be time – the time needed to reduce the demand for liquid fuels and the time it takes nonfossil technologies to penetrate the primary energy market.

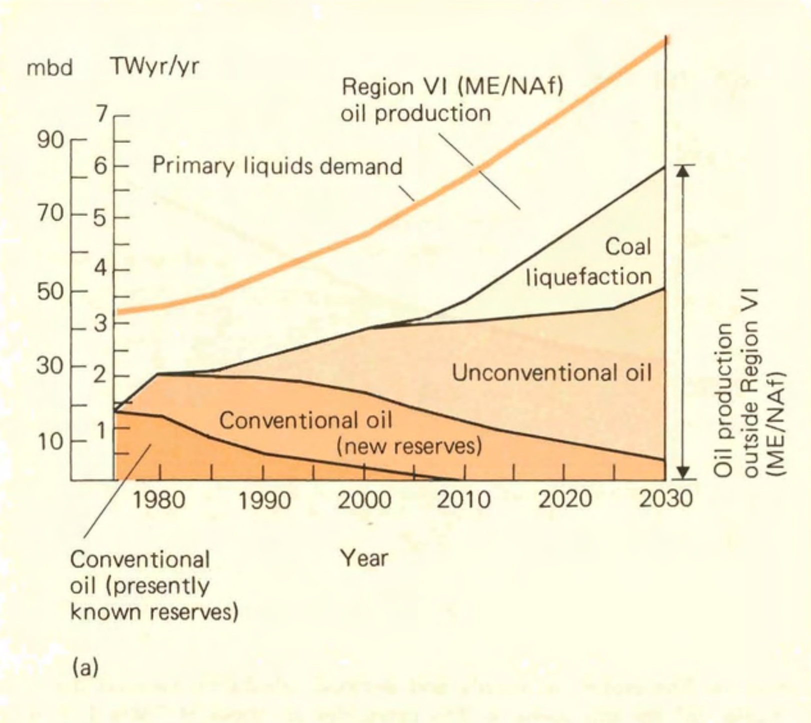
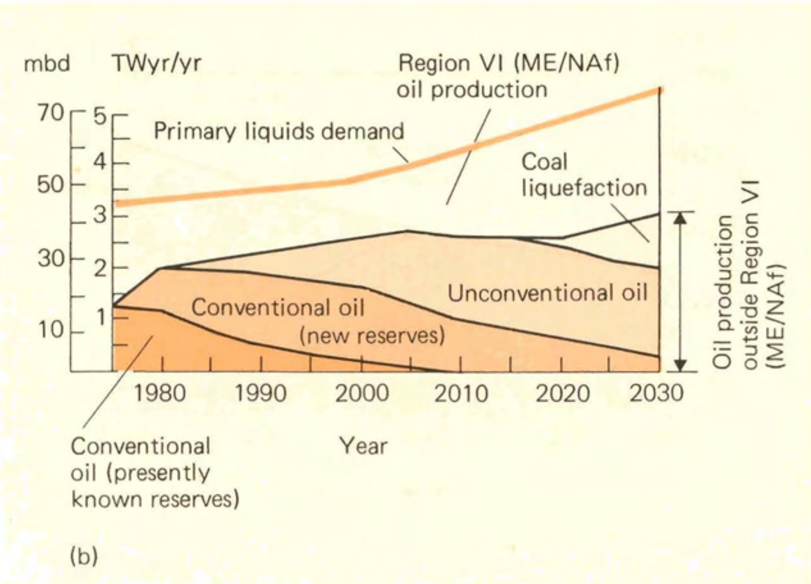


Figure 13. The oil supply and demand calculated for the regions with non-centrally planned economies from (a) the high scenario, (b) the low scenario.



