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A Global and Long-Range Picture of Energy Developments

Wolf Häfele

Summary. Most studies of energy supply and demand ignore either global interdependence or the long time spans necessary to adjust to new energy sources. The International Institute for Applied Systems Analysis has therefore studied on a global scale, for seven major world regions, the balance between energy supply and demand for the next 50 years. Reported here are the results for two benchmark scenarios. In the "low" scenario world energy consumption increases from today's 8.2 terawatt-year per year to 22 terawatt-year per year in 2030; in the "high" scenario, consumption increases to 35 terawatt-year per year. The study showed that time will be the limiting constraint in adapting the energy supply infrastructure to changing resource availability; resources will be available until the second half of the next century, but a strong shift will be required to low-grade fossil fuels such as shale oil and tar sands. Each scenario studied indicated increased environmental problems associated with increased use of fossil fuels, and potential geopolitical problems associated with the world distribution of resources.

A Time Frame for Global and Long-Range Energy Developments

In the middle of the last century wood was the predominant source of energy, meeting roughly 70 to 80 percent of the demand. This meant large-scale gathering and led to a first energy crisis, which was overcome by a fundamental change in technology: Coal was used as a substitute for wood. The higher density of coal meant not only more energy but also easier storability and transportability, features that were essential for the first industrial revolution. Figure 1 shows the decline and rise of market shares of various types of primary energy in the United States. The data are plotted in such a way that a logistic curve becomes a straight line. It should be noted that there are remarkable regularities in the data over extended time periods. One such regularity is the slope of these curves. Its constancy means continued logistic substitution of one source by another over decades. For the United States it has always taken roughly six decades for a new energy source to conquer 50 percent of the market. For the world as a whole the figure is ten decades. The regularities of such market penetrations have been studied in great depth (*1*). What is concluded here is that it is appropriate to consider the time frame 1980 to 2030 when developments of energy demand and supply and their underlying infrastructure are to be discussed.

It also seems appropriate to consider the world as a whole. Indeed, today roughly 25 percent of the world's energy supplies come from one place on the globe, the Middle East, and this creates a strong technical and political linkage for almost all parts of the world. On the demand side the situation is similar. For instance, a political debate continues to focus on the notion of a "new economic order" viewing the world as a whole and addressing the problem of developing the so-called "South" of the world. Although political in nature, this debate nevertheless makes it plain that the demand for energy must also be seen in such a perspective. By contrast, most of the major studies of energy approach the problem on a national scale and use a short- to medium-range planning horizon, say 10 to 15 years. While this is clearly necessary, it is not sufficient. Often the result of such studies is the identification of required imports; the feasibility of such imports is left open. Indeed, others may have planned to import the same barrel of oil. It is thus global comprehensiveness and consistency that must come into focus, particularly when the time frame reaches out to the year 2030.

The IIASA Energy Systems Program

Such a global and long-range view characterizes the approach of the Energy Systems Program of the International Institute for Applied Systems Analysis at Laxemburg, near Vienna, Austria. IIASA was conceived in the late 1960's

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with the idea of studying problems of civilization identified as likely to become overwhelming in industrialized nations in the 1970's and 1980's. The United States and the Soviet Union are the lead nations, but there were ten more nations to found the Institute in 1972 and five more nations have joined in the meantime, bringing the total to 17 member nations (*2*). The institute is nongovernmental, the member countries being represented by their academies of sciences or similar bodies. Topics of research include, among others, food, urbanization, environment, water, industrial management, energy, and the related mathematical methods. The Energy Systems Program started with the beginning of IIASA in 1973 and has now concluded a major study, *Energy in a Finite World* (*3*). Over the years more than 140 scientists from more than 20 nations, East, West, and South alike, have for longer or briefer periods joined the program. From the United States, for example, Alan Manne, Bernhard Spinrad, Amory Lovins, Paul Basile, and others have participated in the study. An explicit attempt was made to incorporate as many views and to be as objective as possible. The idea was to understand the factual basis of the energy problem, that is, to identify the facts and conditions for any energy policy. Given the worldwide nature of the institute it was not the intent to go into the politics or societal aspects of the energy problem as seen from particular nations. In this article I report some major results of IIASA's Energy Systems Program.

The Approach Taken and Its Methodological Problems

In choosing our approach to this global and long-range study our guiding idea was to understand the transitions that will be necessary when the fossil fuels now in use begin to run out. An attempt was made to determine the supply limits for energy from coal, nuclear, and solar sources, with special emphasis being given to the problem of local, renewable energy sources. We also studied the conceivable constraints on energy strategies, such as those imposed by the production of waste heat, the release of carbon dioxide, and the relative risks of each strategy. We found consistently that time is the most precious resource; and time therefore imposes the most severe constraint on possible actions. We then used our results to identify strategies appropriate for the transition from the present infrastructure of energy supply and demand to a futuristic one with explicit emphasis on the evolving energy demand. Since it is not possible to make predictions 50 years into the future, and since such predictions require political and societal considerations that we did not include, we chose the method of scenario writing. We wished to stress internal consistency and global comprehensiveness. This required the development and application of a set of appropriate mathematical models (*4*), because only through quantification can one reach the degree of consistency required to prevent, for example, the same barrel of oil being assigned to two different countries or for two different purposes. However, one must be prudent in interpreting the numerical results thus obtained; they must not be take too literally. In fact, they must be seen as quantitative expressions of the more qualitative situations that underlie the scenarios. The goal is to understand and conceptualize the worldwide situation for the next five decades.

