ON ENERGY AND ECONOMIC DEVELOPMENT

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FOREWORD

The Energy Systems Program at the International Institute for Applied Systems Analysis has completed a comprehensive investigation of the worldwide balance of supply and demand for energy over the next fifty years, and has reported its findings in a series of publications (listed below) under the title *Energy in a Finite World.*

This analysis involved seven years of international and interdisciplinary work aimed at clarifying the factual technoeconomic possibilities for achieving this balance between world energy demands and the possibilities for meeting them. Global scenarios were the devices used to strike this balance; the scenarios were based on seven world regions differentiated on the basis of geography, geopolitics, and economics.

With this global view of what seems possible and what appears to be impossible over the next fifty years within a frame of idealized behavior and preferences, IIASA is now tracing the implications at regional and national levels. Such results will provide a background for efforts undertaken by individual countries to tackle their own local-scale energy problems from an operational viewpoint, where their approach is dictated by decisions taken in the past, current and near-future imperatives, and the necessity to survive and compete in the situations that they face.

In contrast, this paper presents a different, but complementary view of IIASA's energy analysis. Based on the realization that technoeconomic approaches often "solve" problems by splitting them and transferring their parts elsewhere, it searches for the deeper roots of obvious failures in the evolution of the energy segment of man's vital infrastructure, and seeks to identify the limits of sound principles that govern past and present decisions and that become evident when we examine such failures.

From this point of view, the author describes a serious conflict between macroeconomic and microeconomic decisions that will occur if scientific and technological progress does not compensate for a decline in the quality of the world's energy resources. Resolving this conflict is an important matter for institutional and political forces to deal with.

We appreciate the opportunity that the *Scientific American* offered us to present these ideas in its special September 1980 issue devoted to the wider problems of economic development in a world that experiences failures and inadequacies in most of its other basic systems: food, water, settlement, and industrial production.

ROGER LEVIEN
Director

The publications in the series *Energy in a Finite World* are all reports by the Energy Systems Program Group of the International Institute for Applied Systems Analysis, Wolf Häfele, Program Leader:

> *Energy in a Finite World: 1. Paths to a Sustainable Future*, Ballinger Publishing Company, Cambridge, Massachusetts 02138, USA, 225 pages. An account for the general reader.
> *Energy in a Finite World: 2. A Global Systems Analysis*, Ballinger Publishing Company, Cambridge, Massachusetts 02138, USA, 837 pages. A comprehensive account of the technical details of the analysis.
> *Energy in a Finite World: Executive Summary*, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria, 74 pages. A brief account for the general reader; copies available from the Publications Department of the Institute free of charge.

The Appendix to this reprint lists other selected energy-related IIASA publications.

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Energy

by Wolfgang Sassin

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Energy

The future growth in the global demand for energy will come mainly from the less developed countries. If the demand is to be satisfied, the transfer of technology from the developed countries is essential

by Wolfgang Sassin

The world economy entered a new era in 1973, when the Organization of Petroleum Exporting Countries (OPEC) announced the first in a series of sharp increases in the price of crude oil sold on the world market. The sudden, widespread recognition of the finiteness of the earth's liquid fossil-fuel resources, brought on largely by the OPEC action, has left the majority of petroleum-importing countries—developed and less developed alike—in a continuing state of shock and uncertainty, which has come to be epitomized as the "energy crisis." It is not possible to predict with any confidence how long the transition to a stabler world energy perspective will last or exactly what its outcome will be. What is clear is the need, more urgent now than ever, to reevaluate the role of energy consumption as both the prime mover and the key indicator of economic development.

For the past six years my colleagues and I in the Energy Systems Program of the International Institute for Applied Systems Analysis (IIASA) at Laxenburg in Austria have been conducting just such a reevaluation, with a view to projecting a range of possible future trends in the world's energy supply and demand. In this article I shall draw heavily on the results obtained so far in that continuing study.

From the beginning of the Industrial Revolution, dating at least from James Watt's steam engine of the 1760's, energy conservation has been an integral part of the strategy of development. Various lines of technological progress, ranging from the invention of new mechanical devices to the development of industrial chemical processes, are characterized by a steady improvement in performance measured in terms of energy efficiency [*see top illustration on next page*]. The success of the basic engineering doctrine of "doing more with less" has resulted in a proliferation of "technical slaves" capable of substituting for human labor or animal power. The food the slaves consume is energy.

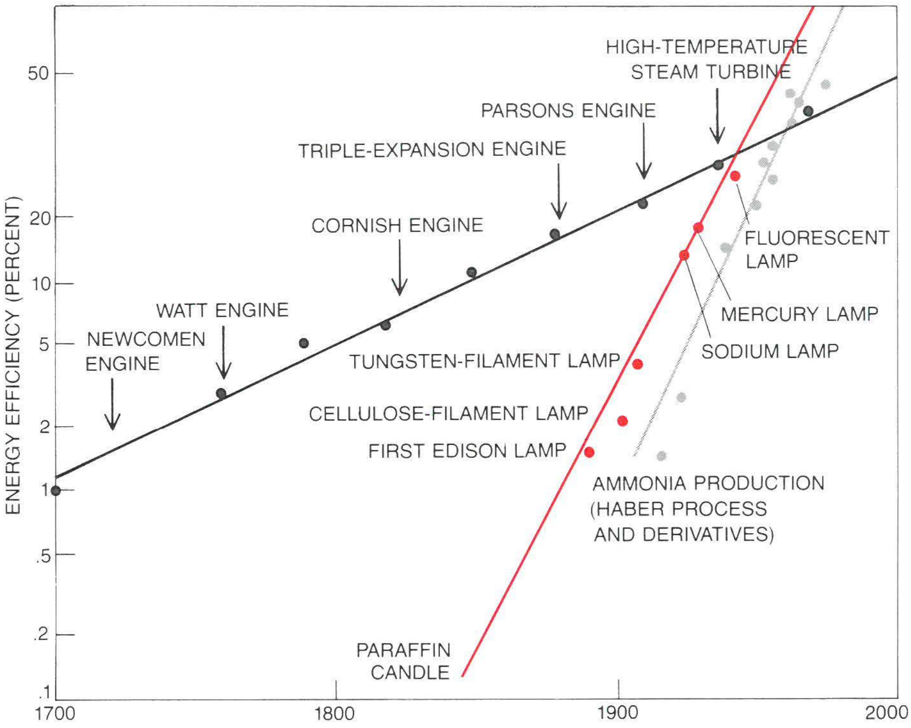
The acceleration of modern technology, fueled by a seemingly limitless supply of cheap oil, was particularly rapid in the already industrialized countries of the capitalist and communist blocs (respectively the "first world" and "second world") in the first decades after World War II. Recently the trend toward ever greater energy efficiency and hence greater opportunity for economically feasible energy use has been augmented in these countries by the advent of automatic information-handling systems to help supervise the work of the technical slaves. The result is a world in which the distribution of energy consumption is grossly uneven.

As of 1975 the average rate of energy consumption in the world was approximately two kilowatt-years per person per year, or in simpler terms two kilowatts of quasi-continuous power per person. The average American consumed some 11 kilowatts, however, whereas the average inhabitant of the less developed "third world" consumed less than a kilowatt. (The average European accounted for about five kilowatts.) Since there is a well-established correlation between the energy input to a national economy and its economic output, measured in monetary units such as dollars, a graph representing the worldwide distribution of the consumption of energy also serves as a fair approximation of the spectrum of economic activity [*see bottom illustration on next page*].

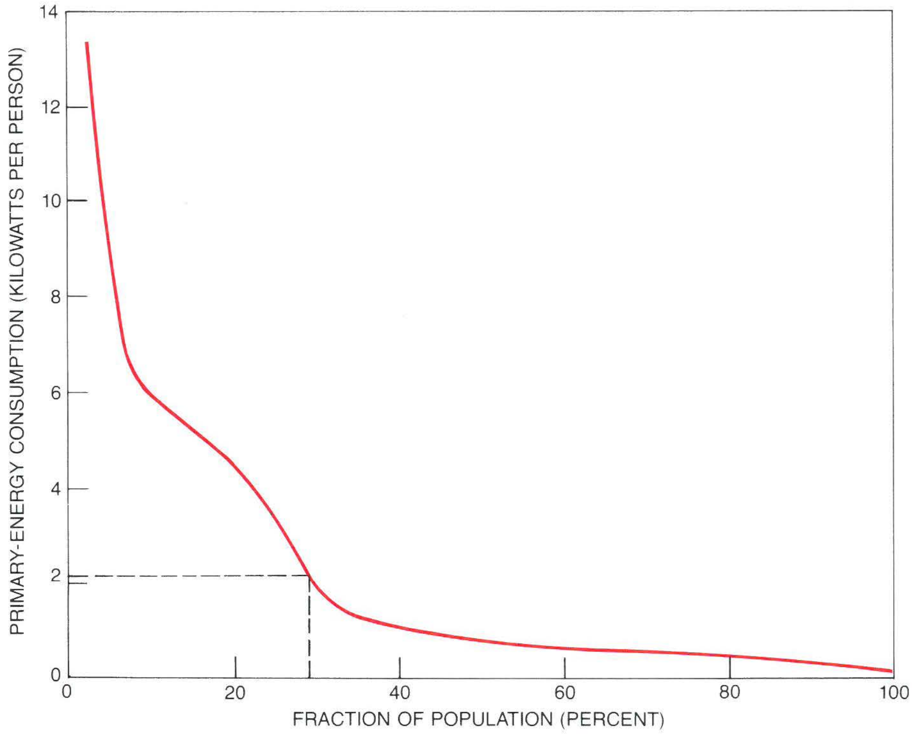
There is no doubt that the further spread of modern technology to the less developed parts of the world will result in a greatly increased demand for energy, aggravating the energy crisis. The only real uncertainties concern the rate and the ultimate extent of the growth in energy demand, and the makeup of the energy resources that will be called on to meet it. In order to investigate the potential future evolution of the global energy balance under these circumstances the IIASA Energy Systems Program has sought first of all to quantify as many as possible of the variables that have a bearing on this vital issue.