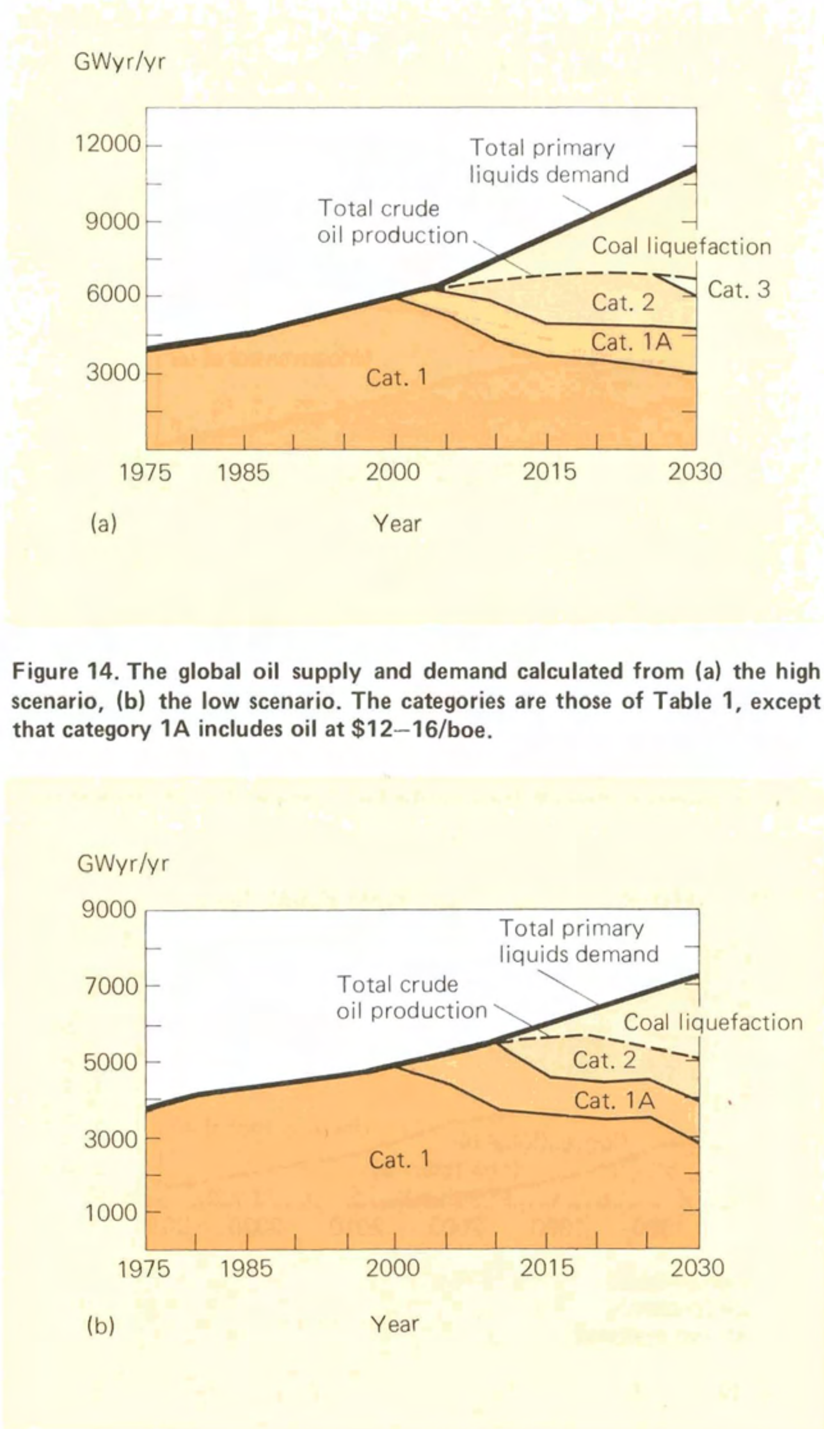


Figure 14. The global oil supply and demand calculated from (a) the high scenario, (b) the low scenario. The categories are those of Table 1, except that category 1A includes oil at $12–16/boe.

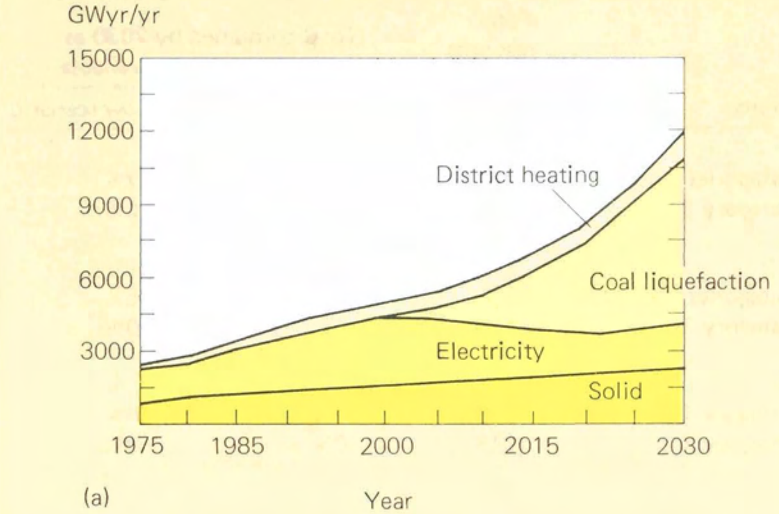


Figure 15. The global coal supply and demand calculated from (a) the high scenario, (b) the low scenario.

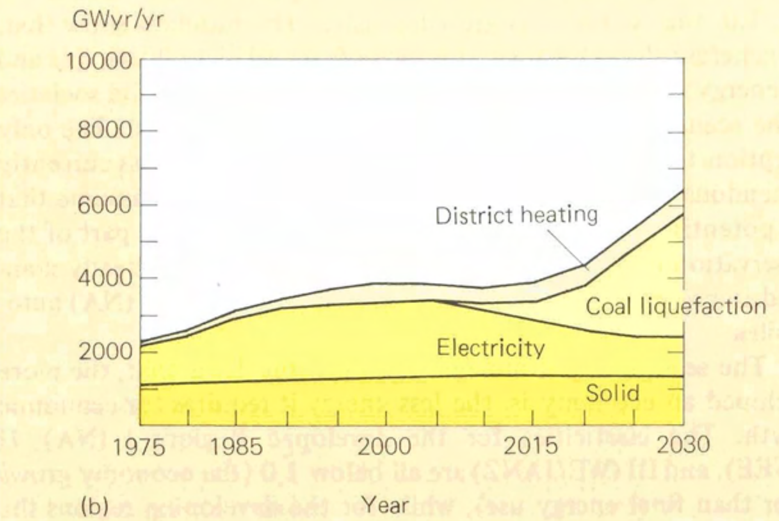


TABLE 11 The cumulative uses of fossil fuels.

Resource	Total resource available (TWyr)	Total consumed by 2030 as percentage of total available	
		High scenario	Low scenario
Oil			
Categories 1 and 2	464	68%	57%
Category 3	373	1%	0%
Gas			
Categories 1 and 2	408	49%	36%
Category 3	130	0%	0%
Coal			
Category 1	560	61%	40%
Category 2	1019	0%	0%

Two important economic interpretations of the scenario results are displayed in Table 12 and Figure 16. The table shows how the projected growth in final energy consumption compares with the economic growth rates that were assumed at the beginning of the scenarios. The comparison is in terms of the *final energy to gross domestic product elasticity* (for definition, see the Appendix). The higher this number, the faster final energy use is growing in relation to the economy as a whole. If the value is greater than 1.0, final energy use is growing faster than the economy; if the value is less than 1.0, the economy is growing faster. The numbers show that, as a general rule, as the scenarios move from 1975 to 2030, less and less energy is needed to fuel economic growth; that is, the societies of the scenarios are becoming ever more conservationist. The only exception to this trend is Region I (NA), because of its currently tremendous potential for conservation. The scenarios assume that this potential will be exploited quickly; in fact, a large part of the conservation occurring before 2000 is due simply to already mandated improvements in the fuel efficiencies of Region I (NA) automobiles.

The second important message of Table 12 is that, the more developed an economy is, the less energy it requires for economic growth. The elasticities for the developed Regions I (NA), II (SU/EE), and III (WE/JANZ) are all below 1.0 (the economy grows faster than final energy use), while for the developing regions the elasticities are predominantly greater than 1.0 (final energy use grows faster than the economy).

TABLE 12 Final energy to GDP elasticities, 1950–2030, for the IIASA high and low scenarios.

	Historical	Scenario projection							
		1975–1985		1985–2000		2000–2015		2015–2030	
Region	1950–1975	High	Low	High	Low	High	Low	High	Low
I (NA)	0.84	0.31	0.24	0.43	0.38	0.53	0.53	0.48	0.46
II (SU/EE)	0.68	0.59	0.54	0.58	0.57	0.52	0.50	0.53	0.41
III (WE/JANZ)	0.84	0.77	0.67	0.65	0.64	0.58	0.60	0.51	0.49
IV (LA)	1.21	1.07	1.10	1.01	1.03	0.97	0.95	0.90	0.88
V (Af/SEA)	1.42	1.20	1.19	1.08	1.12	1.05	1.14	1.01	1.06
VI (ME/NAf)	1.17	1.12	1.21	1.07	1.11	0.95	1.01	0.81	0.93
VII (C/CPA)	1.53	1.10	1.02	1.02	0.98	1.02	0.99	0.96	0.90
World	0.87	0.69	0.64	0.73	0.73	0.78	0.79	0.77	0.74

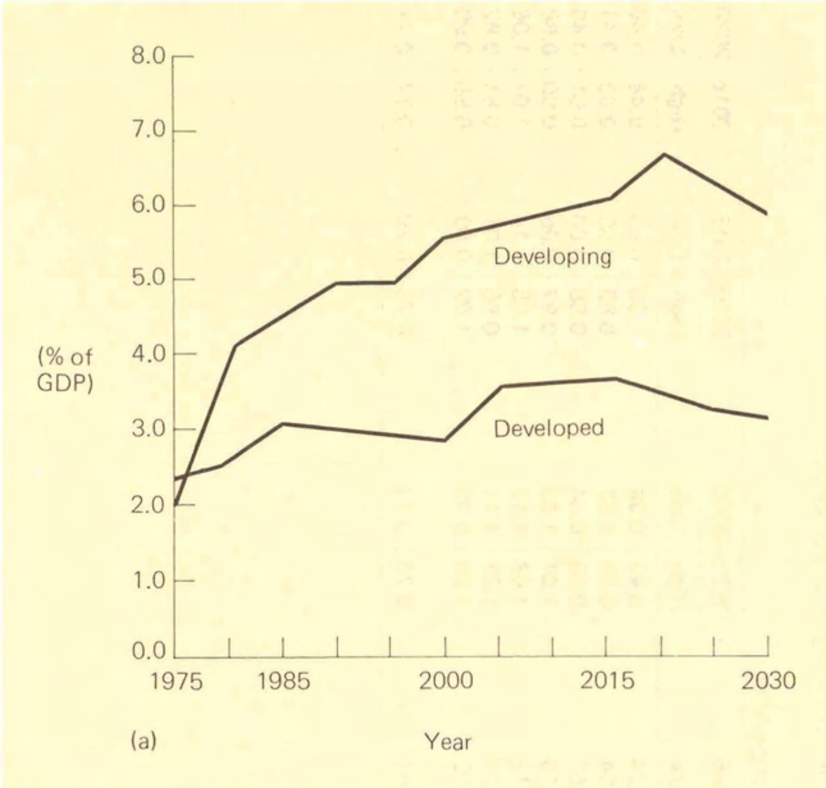
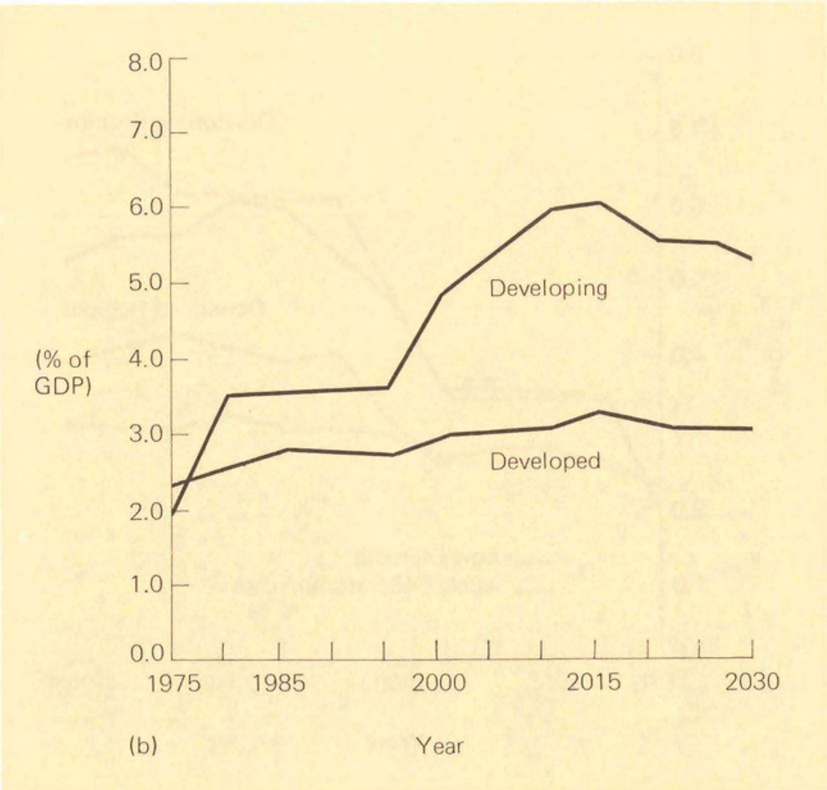