The task of quantification is complicated by many factors, among them the difficulty of determining the energy efficiency of a nation's productive capital stock (as technical slaves are usually called by economists). Normally one adds the theoretical heating values of the various forms of energy entering an economy and then compares this primary input with the designed output of the productive capital stock. Alternative primary forms of energy can differ widely, however, in their actual utilization. Some can be easily transported,

TSAIDAM BASIN, an extremely large interior sedimentary basin occupying much of northwestern Qinghai Province in the sparsely inhabited western part of China, is potentially a major energy-resource basin. Formed during the Mesozoic and Cenozoic eras, the basin covers an area of approximately 100,000 square kilometers. Exploration for evidence of fossil-fuel deposits began here in the mid-1950's, and several oil and gas fields have since been discovered and opened for production. Exploratory drilling is currently centered in the westernmost part of the basin, including the area shown in the enhanced false-color Landsat mosaic on the opposite page, made by digitally merging two consecutive Landsat scenes acquired as the satellite moved along its roughly north-south polar orbit. The mosaic was prepared by staff scientists at the U.S. Geological Survey's EROS Data Center who are participating with researchers from China's Ministry of Petroleum Industry in a joint program to investigate the applicability of remote sensing by satellite to petroleum exploration. Members of the U.S. team who visited the arid, perennially windswept site last year reported seeing numerous drill rigs operating in the area just north and east of the lake near the center of this image, particularly in the vicinity of an outcropping known to the Chinese as Yushashan (Tar Sand Hill). Before the establishment of the People's Republic in 1948 China was a net importer of petroleum; today its petroleum industry satisfies most domestic needs and provides a minor surplus for export.



INCREASING ENERGY EFFICIENCY characterizes three different lines of technological progress: the improvement in the performance of various steam engines (*black line*), the development of superior forms of lighting (*colored line*) and the refinement of industrial methods for producing ammonia (*gray line*). Energy efficiency is defined for this purpose as the ratio between the output and the input of thermodynamically "free" energy to a conversion process. When the energy efficiencies in each category are plotted on a logistic scale, as they are here, the data points lie along a straight line; on a linear scale the lines would be *S*-shaped curves.



DISTRIBUTION OF ENERGY CONSUMPTION in the world varies widely, as this graph for the year 1975 indicates. The total amount of primary energy generated commercially that year was on the order of 8.2 terawatts (trillions of watts), and the world population was about four billion. The average rate of energy consumption was therefore approximately 2.1 kilowatts per person (*broken-line scale markers*). The top 5 percent of the world's population in terms of energy consumption, however, averaged more than 10 kilowatts per person, whereas the bottom 50 percent averaged less than a kilowatt. An average energy-consumption rate of a kilowatt corresponds to the combustion of about a metric ton of coal per person per year.

stored and converted; others cannot. Such limitations may entail significant losses, since part of the original energy must be reinvested to "step up" the quality of the final-energy form. The success of any energy industry is ultimately dependent on its ability to produce final-energy forms that are attractive in terms of both low cost and (normally) low primary-energy losses.

Toward that end the established energy industries in the developed countries have over the years tapped ever more versatile forms of primary energy, that is, forms requiring less upgrading. Thus the industrialized countries have passed in a rational progression from wood through coal to oil, natural gas and uranium. This powerful trend in the direction of greater overall energy efficiency is manifested in the historical record of the relative shares of the major primary-energy forms in the global energy balance [*see illustration on opposite page*]. Switching from abundant coal resources to more efficient, if less abundant, oil and natural-gas resources has led to economic gains in excess of the costs involved in setting up worldwide distribution systems for oil and gas. A crucial question for the future is whether this traditional cost-minimizing strategy will continue to serve the common good.

The research at IIASA has focused on the medium-term (to the year 2000) and long-term (to 2030) aspects of energy and its interaction with other constituents of an economy. A major objective has been to analyze the possibilities of extending the supply of energy to provide more oil, gas, coal, nuclear fuel and other forms of energy, including new ones. Any such exercise would be meaningless, however, without a simultaneous evaluation of the future energy demand, the force driving any extension of the supply.

Our approach is based on the assumption of a cooperating world, free of major wars or social disruptions. This assumption is in turn a prerequisite for several other operating assumptions: the guarantee of open access by all nations to the world's energy resources, the universal availability of effective means of energy production and conversion, and the widespread adoption of energy-efficient consumer technologies. It goes without saying that this may not be the way of the future. Nevertheless, quantifications based on such assumptions serve a useful purpose: they establish the minimum technological and economic effort required to balance energy supply and demand.

The potential evolution of the world energy balance is analyzed at IIASA in the form of scenarios. Such scenarios are not merely extrapolations of past trends. They contain an element of judgment, insofar as inconsistencies arising from conflicting trends have to be resolved. Carefully constructed scenarios can be seen as ways of describing potential futures. They are not predictions. Instead they take into account both fond aspirations and realistic expectations. The results presented in the remainder of this article refer to the picture of the future world energy balance that emerges from the IIASA scenarios.

The transition from a stable world population of about a billion people in 1800 to one of perhaps 10 billion is already well under way. By a conservative estimate the world's population will double, from four billion to eight billion, within the next 50 years. Whereas the growth of energy demand in the period after World War II stemmed mainly from industrial development in the northern countries, where the population was already fairly stable, the future energy demand will be generated mainly by the demographic growth of the southern countries. In order to take into account the large differences between countries in their levels of economic development, their population dynamics, their energy resources and other pertinent factors the IIASA has divided the world into seven major regions [*see illustration on next page*]. A complex set of computer models serves to project the economic and technological development of each of these regions.

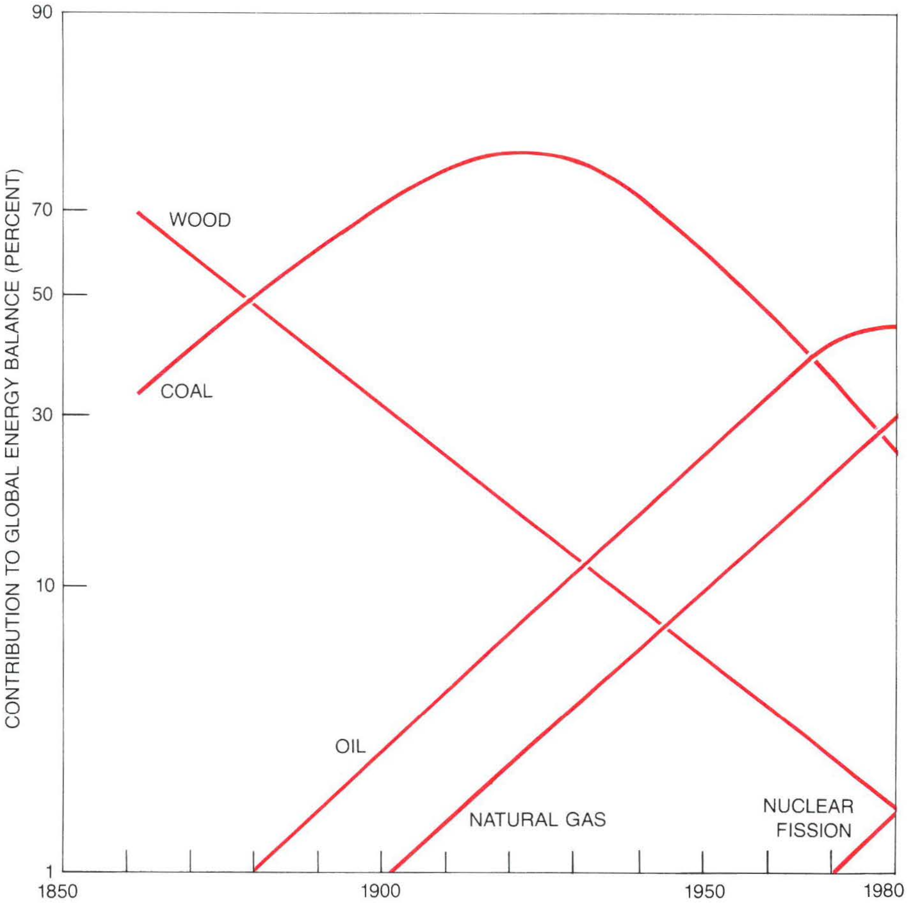
It was found fairly early that a simple extrapolation of the trends established in the period from 1950 to 1975 would lead to a growing discrepancy between global energy supply and global energy demand. Only by postulating a considerable reduction in the projected rate of economic growth in all the regions and a parallel sharp increase in the global energy supply—in terms of both estimated reserves and production capacities—was it possible to bring the future supply and demand totals into anything like a reasonable balance. In view of the uncertainties of such a dual "solution" to the world energy problem, two scenarios were developed. These models, termed the low-growth scenario and the high-growth scenario, were then applied to each of the seven major regions.