Figure 16. Direct plus indirect energy investments as a share of gross domestic product for developed and developing regions: (a) high scenario, (b) low scenario.

The capital investments required to support the expanding energy supplies of the scenarios are indicated in Figure 16, which shows the percentages of the gross domestic product that must be invested in energy facilities. As might be expected, the situation is most difficult in the developing countries, where, in the high scenario for example, energy investments peak at 6.6% of GDP around 2020.

In addition to the two benchmark scenarios, three alternative cases were also analyzed, though in less detail. As suggested by their titles, two of these – the nuclear moratorium case and the enhanced nuclear case – involved major changes in the assumptions concerning energy supply. The third alternative arose from a major change



on the demand side: What are the implications if we assume that the global primary energy demand in 2030 does not exceed 16 TWyr/yr (compared with the low scenario value of 22.4 TWyr/yr)? The key characteristics of the three alternative cases turned out to be as follows.

- The nuclear moratorium case indicates that the energy demands of the low scenario can indeed be met without new nuclear capacity. Fossil fuel supplies are depleted more alarmingly than in the low scenario, gas assumes an especially important role, and solar electric power expands at its maximum rate (see Section 2). Needs are met, but costs are higher than in the low scenario (Figure 17). As the cushion of fossil fuels is diminished, time therefore becomes a tighter constraint.

- In the enhanced nuclear case, in which energy demand is assumed to be at the same levels as in the high scenario, the unsettling depletion of fossil resources, so characteristic of both scenarios and the nuclear moratorium case, is abated only slightly. Despite

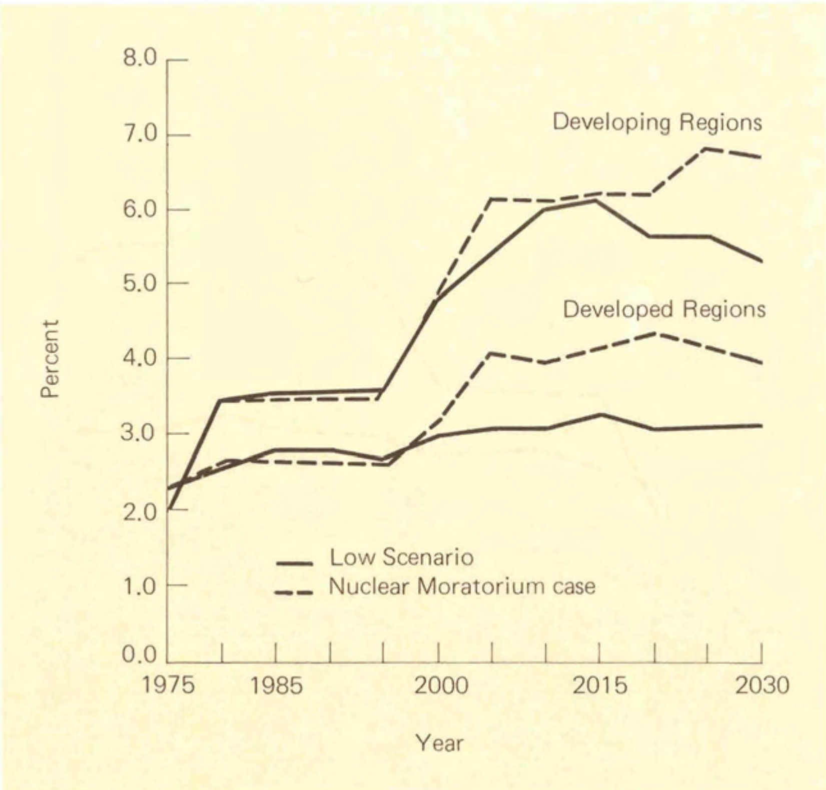


Figure 17. The total energy investment as a share of the gross domestic product for the low scenario and the nuclear moratorium case.

the use of nuclear-generated hydrogen to produce liquid fuels from coal efficiently, in 2030 only 14% of the liquid fuels produced are of nuclear origin, and the overall share of the global primary energy market held by nuclear power is only 29%. Although this is higher than its 23% market share in the high scenario, it remains below the 2030 potential of 40% that appeared in both Sections 2 and 3. The required investments are slightly higher than those of the high scenario (Figure 18).

- The case in which primary energy demand reaches only 16 TWyr/yr in 2030 necessarily implies zero growth during the next 50 years in the world's average per capita energy consumption. This is because 16 TWyr/yr represents a doubling in the world's primary energy consumption over the 1975 to 2030 period, which

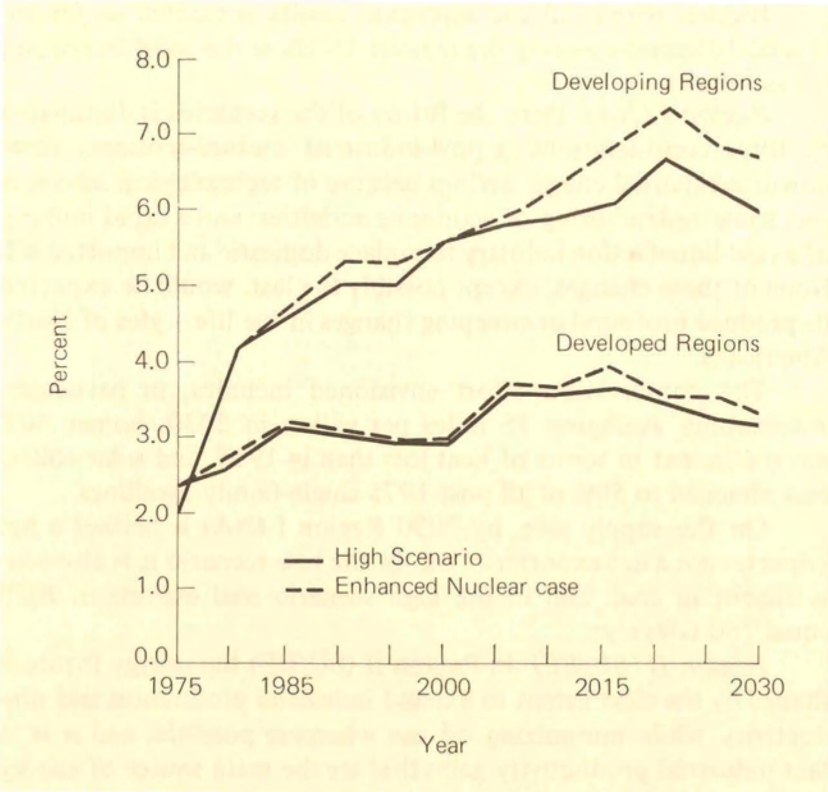


Figure 18. The total energy investment as a share of the gross domestic product for the high scenario and the enhanced nuclear case.

corresponds precisely with the projected doubling of the world's population during the same period – from 4 billion in 1975 to 8 billion in 2030. For the developing countries this case assumes, however, that projected energy uses are essentially as in the low scenario. The result is that per capita energy consumption in, particularly, Regions I (NA) and III (WE/JANZ) must drop significantly. Mathematically this can be accomplished by imposing a variety of assumptions: faster technological advances, a more rapid economic shift away from heavy industries and toward the service sector, reducing the projected uses of cars and planes, no air conditioning at all in Region III (WE/JANZ), and so forth. Whether these mathematical manipulations could be reproduced in the real world by manipulating taxes, regulations, prices, subsidies, and all the rest is an open question. It is clear, however, that the carefully coordinated effort required would be unprecedented.

Hidden within all the aggregate results presented so far are crucial differences among the regions. Of these the most important are as follows.

Region I (NA). Here the future of the scenarios is dominated by three considerations: a post-industrial, mature-economy slowdown; substantial energy savings because of technological advances and some restructuring of economic activities; and a rapid buildup of a coal-liquefaction industry to replace domestic and imported oil. None of these changes, except possibly the last, would be expected to produce profound or sweeping changes in the life-styles of North Americans.

The conservation effort envisioned includes, in particular, automobiles averaging 35 miles per gallon in 2030, homes 40% more efficient in terms of heat loss than in 1975, and solar collectors attached to 50% of all post-1975 single-family dwellings.