Both of the IIASA scenarios imply a dramatic break with past economic trends. The low-growth scenario in particular entails much lower rates of economic development than those of the period 1950–75. Although the projected growth rate in this scenario would be generally higher in the developing regions than in the developed ones, it would still not be high enough for an adequate technological infrastructure to be built up in most of the developing countries for many decades to come.

In addition to the modest economic projections built into these scenarios both of them incorporate optimistic estimates of the potential for energy conservation. They also reflect current trends toward an increase in the contribution to the gross national product made by the services sector of the economy, toward a substantial improvement in energy efficiency in all sectors and toward early "saturation" effects in certain energy-intensive activities, such as transportation. This approach has enabled us to obtain quite detailed projections, reflecting various ways of life and technological conditions, of the specific demand for energy required for a given amount of economic output, measured as a function of the level of economic activity achieved in a particular region [*see illustration on page 8*]. It is evident from such projections that "decoupling" energy and economic growth in an advanced economy is quite different from doing so in a subsistence economy. In view of the rudimentary industrialization achieved so far in the developing countries it seems clear that in the decades ahead it will be harder for them to limit their growth in energy-intensive technology than it will be for the developed countries to reduce theirs.

Complementary to the effort made to reduce the energy-demand figures in the IIASA scenarios has been the attempt to increase estimates of potential future energy supplies. The escalating price of crude oil, the form of primary energy now at the top of the world price scale, is bringing into the marketplace energy resources that were formerly not considered economically competitive. Our study ranks potentially recoverable resources of coal, oil, natural gas and uranium as a function of increasing production costs [*see top illustration on page 9*]. The totals we get in this way are much higher than the "proved" reserves identified as economic at present. Our figures nonetheless represent a reasonable hope; they suggest that with the help of vigorous exploration and advanced production technologies (either already in existence or yet to be developed) the world could roughly triple its present energy reserves by 2030.

By this accounting fossil-fuel reserves would amount at that time to the energy equivalent of 3,000 terawatt-years within production-cost ranges at or even below current market prices. (A terawatt-year is the standard energy unit in the IIASA studies; it is 10^{12}, or a trillion,



SUBSTITUTION OF PRIMARY-ENERGY FORMS has historically been in the direction of greater overall energy efficiency. In effect this trend has manifested itself in the movement toward ever more versatile forms of primary energy, that is, forms that require less upgrading to provide final-energy forms. In this graph of the substitution of primary-energy forms in the U.S. the colored lines are averages of the historical data. The data are again plotted on a logistic scale, which represents *S*-shaped functions as straight lines. The lines are remarkably regular.

watts supplied or consumed for a year.) Divided by a global energy demand of about 30 terawatt-years per year, which is what we estimate as the annual rate of energy consumption in 2030, this projection translates into an energy reserve with an exhaustion time of roughly a century. It is imperative, however, that such optimistic resource estimates be interpreted within the correct framework.

First, the economic evaluation of energy resources (measured, for example, by the price/cost ratio) in an evolutionary process leading to ever cheaper energy supplies does not apply to the uphill fight in costs that confronts the world in the years ahead. Second, the 3,000 terawatt-years' worth of oil, gas and coal we have projected will be qualitatively different from the reserves associated with these forms of energy today. The rise in production costs from one category to another reflects important changes that will further constrain the usefulness of such energy resources. For example, the oil in the IIASA production-cost Category 3 consists primarily of tar sands and oil shales, both resources that are accessible only by mining and retorting, not by drilling. The transportation and refining of a barrel of oil produced in this way will be considerably more costly than they are for a barrel of today's Saudi Arabian light crude. Moreover, environmental limitations quickly enter the picture if these resources are to be recovered and processed not in desert areas but close to heavily populated consuming ones.

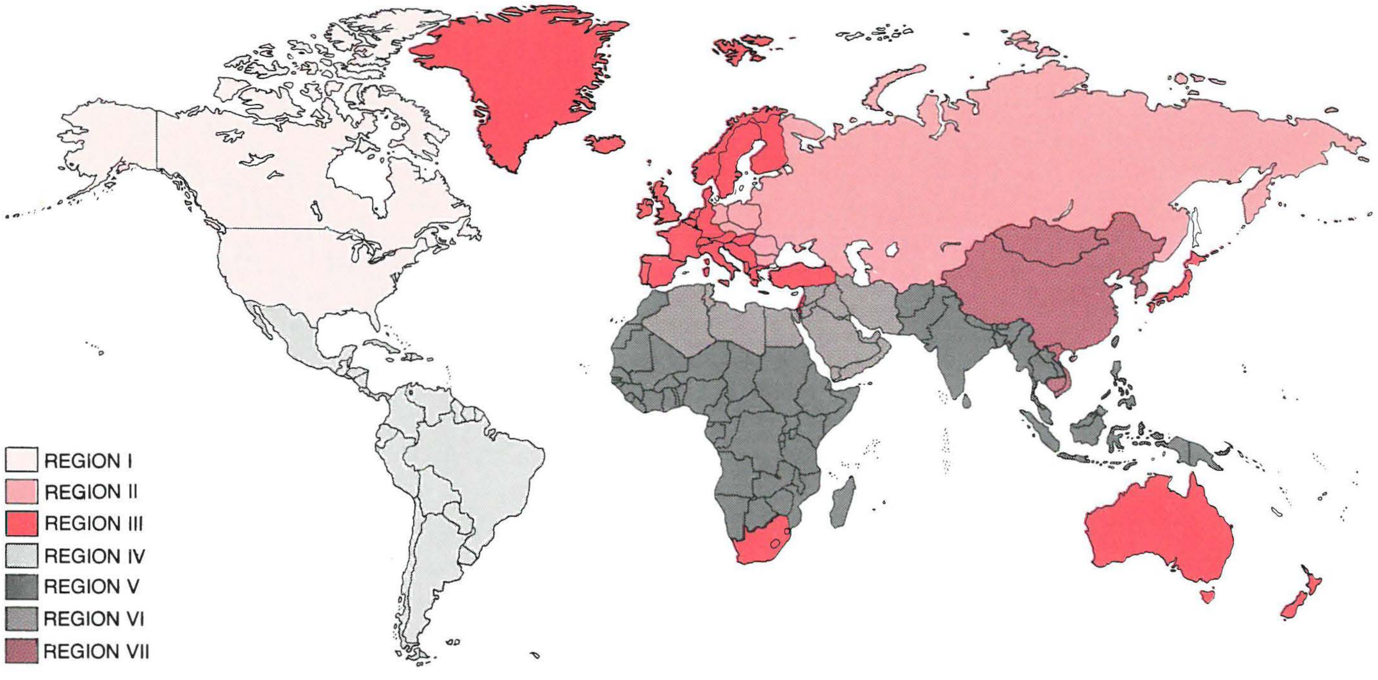
In short, tapping a major fraction of the resources projected in the IIASA models implies a difficult transition, not only from cheap fuels to expensive ones but also from comparatively clean and easy-to-handle fossil fuels to dirty and less versatile ones. Such a transition will also call for important adjustments outside the narrowly defined energy sector of the world economy, and it will take time.

What is true of fossil-fuel power systems applies even more to advanced, non-fossil-fuel systems such as fission reactors that "breed" their own fuel, solar-power generators and fusion reactors. Since the fuel resources in these systems are in effect unlimited, the resource base does not influence the achievable levels of deployment. "Infinite" energy resources of this type can be said to substitute capital for the finite natural resources that are depleted in fossil-fuel systems. Hence the rate at which an economy can afford to expand its fixed energy-generating capital stock will determine the price of these quasi-permanent power sources and accordingly their potential share of the world energy market.

A satisfactory determination of this price cannot yet be made. It would presumably balance the capital investments that would have to be diverted from general productivity with the benefits that would accrue to a national economy from adding a quasi-permanent power source. There is a striking similarity between the ambiguities inherent in determining a "fair" price for scarce fossil-fuel resources and those inherent in determining the price of "infinite" energy endowments such as breeder reactors and solar-power generators.

In the absence of long-term price estimates a projected balance between energy supply and demand must rely on considerations of cost and other constraints. In the IIASA analysis such constraints were imposed by a specific assortment of final energy requirements that would have to be met by the energy-supply sector of the economy; other possible constraints include the maximum deployment rates of new energy technologies and limitations imposed by the exhaustion of certain categories of resources.

Within such constraints primary-energy-supply scenarios were constructed that correspond to the high-growth and low-growth economic-development scenarios discussed above. The relative shares of primary-energy resources could then be calculated for the high-

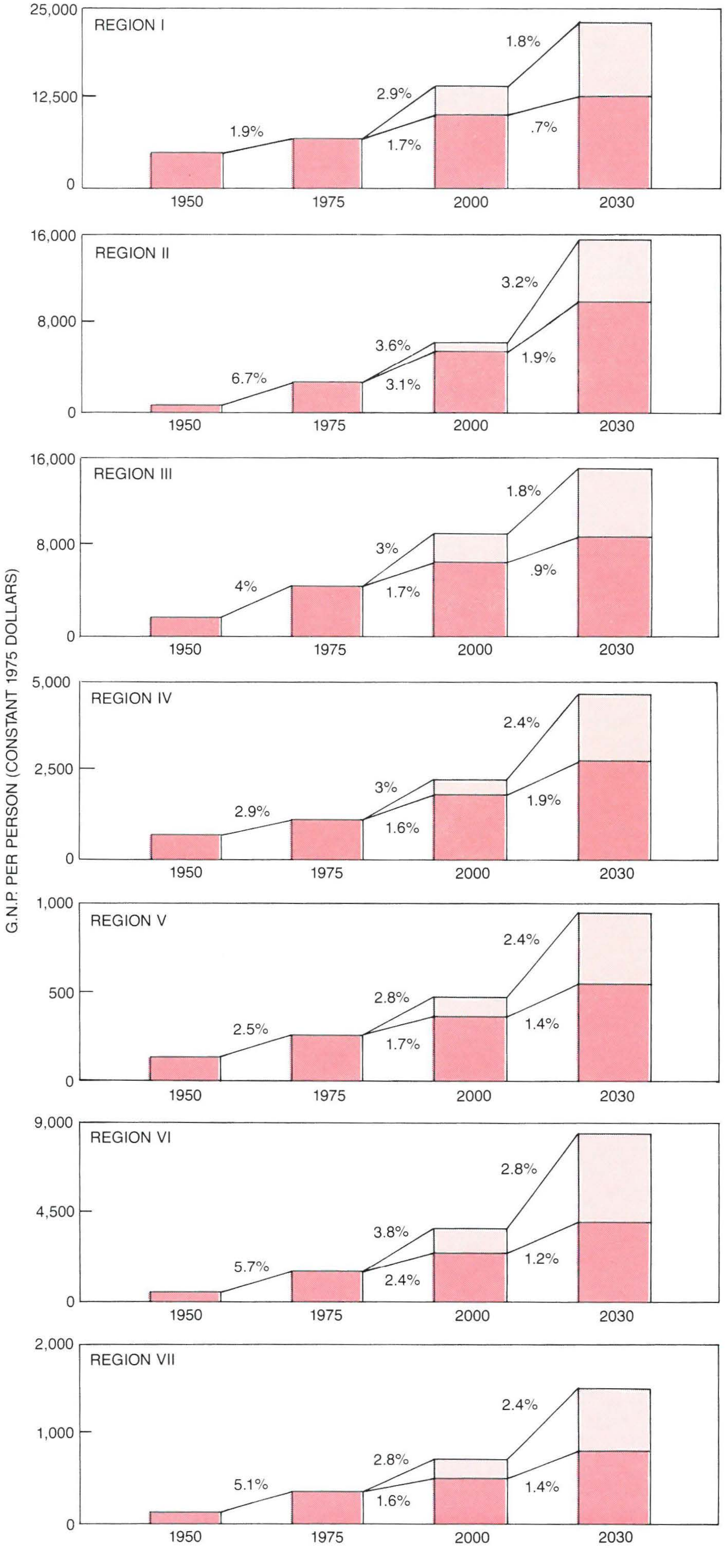


WORLD IS DIVIDED into seven major energy-related regions in the scenarios constructed by the author and his colleagues in the Energy Systems Program of the International Institute for Applied Systems Analysis (IIASA). The regions were selected mainly on the basis of economic factors rather than geographic proximity. Region I, North America, has a highly developed market economy and is comparatively rich in energy resources. Region II, the U.S.S.R. and the rest of eastern Europe, has a developed planned economy and is also quite rich in energy resources. Region III, a far-flung entity consisting of western Europe, Japan, Australia, New Zealand, South Africa and Israel, is highly developed economically but rather poor in energy resources. Region IV, Latin America, is a developing region that is fairly rich in energy resources. Region V, which encompasses central Africa, southern Asia and parts of southeastern Asia, is made up typically of less developed countries with scarce energy resources. Region VI includes the oil-rich developing countries of the Middle East and northern Africa. Region VII, China and the other centrally planned Asian economies, is a less developed area that is generally self-sufficient in energy. The seven IIASA regions are not to be confused with different groupings discussed elsewhere in this issue.

growth scenario, say, as a function of time, aggregating the separate calculations for each of the seven major IIASA regions. Although the patterns of primary-energy deployment were somewhat different at the regional level for the low-growth scenario, the aggregate supply structure for the entire world turned out to be practically the same as in the high-growth scenario.

The projected figures for the high-growth scenario show that over the 50-year span of the IIASA study natural gas will maintain its present share of approximately 20 percent of the world energy market but that oil will gradually decline, from 40 percent in 1980 to 20 percent in 2030. To make up for this shortfall and, what is equally important, to meet the demand for liquid secondary-energy forms an increasing amount of coal will have to be converted into synthetic fuels. The diversion of this much coal from electric-power generation will in turn have to be partly compensated for by the further penetration of nuclear power into the market for generating electricity. Because of anticipated resource limits on the supply of natural uranium, breeder reactors will assume an ever increasing share of the world energy-supply market from the year 2000 on. Renewable energy sources, hydroelectric power and geothermal power will add up to a fairly constant share of somewhat less than 10 percent of the total energy supply, an estimate that implies a substantial increase in the absolute power-generation levels for all these comparatively minor supply categories. From the base year of the IIASA study (1975) to 2030 the total primary-energy consumption rate is projected to rise from 8.2 terawatt-years per year to 36 terawatt-years per year in the high-growth scenario and to 22 terawatt-years per year in the low-growth one.

The size of the industrial operations postulated as achievable in the two energy-supply scenarios can be gauged by comparing present and future rates of deployment of the various primary-



MODEST ECONOMIC GROWTH projected in both the high-growth and the low-growth energy-demand scenarios constructed by the IIASA analysts is presented in this set of bar charts for each of the seven major world divisions considered in their study. The percent figures on the connecting lines give the historical and projected rates of economic growth for each region in terms of the annual growth in the gross national product per person in that region for three different time intervals between 1950 and 2030. All the figures are average annual growth rates (rounded to the nearest tenth of a percent) over the interval in question; actual projections in the IIASA scenarios assumed decreasing growth rates. Light-colored parts of bars show the difference between high- and low-growth scenarios.

energy sources [*see bottom illustration on opposite page*]. In the high-growth case oil production would have to double by 2030 and coal production would have to quintuple. The challenges facing the energy-supply industries in the low-growth scenario also appear to be formidable.

The tension in the two IIASA scenarios between prodigious energy-consumption figures and modest economic-development prospects is symptomatic of the long-term global energy problem. To put the present trends and future challenges of the energy market in perspective it will be helpful to recall at this point several of the more detailed conditions underlying the IIASA scenarios. These conditions are as follows. (1) The energy resources to be consumed within each IIASA region will have to be made available at production-cost prices. With the exception of oil this rule will also apply to exports to other regions. (2) Oil production in Region VI (the Middle East and northern Africa) will have a ceiling of 33 million barrels per day. In addition Region II (the U.S.S.R. and its allies in eastern Europe) and Region VII (China and the other centrally planned Asian economies) will not participate in the oil trade between regions. (3) Each of the seven major world regions will build up a cost-minimizing energy-supply system of its own to meet regional demands for final energy. (4) Each region will in addition assume for itself the burden of switching to a more expensive energy infrastructure when the time comes.