On the supply side, by 2030 Region I (NA) is neither a net importer nor a net exporter of oil. In the low scenario it is also self-sufficient in coal, and in the high scenario coal exports in 2030 equal 750 GWyr/yr.

Region II (SU/EE). In Region II (SU/EE) the energy future is shaped by the clear intent to expand industrial production and productivity while minimizing oil use wherever possible, and it is in fact industrial productivity gains that are the main source of energy savings.

Through minimizing liquid fuel use and exploiting the vast gas and coal resources of Soviet Asia for district heat and power supplies the Soviet Union avoids becoming an oil importer. Oil exports from the Soviet Union to Eastern Europe continue, and exports of coal and gas from the region as a whole expand. The use of primary energy sources shifts toward nuclear power and coal. In the high scenario nuclear power's share in 2030 is 33%; coal's is 38%.

Region III (WE/JANZ). Although levels of GDP per capita in Region III (WE/JANZ) in 2030 exceed those of Region I (NA) in 1975, Region III (WE/JANZ) does not adopt North American life-styles entirely. Extensive use of public transit systems continues, the use of air conditioning remains small, and the use of electricity for home appliances does not even reach 1975 United States levels.

In 2030 in the high scenario Region III (WE/JANZ) is still importing 600 GWyr/yr of oil from Region VI (ME/NAf). In the low scenario the oil imports in 2030 are even higher, equalling 1100 GWyr/yr. The situation concerning coal imports is, however, the reverse: 1600 GWyr/yr for the high scenario in 2030, but none for the low scenario.

Region IV (LA). Like other developing regions, Latin America experiences a more rapid growth in GDP than the developed regions. The range is from a 1975–2030 average of 3.5% per year in the low scenario to 4.4% per year in the high scenario.

Oil has been and continues to be the dominant energy source. In 2030 oil production in Latin America equals 30% in the low scenario and 45% in the high scenario of the total global oil production in 1975. Nevertheless, in both scenarios oil's share of the primary energy supply drops slightly. By 2030 the region is no longer an oil exporter in either scenario.

Region V (Af/SEA). Here the picture painted by the scenarios is bleakest. Endowed with neither energy resource riches nor capital wealth, while having large and rapidly growing populations, the favorable long-term energy options for Region V (Af/SEA) seem few.

GDP growth rates are higher than in the developed regions, averaging from 3.3% per year (low scenario) to 4.3% per year (high scenario) during the 1975–2030 period. The current shifts toward the industrial, service, and energy sectors continue, as does the decline in the agricultural sector (from 36% of GDP in 1975 to 16% by 2030 in the high scenario).

Currently the region is a net oil exporter because Nigeria, Gabon, and Indonesia are exporters and aggregate liquid fuel demands are relatively low. In both scenarios, however, the region becomes a net oil importer by the turn of the century, putting it squarely in competition with Region III (WE/JANZ) for Region VI's (ME/NAf) oil.

Region VI (ME/NAf). Internationally, by 2030 Region VI (ME/NAf) is the only oil exporting region, and domestically, approximately 90% of its primary energy needs are met by oil and gas. Its economic growth rates are the highest of the developing regions at 3.6% per year (low scenario) and 5.1% per year (high scenario) as 1975–2030 averages. In the high scenario this leads to GDP per capita levels in 2030 that exceed those of Region I (NA) in 1975.

Region VII (C/CPA). GDP growth rates in Region VII (C/CPA) are high, but so are population growth rates. By 2030, GDP per capita levels reach approximately those of Region IV (LA) in 1975. The region remains neither an importer nor an exporter of energy. Its domestic oil supplies are effectively exhausted around 2030 in both scenarios, thus requiring increasing coal production and coal liquefaction in the 21st century. In the high scenario coal production in 2030 reaches 3.2 TWyr/yr, as compared with 0.45 TWyr/yr in 1975.

This summary of scenario results is intended as neither a prediction of the future nor a prescription for solving the world's energy problem. Rather it reports an exercise designed to provide insights and a better understanding of the long-term global nature of that problem. The objective was simply to detail the engineering and economic consequences that might follow from several different sets of reasonable assumptions. Thus the futures described in the two scenarios and three alternative cases do not chart a path toward any special goal; more particularly, they do not chart a path toward a sustainable global energy system. That is the concern of Section 5.

5
Paths to a Sustainable Future

A central objective of the IIASA study was, as stated at the outset, to determine how the world might successfully negotiate the transition to a truly sustainable global energy system. This motivated the historical analysis of Section 2 (Where have we come from?), the long-term evaluation of supply possibilities in Section 3 (Where might we want to get to?), and the detailed analysis of the more near-term future in Section 4 (In what direction are we currently headed?). In the end, the results did not, by themselves, provide a definitive answer to the original question – but they did prove suggestive, and it is these suggestions that are the subject of this last section.

There is an underlying unifying theme running throughout the work that, while not surprising in hindsight, was not obvious at the beginning. It has to do with the general pattern of the world's response to the increasing scarcity and expense of energy resources.