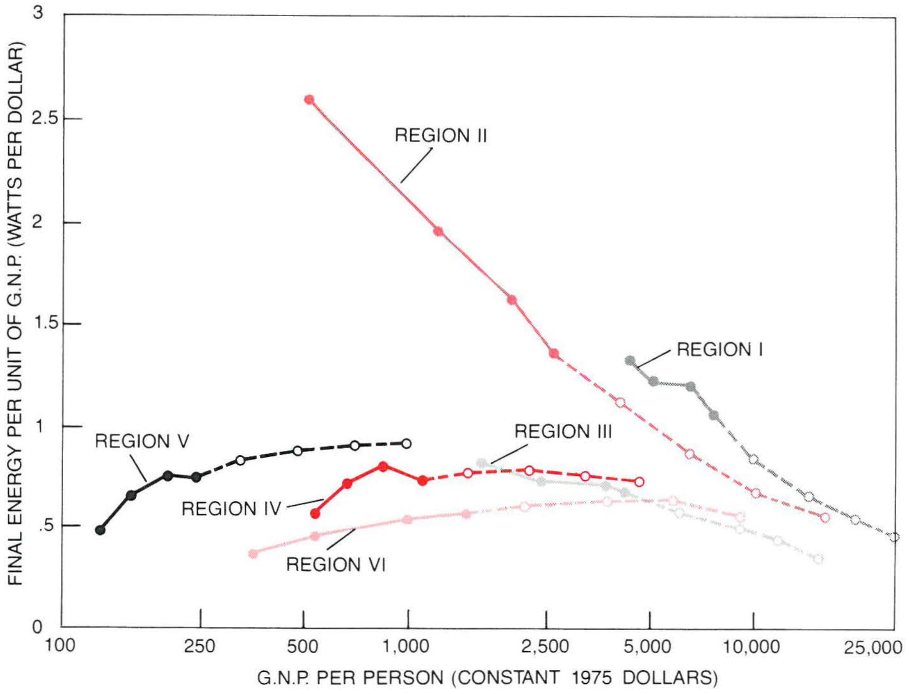
Together with various other methodological provisos these four conditions enable us to project a viable, if not entirely satisfying, solution to the global energy problem. The cheapest energy resources would be used up gradually, and no region would be forced to pay exceptionally high energy costs long before the others would have to follow. Except for the oil trade originating in the Middle East and northern Africa, such a world would abstain from using energy as leverage for the redistribution of general economic productivity.

Both the high-growth and the low-growth scenarios are put forward as possible long-term evolutionary processes. As such they imply a number of actions and achievements, both technical and institutional, over the next 50 years. What are the crucial checkpoints that must be passed for these global evolutionary scenarios to be realized?

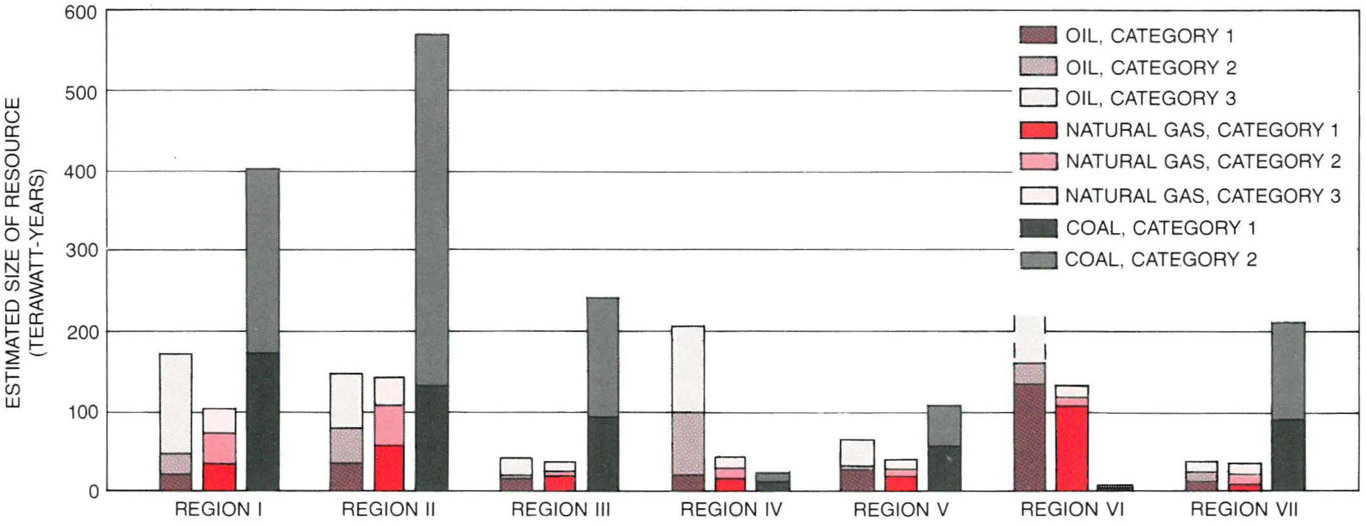
A particularly difficult problem within the general energy puzzle is how to ensure an adequate supply of liquid fuels through roughly the year 2000. It appears from our analysis that if one excludes from consideration the centrally planned economies (which need not be driven into the tightening international oil trade, since they have comparatively ample oil resources of their own), the world will continue for some time to depend on oil exports from the Middle East and northern Africa. Outside this region new reserves will have to come on stream very quickly, from both proved and unproved fields, including those in deep offshore areas and polar areas. The large contributions projected from such sources by 1990 will require that enormous effort be put into exploration and development. It is questionable whether such a pace will actually be achieved; accordingly it seems all the more important to prepare in plenty of time for the large-scale production of oil from unconventional sources beginning in about 1990. Substantial shortfalls in the production of oil by either conventional or unconventional means below the volumes projected in the IIASA high-growth scenario would require the introduction of coal liquefaction on a globally significant scale before the year 2000. Except for a possible delay of 10 years in the production of synthetic liquid fuels from coal the low-growth scenario leads to an oil shortfall that is almost identical with that in the high-growth scenario.

The short-term and medium-term liquid-fuel problem is a tremendous challenge to technology, but there is an even more pressing aspect of the problem, which is related to the quick shift that is bound to take place in the energy-trade relations between and within developed and developing regions in about the year 2000 [*see top illustration on page 11*]. At that time two important turning points will have been reached. First, the three major developing regions that are now net oil exporters will divide into two subcategories: two that will continue to be net oil exporters, namely Region VI (the Middle East and northern Africa) and Region IV (Latin America), and one that will abruptly become a major oil importer, namely Region V (central Africa, southern Asia and parts of southeastern Asia). Second, the oil-buying competition between Region I (North America) and Region III (western Europe, Japan, Australia, New Zealand, South Africa and Israel) will be succeeded by a competition between Region III and the energy-poor group of developing countries in Region V. If Region I is not able to reduce its oil imports significantly by the year 2000, the competition for imported oil among developed and developing countries beyond 2000 will become even sharper. What institutional arrangements would be able to manage these two likely transitions in the terms of the energy trade among major world regions around the year 2000?

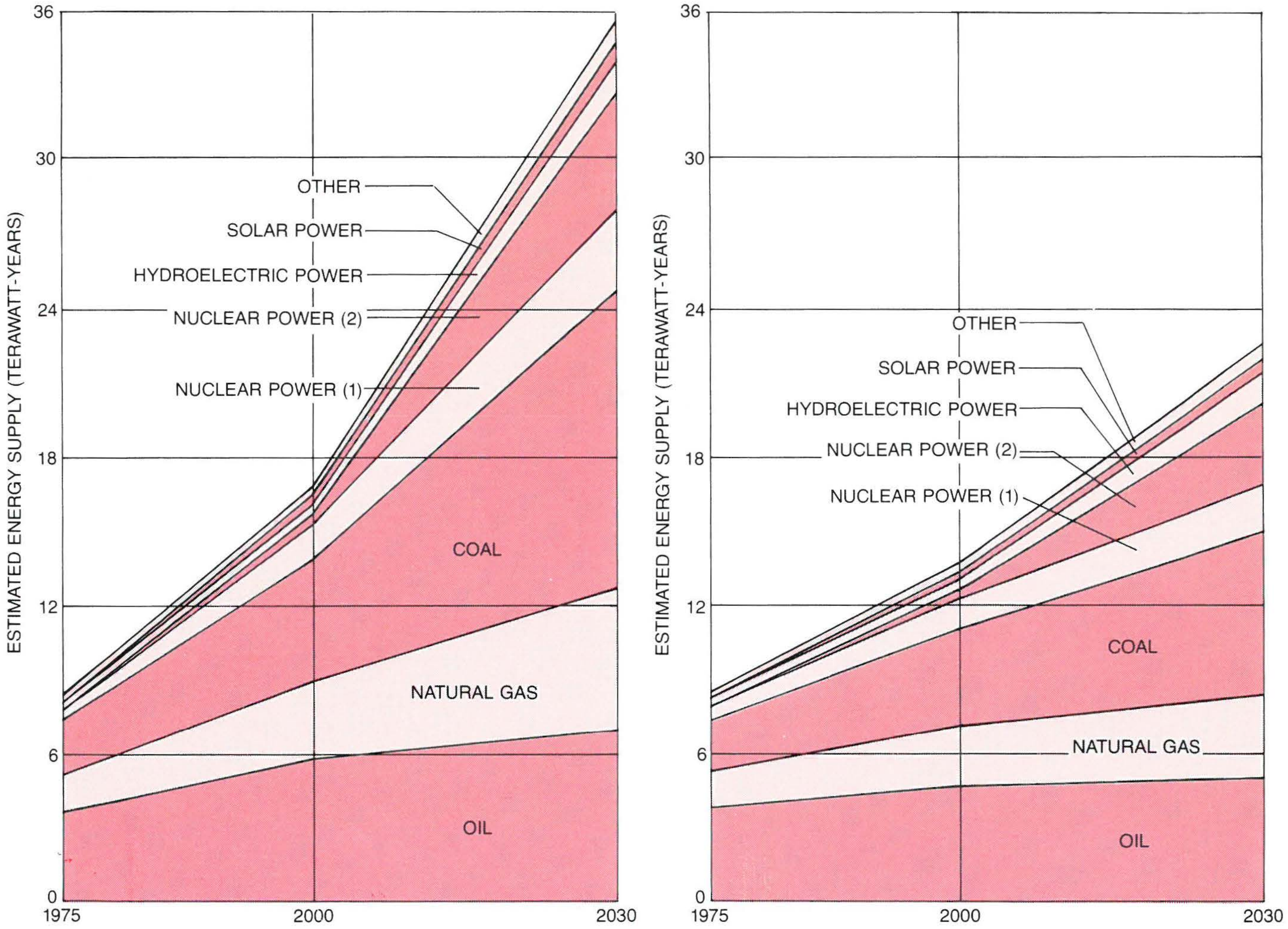
The full weight of such questions of energy-related medium-term economic stability will be felt in western Europe and Japan. In the high-growth scenario the dependence on imported oil in the Region III countries could be reduced by increasing imports of coal (or coal products) and natural gas. The low-



SPECIFIC DEMAND FOR FINAL ENERGY required to produce a given unit of economic output was projected in the IIASA low-growth energy-demand scenario as a function of the average level of economic activity achieved in six of the seven regions in the study. The dots give the historical data for the years 1950, 1960, 1970 and 1975; the open circles indicate the projected figures for 1985, 2000, 2015 and 2030. According to the author, the graph suggests that in the decades ahead it will be harder for the developing countries to limit their growth in energy-intensive technology than it will be for the developed countries to reduce theirs.



FOSSIL-FUEL RESOURCES judged to be ultimately recoverable in each of the seven regions considered in the IIASA scenarios are categorized according to increasing production costs. The cost categories represent estimates of costs at or below the stated volume of recoverable resources (in constant 1975 dollars). For oil and natural gas production-cost Category 1 includes all resources recoverable at a price equivalent to $12 per barrel of oil; Category 2 covers the range from $12 to $20 per equivalent barrel of oil, and Category 3 covers the range from $20 to $25 per equivalent barrel of oil. For coal Category 1 includes all resources recoverable at or below $25 per metric ton; Category 2 covers the range between $25 and $50 per metric ton. In the case of coal only a part of the ultimate resource (about 15 percent) was included, because the figures were already large and because many uncertainties surround long-term coal resources and production technologies. No estimate was made of recoverable Category 3 oil resources of the Middle East and northern Africa (Region VI).

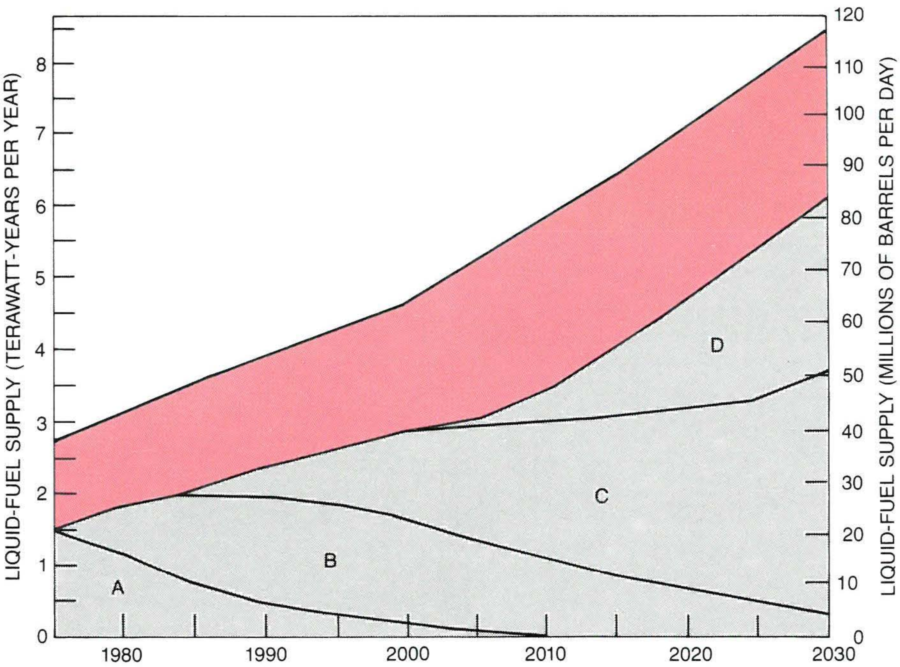


GLOBAL CONSUMPTION RATE of a variety of primary-energy forms is projected to rise from a total of 8.2 terawatt-years per year in the base year of the IIASA study (1975) to 36 terawatt-years per year in 2030 according to the high-growth scenario (*left*) and to 22 terawatt-years per year in 2030 according to the low-growth one (*right*). Nuclear-power sources are divided in these projections into conventional fission reactors (*Nuclear 1*) and advanced breeder-type fission reactors plus fusion reactors (*Nuclear 2*). The projections for direct solar power and other forms of primary energy, such as "biomass" conversion, are considered optimistic by the IIASA analysts.

growth scenario avoids such additional fossil-fuel imports, but like the high-growth scenario it pushes Region III into an extended competition for imported oil at a crucial time: beyond 2000, when very expensive oil will have to be shared with the much needier developing regions.

The imminent need to switch to large-scale substitutes for conventional oil, evident in both of the IIASA scenarios, raises some important environmental questions. Deep offshore oil, heavy crude oil, tar sands and oil shales will all have to be exploited vigorously beginning in about 2000. Apart from the deep offshore oil deposits and those in polar areas most of the recoverable hydrocarbons in this category are in nondrillable formations in a few large geological basins. By 2000 these basins will come to play a role analogous to that of the giant oil fields of the Middle East today. The IIASA high-growth scenario envisions an energy-production rate of a terawatt-year per year from this "minable" hydrocarbon group in about 20 years, most of which would have to come from three places: the Athabasca tar sands of northern Alberta in Canada, the Orinoco heavy crudes of Venezuela and the Green River oil shales of Colorado, Utah and Wyoming in the U.S. The local environmental consequences of such large operations cannot yet be adequately assessed on the basis of past or present experience.

When one computes the energy ratio (defined as the net useful energy output divided by the energy invested in production) for alternative schemes for the production of unconventional liquid fuels, one finds that an output on the order of .3 or .4 terawatt-year per year per basin would call for the combustion of more than .1 terawatt-year per year of low-grade fossil fuel. In addition to the huge quantities of waste heat and chemical pollutants that would be liberated the water-supply problems would be prodigious. Depending on the extraction process, the production of several tenths of a terawatt-year per year of synthetic liquid fuel would consume on the order of tens of cubic meters of water per second. Significant problems are already encountered with wet cooling towers in areas such as the valley of the Rhine and its tributaries, where the water requirements are much smaller. Major problems related to land use, soil erosion and water pollution are likely to place further limits on the recovery of these nonconventional oil resources. The same limitations apply to the production of synthetic liquid fuels from comparatively cheap open-pit-mined coal, for example in the vast coal basins of the northern Rocky Mountain states in the U.S. and of the Kansk-Achinsk region in south-central Siberia.