As we have become more aware of the problems of energy resources throughout the 1970s, we have begun to adapt in ways that make better use of the limited energy currently available. Sometimes we label these adaptations conservation; sometimes we call them improvements in efficiency; sometimes they are referred to as productivity increases. Whatever we call them, they all involve reducing the energy needed to produce some service (be it a well heated sitting room or intercity jet travel) by replacing it with something else. In some cases this replacement is in the form of capital resources (e.g., investing in home insulation); in others it can be classified as labor (e.g., periodic tuneups of an automobile to increase its gas mileage); and in still others it may be labeled simply ingenuity or know-how (e.g., anything from more carefully planned shopping trips to large-scale reconfigurations of industrial processes).

At a personal level, we are all familiar with such adaptations – such substitutions of capital, labor, or know-how for energy in producing services. At more collective levels, ranging from small business enterprises to international alliances, we are becoming more familiar with them. And what will appear in the discussion to follow is the conviction that what may now seem to us to be perhaps quite sophisticated, energy-conserving arrangements of our resources of capital, labor, know-how, and energy indicate only the direction in which we can travel. They in no sense even begin to suggest the limits of what can be done.

Of particular importance is the notion of investing these resources to increase the stock available in each category. Again, these ideas are hardly unfamiliar – investments in education, in research and development, in capital equipment, in exploratory drilling have all contributed, and continue to contribute, to the resources that we can put to use. What is less familiar is what these same concepts lead us to when applied from a global perspective contemplating the next half century and beyond.

Nuclear fission, nuclear fusion, and hard solar power were described in Section 3 as possible bases for a sustainable energy system. However, that analysis ignored entirely the question of energy demand – in what forms energy will in fact be needed – and from this perspective it is clear that nuclear power and solar power are not without their disadvantages. As generally conceived, they produce energy in the form of heat that is assumed to be used directly sometimes or, more often, converted to electricity. And both heat and, to a lesser extent, electricity have their drawbacks: they are difficult to store and to transport. It is for these reasons that, in situations where favorable storage and transport characteristics are particularly important, we have tended to rely on chemical energy carriers, principally in the form of the fossil fuels.

It is precisely these fossil energy carriers, however, that are getting scarcer. While electricity can replace them to some degree, for the reasons listed above we might be better off developing an alternative that is itself a chemical, rather than an electrical, energy carrier.

A possible candidate is hydrogen. It is attractive, first, because the technology for converting electricity to hydrogen via the electrolysis of water is well developed. Second, processes for converting nuclear or solar heat directly to hydrogen without the intermediate step of electricity production appear promising. Third, hydrogen is much more easily stored than electricity and might be particularly suited to large-scale storage in depleted natural gas reservoirs. Fourth, the piping networks and the infrastructure associated with further large-scale use of natural gas would be especially suited to a gradual replacement of natural gas by hydrogen. And fifth, when hydrogen is burned (recombined with oxygen), it produces essentially only water vapor, thus making its use environmentally attractive.

To introduce hydrogen on a scale comparable with that of electricity cannot be done overnight; but it can most certainly be started in a way that contributes from the beginning to solving the critical, immediately pressing liquid fuels problem. Consider, first, hydrogen production. Among the many possible production processes there are some that begin by converting methane (the principal component of natural gas) into methanol, a liquid hydrocarbon fuel. Thus, even to introduce just the first step of such processes would be to introduce a capability to convert natural gas to liquid fuel – to convert a large resource that is often wasted (flared) because of the world's currently undersized long-distance gas transportation system into a form in which it can be much more easily transported, stored, and used.

Once hydrogen is available, moreover, it can be used to exploit more efficiently the most extensive of the fossil fuels – coal. Specifically it would allow the introduction of allothermal coal-liquefaction schemes, as discussed in Section 3. Thus, hydrogen produced by nuclear or solar facilities, in conjunction with the heat generated by the same facilities, could be used to extend by a factor of three to four the portion of our coal resources that must be devoted to producing liquid fuels. In view of the results of Section 4, such an extension could be critical.

Still, to produce and use synthetic liquid hydrocarbons from coal and other fossil resources is to consume the store of carbon atoms that is available in these particularly convenient forms. If liquid hydrocarbons are therefore to play any kind of role in a sustainable energy system, the problem that must be solved is that of recycling carbon – of extracting carbon dioxide from the atmosphere and combining it, rather than fossil fuels, with hydrogen to produce liquid hydrocarbons. The simplest way to exploit the carbon reservoir in the atmosphere is to use the plants that are already extracting carbon dioxide continuously. Much technology for converting biomass into liquid fuels has been developed, and here again, external sources of hydrogen and heat can help conserve the carbon resource. A more direct way to conserve the carbon atoms incorporated in synthetic hydrocarbons is to capture immediately the combustion gases released when the fuel is burned and then recycle them.

These are only suggestions. They are motivated by the effort to fill a crucial gap revealed by the analyses of the last three sections, the gap between the immediate but apparently persistent demand for liquid hydrocarbons and the supply of heat and electricity that could be produced by the only possible sustainable energy sources: those based on nuclear and solar technologies. The central notion in filling this gap is the importance of using the world's store of carbon atoms prudently. The basic ideas are familiar – recycling and using coal as a bridge to the future. Only the scale is different: the continual recycling of the world's supply of carbon atoms forever – and the investment of our coal resources in building not only a bridge to the 21st century, but quite possibly a bridge extending all the way to the 22nd century.