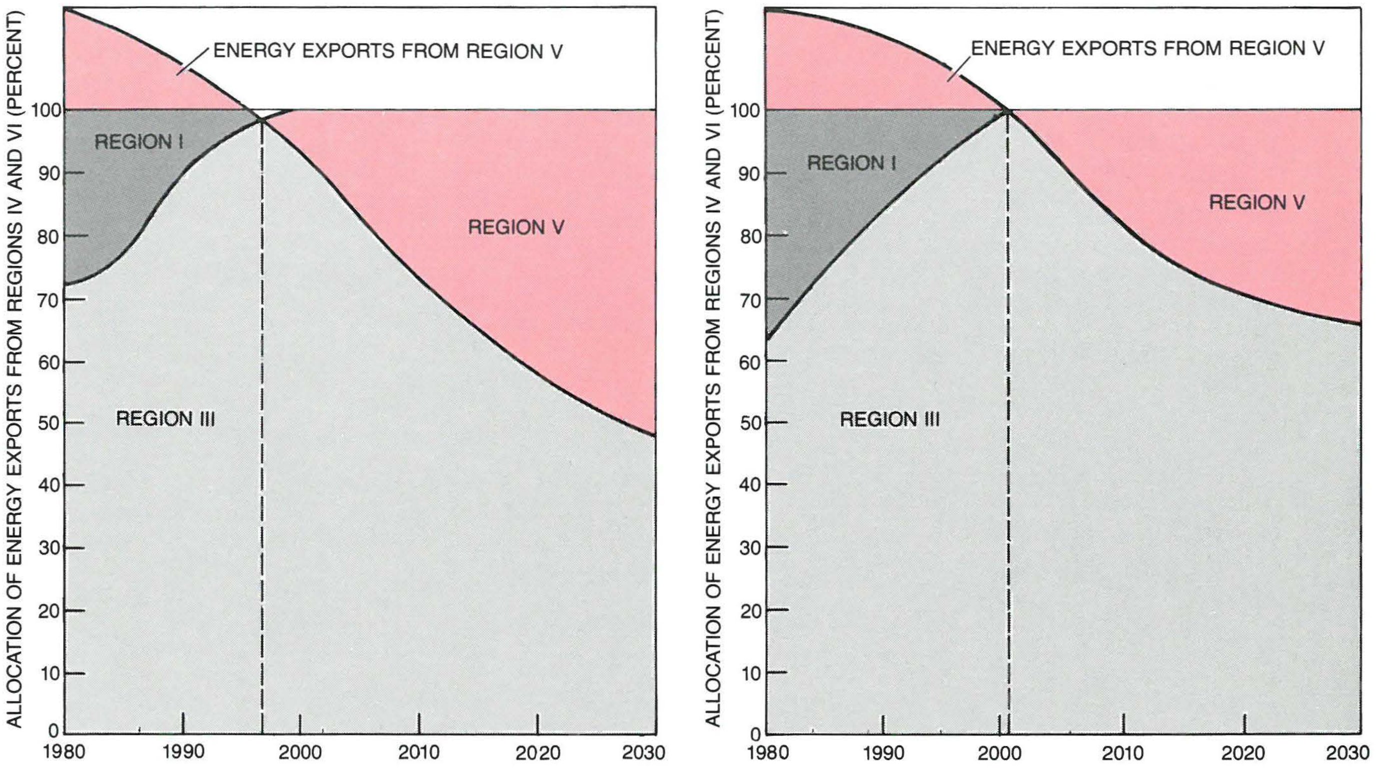
LIQUID-FUEL SUPPLY is projected according to the IIASA high-growth scenario for the world excluding the centrally planned economies (Region II and Region VII). The top line gives the estimated demand for liquid primary-energy forms in the five regions that are expected to participate in the international liquid-fuel trade through 2030. The gray area includes various kinds of liquid fuel produced outside the Middle East and northern Africa (Region VI); the fuel sources represented include known reserves of conventional oil (*A*), new reserves of conventional oil (*B*), unconventional forms of oil, such as tar sands, oil shales, heavy crudes and other products of enhanced-recovery techniques (*C*), and synthetic fuels made by the liquefaction of coal (*D*). Gap between supply and demand is filled by oil produced in Region VI (*colored area*), which is expected to reach a peak output of 33 million barrels per day in 2010.

Over and above the local and regional problems that are likely to be encountered in recovering such additional fossil-fuel resources, both of the IIASA scenarios would lead to a worldwide risk that cannot be adequately quantified at present. It is the risk arising from the release of the carbon contained in such fuels, which would be largely in the form of carbon dioxide. Significant increases in the atmospheric concentration of carbon dioxide have been monitored for the past two decades. The possible consequences of the two IIASA primary-energy-supply scenarios have been estimated on the basis of various physical models, which describe the effects of increased atmospheric carbon dioxide on the carbon cycle in the environment and on the exchange of radiation between the earth and space. The reliability of these models is not yet well enough known, but research and monitoring programs are under way to improve the scientific basis for judging the global carbon dioxide issue.

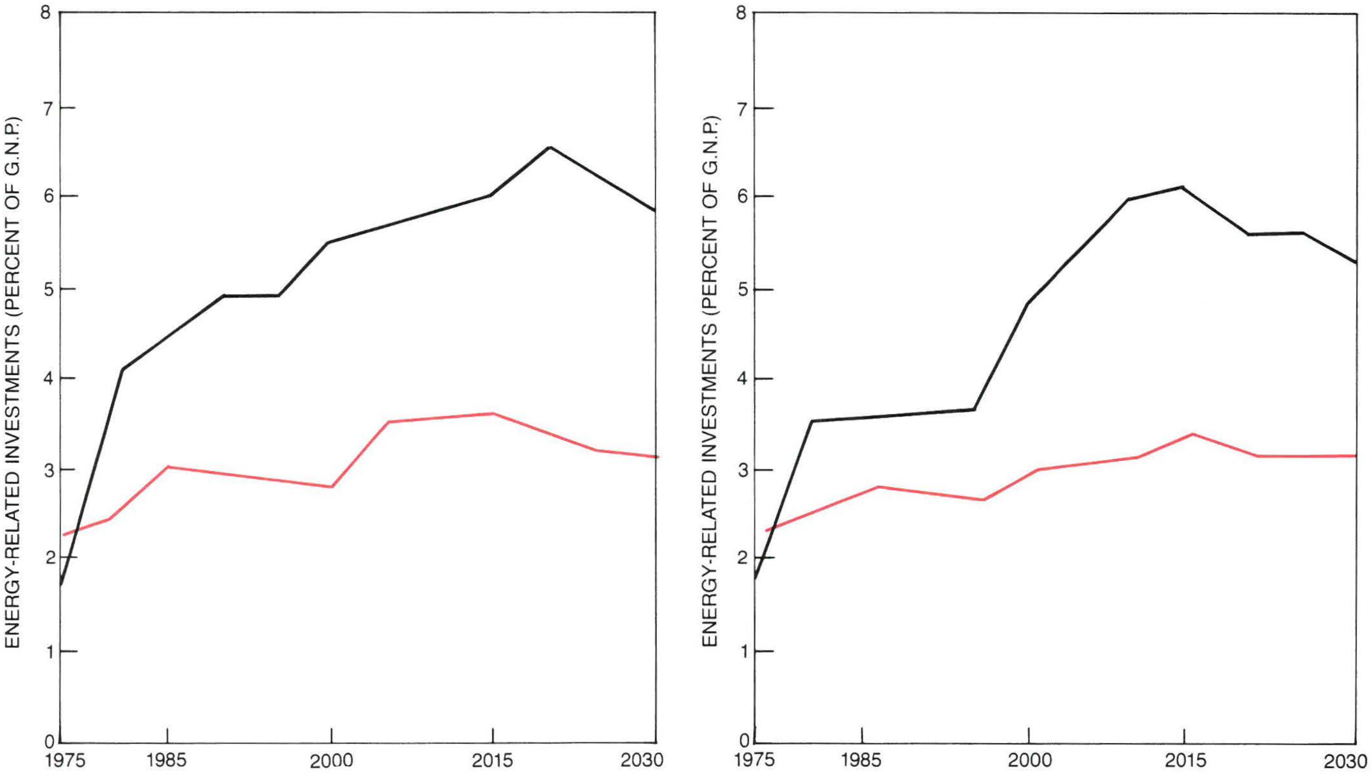
Finally, there is another potential economic constraint on the world's future energy supply, arising from the rather heterogeneous geographic distribution of all fossil-fuel resources. A large fraction of the world's aggregate G.N.P. must be invested to build up the energy-production infrastructure in both of the IIASA scenarios. It is conceivable that adequate rates of investment can be achieved, but it will surely be difficult for the developing countries. Averaging energy investments over regions as we have done tends to obscure the increase in the amounts of capital that will have to be transferred across national boundaries to develop the great resource basins for the purpose of producing more fossil-fuel power. The development within the next two decades of any one of the major energy-resource basins will require not billions of dollars but hundreds of billions. Problems associated with the accumulation and control of that much capital are likely to lead to fiscal complexities that are unknown at present even to the largest of the world's national economies.

The developing countries, in view of their difficult situation, are likely to extend their use of local renewable energy sources as far as is practical. Excluding the large-scale direct use of sunlight, which under the most favorable circumstances will remain economically infeasible for decades to come, the largest potential renewable energy source is wood and similar solid biological matter ("biomass"). Wood is still widely burned as a fuel in the developing countries, where it supplies a significant fraction of present energy needs.

The limitations on such renewable energy sources can be demonstrated by comparing natural energy-supply densi-



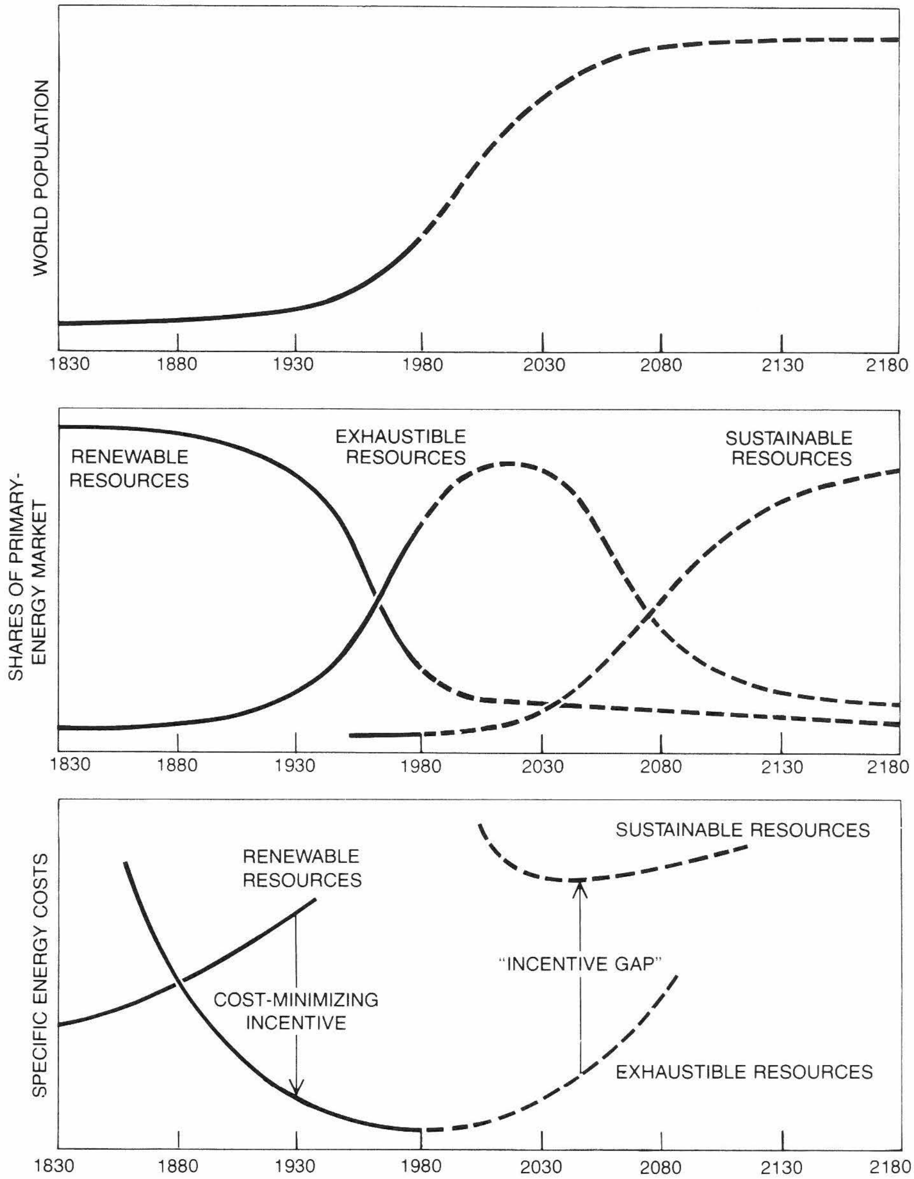
ABRUPT TRANSITION in the allocation of energy exports from the resource-rich developing countries of Region IV (Latin America) and Region VI (the Middle East and northern Africa) is forecast in both of the IIASA scenarios for about the turn of the century. At that time Region V (central Africa, southern Asia and parts of southeastern Asia) will switch from being a net exporter of energy (*colored area at top left in each graph*) to being a net energy importer (*colored area at upper right*). The present oil-buying competition between Region I (North America) and Region III (western Europe, Japan, Australia, New Zealand, South Africa and Israel) will presumably then be succeeded by a competition between Region III and Region V. If Region I does not succeed in reducing its oil imports essentially to zero by this point, the competition for imported oil between developed and developing countries could become sharper. The timing of the expected transition differs by only a few years between the high-growth scenario (*left graph*) and the low-growth one (*right graph*).



DIRECT AND INDIRECT INVESTMENTS required to build up the energy-supply systems of the developing regions (*black curves*) are bound to consume a larger share of those regions' aggregate G.N.P. than the corresponding investments required in the developed regions (*colored curves*). The investments called for in both the high-growth scenario (*left*) and the low-growth one (*right*) were averaged in the IIASA study over the two types of region, a procedure that tends to minimize the large amounts of capital that will have to be transferred across national boundaries to develop the great fossil-fuel resource basins on which much of the world's future energy supply will depend.

ties with the existing or expected density of human energy demand. The harvesting of certain fractions of natural energy flows in the environment results in specific energy-yield densities, which can be expressed in terms of the energy turnover per year per geographic area. Only in the most favorable cases could these supply densities exceed the demand densities identified for the IIASA regions in the two scenarios. They fall short of even the present demand densities of urban settlements.

The IIASA scenarios allocate all together almost 10 percent of the projected global energy supply to renewable energy sources. By 2030 this would amount to between two and four terawatt-years per year, a range close to the maximum energy-yield estimates from all resource-limited sources in most of the world's developing regions. Accordingly one has to expect a vigorous exploitation of all the biomass in Asia and Africa and much of it in Latin America. This prospect immediately raises questions of ecological stability, soil erosion, water requirements and global climatic effects. The cumulative impact of stretching agriculture, bioenergy production and hydroelectric power to their natural limits would transform the face of the earth in the decades to come. The responsible limits to such an ecological transformation are not known.



"INCENTIVE GAP" is foreseen by the author in the long-term transition from exhaustible energy resources (fossil fuels) to sustainable ones (such as breeder reactors, direct solar power and fusion reactors). The transition will be fundamentally different from the earlier changeover from renewable energy resources (such as wood) to exhaustible ones in that it will have to be made at a time of rising rather than falling energy costs. It follows that traditional cost-minimizing principles of economics cannot be relied on to stimulate the kinds of technological innovation needed to make the transition successfully. In this set of idealized graphs the incentive gap is placed chronologically in the context of the world-population trend (*top*), the substitution of primary-energy forms (*middle*) and the specific energy costs of the three major categories of primary-energy forms (*bottom*). All three graphs have arbitrary vertical scales.

This projected view of how the world could balance energy supply and demand in the next two to five decades brings out issues at the interface of technology and politics. These issues emerge primarily from discrepancies among "what could be," "what should be" and "what will be."

There is little doubt that the world will soon be inhabited by more people than the traditional renewable energy sources can sustain. This will be true even if the majority were to forgo achieving the material well-being the present-day developed countries enjoy. The developed countries were forced to give up renewable energy sources for fossil fuels on their way to industrialization as their energy demand began to exceed the local energy supply. The early transition from wood to coal in western Europe and the U.S. was largely driven by this requirement. The dependence of such countries on oil, natural gas and coal is now a worldwide phenomenon. Since the world's recoverable resources of fossil fuels appear to be quite large, the industrialized countries could in principle be supplied with enough energy to last for more than a century, even if the developing nations were to gradually build up a modern technological infrastructure and increasingly share in these supplies. Indeed, it was fashionable in the 1960's to conclude that there would be enough fossil fuel to allow for a timely buildup of energy sources that are not resource-limited, such as nuclear power and direct solar power.

What seems to have turned the energy picture upside down in the 1970's was a small shift in trends that is not even now fully appreciated. For example, it appears that the transition from fossil-fuel energy to nuclear energy will probably be an uphill fight in terms of cost and effort. This trend is in striking contrast to the earlier experience of dropping energy costs, which accompanied the transition from renewable energy sources to fossil fuels. The ultimate consequences of such shifts are difficult to foresee, because they depend on the resolution of a conflict between hitherto sound economic principles: the minimizing of costs and the seizure of markets through technological innovation.

The recent history of the oil market provides an early warning of that dilemma. The drastic increase in all energy prices is starting to bring in more expensive energy supplies and conservation technologies that can be justified economically. Yet the actual production costs of energy remain rather low. The economic differential between energy prices and production costs, skimmed in the form of windfall profits by those in control of the prices, is definitely not being applied now to the buildup of new supply capacities at or near the new energy price levels. The OPEC countries are using their surplus oil income to develop their economies; the governments of the developed countries are financing public investments from energy royalties or energy taxes, trying to stimulate consumption and so further economic growth through social-transfer payments. In this situation high energy prices can be perceived primarily as a means for redistributing the benefits of high industrial productivity. As long as the actual costs of energy production remain low there is no reason for the global extension of an energy-intensive technological infrastructure to be seriously impeded.

In the years ahead energy investments will certainly be directed toward the deployment of second-best resources. The principle of the minimizing of costs will therefore first lead to the exhaustion of fossil-fuel resources that are easy to produce, convert, transport and burn. In spite of the fact that production costs for unconventional fossil fuels will in time reach a break-even point with the substitutes derived from nuclear power and solar power, reaching that point will not facilitate the quick buildup of the fixed capital stock representing these sustainable energy sources. The less rewarding the basis is on which an old infrastructure has to operate, the slower will be the pace at which one can afford to install an even less rewarding new infrastructure. In short, the transition to sustainable energy sources such as breeder reactors, direct solar power and fusion power might well become more difficult with time.

If this turns out to be the case, the entire global process of development must be seen as a race against time. It can only be won once the regions disposing of high industrial productivity and the regions disposing of limited cheap resources ally their different kinds of wealth in order to pay the price for building up a basis for sustainable energy sources. It will never be a minimum-cost operation. The transition from renewable energy sources to sustainable energy sources, the first steps of which have been conceptualized in the IIASA scenarios, appears to parallel a step mankind took in the Neolithic period, namely the transition of the food system from hunting and gathering to animal husbandry and farming. This time we have fossil fuels to ease the transition, but we have less time than our ancestors did. The transition to sustainable energy sources—breeder reactors, direct solar power and fusion power—cannot be put off to an era when the globe will have nearly exhausted its one-time energy endowment.

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