Only the outlines of how the world's energy system might ultimately develop can be sketched here. How they might be filled in must be left for subsequent analysts, and whether the course suggested here will be pursued at all must be left for subsequent generations. It is clear, however, that building a sustainable energy system will require the continual expansion of the world's productive capabilities – in all dimensions. This is why it is so important that the eight billion or so people living in 2030 be rich, not poor, and much richer than today. That they be rich does not mean that they must discover some new treasure of physical resources that has been completely overlooked in the study reported here; it means instead that they and their predecessors will have learned how to use the limited resources available more efficiently, more ingeniously, more productively. The process is continuous, and it is cumulative.

Appendix

Forms of energy

This report distinguishes between primary, secondary, final, and useful energy.

Primary energy refers to energy in the form of natural resources. Examples are oil, natural gas, freshly mined coal, water flowing over a dam, and natural uranium.

Secondary energy forms are those to which primary energy is usually converted in order to be transported to consumers. Examples are gasoline, electricity, charcoal, sorted and graded coal, and cut and split firewood. Note that a resource such as natural gas can be considered both as a form of primary energy and a form of secondary energy. The form in which it appears in nature is also the form in which it is transported to consumers.

Final energy refers to the forms in which energy is consumed once it has reached the user – the energy in a motor, a stove, a computer, or a lightbulb. Once again it is worth noting that natural gas can also be considered a form of final energy.

Useful energy is the energy ultimately stored in a product or used for a service – a well-lit room, a moving car, or a telephone conversation.

Energy units

There are two fundamental types of energy units: those that describe *amounts* of energy, and those that describe *rates* at which energy is supplied, converted, transported, or used. In the first category are units such as barrels of oil equivalent (boe), tons of coal equivalent (tce), or kilowatt-hours of electricity (kWhr(e)). In the second category are million barrels of oil per day (mbd), tons of coal equivalent per year (tce/yr), and kilowatt-hours of electricity per year (kWhr(e)/yr).

The unit used most commonly in this report for *amounts* of energy is the terawatt-year (TWyr). One terawatt-year (1 TWyr) is equal to 1,000,000,000,000 watt-years (which can also be written as 10^{12} Wyr). It is therefore also equal to 1,000,000,000 kilowatt-years (10^9 kWyr) or 1,000,000 megawatt-years (10^6 MWyr) or 1000 gigawatt-years (10^3 GWyr).

The unit most commonly used here for *rates* of energy supply, conversion, transportation, and use is the terawatt-year per year (TWyr/yr). The unit terawatt (TW), which is sometimes used in place of terawatt-year per year (TWyr/yr), is in this report reserved for the description of the *capacities* of various energy conversion facilities. Thus the capacity of an electricity generating station might be listed as 1000 MW(e) (= 0.001 TW(e)). Since energy conversion facilities seldom operate at their installed capacity all year long, their ratings in TW or GW or MW will differ from the actual rate at which they convert energy, as expressed in TWyr/yr, GWyr/yr, or MWyr/yr.

Some particularly useful conversion factors are

1 TWyr = 30 quads (30×10^{15} British thermal units [BTU])

1 TWyr = 30 trillion cubic feet of gas
(30×10^{12} ft^3 of gas)

1 TWyr = 1.1 billion metric tons of coal equivalent
(1.1×10^9 tce)

1 TWyr = 5.2 billion barrels of oil equivalent
(5.2×10^9 boe)

Elasticity

The final energy to gross domestic product elasticity e is defined as follows: if $E(t)$ is the amount of final energy consumed at time t and $G(t)$ is the gross domestic product at time t, then, for $t_1 < t_2$, the elasticity e is the exponent in this equation:

$$E(t_2)/E(t_1) = [G(t_2)/G(t_1)]^e$$

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Report by the Energy Systems Program Group of IIASA, Wolf Häfele, *Program Leader.* 837 pp. $45.00.

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1. Energy Models

RR-80-31. The IIASA Set of Energy Models: Its Design and Application. P.S. Basile. December 1980. 65 pp. $7.00

RR-78-17. MEDEE-2: A Model for Long-Term Energy Demand Evaluation. B. Lapillonne. November 1978. 45 pp. $6.00

RR-79-8. The Economic IMPACT Model. Yu.D. Kononov, A. Por. October 1979. 72 pp. $8.50

The Energy Supply Model MESSAGE. L. Schrattenholzer. 1981. (Forthcoming Research Report.)

A Long-Term Macroeconomic Equilibrium Model for the European Community. H.H. Rogner. 1981. (Forthcoming Research Report.)

Modeling of Large-Scale Energy Systems. Proceedings of the IIASA–IFAC Symposium on Modeling of Large-Scale Energy Systems. W. Häfele, Editor, L.K. Kirchmayer, Associate Editor. 1981. 462 pp. (Available from Pergamon Press.) $72.00

CP-74-3. Proceedings of IIASA Working Seminar on Energy Modeling, May 28–29, 1974. May 1974. 342 pp. $13.00

RR-74-10. A Review of Energy Models: No. 1 – May 1974. J.-P. Charpentier, Editor. July 1974. 102 pp. $8.50

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Dynamic Linear Programming Models of Energy, Resources, and Economy Development Systems. A Propoi, I. Zimin. 1981. (Forthcoming Research Report.)

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