Since it is neither possible nor desirable to write scenarios for 150 nations, we chose instead to study seven world regions (see Fig. 2) selected mostly on the basis of economical status rather than geographical proximity. Region I, North America, has a developed market economy and is rich in resources. Region II, the Soviet Union and Eastern Europe, is characterized by its developed, planned economies and rich resources. Region III includes member countries of the OECD (Organization for Economic Cooperation and Development) (except North America) and is characterized by poor energy resources. Region IV is Latin America. Region V, Southeast Asia and Africa, is a developing region with a high population and only a few resources. Region VI includes the oil-rich Arab countries. Region VII includes the centrally planned Asian economies.

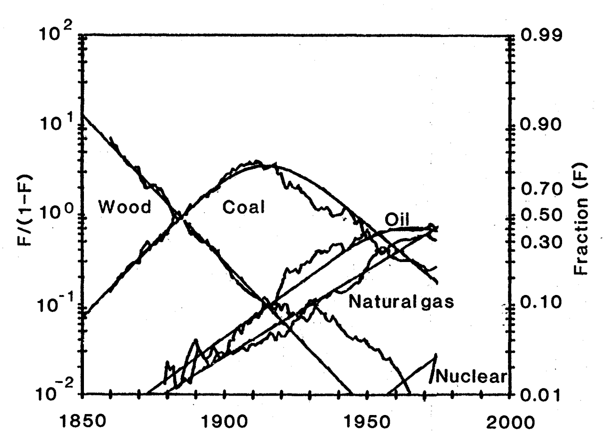

Fig. 1. Primary energy substitution, United States.

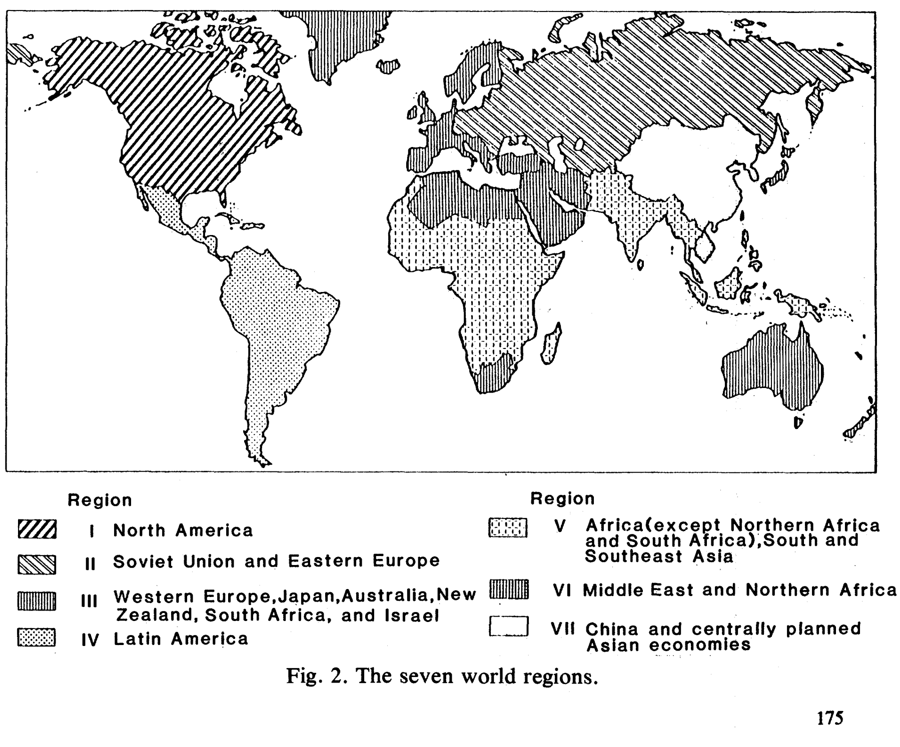

Fig. 2. The seven world regions.

These regions were used to construct the two benchmark scenarios described below that provide an overall picture of the global energy situation. However, each individual nation or group of nations also requires a more specific analysis that is consistent with the overall global picture. Such work is now in progress. For example, the IIASA Energy Systems Program is engaged in an active dialogue with the European Communities in Brussels. The Communities, using a bottom-up approach, are planning specific energy strategies by adding up the expectations of the member countries, while IIASA, with a top-down approach, is providing the global picture of energy availability. The results have been both unexpected and helpful (*5*). A similar dialogue is going on between IIASA and Bulgaria, the Federal Republic of Germany, the Soviet Union and, to some extent, OPEC (Organization of Petroleum Exporting Countries) members and other nations and groups.

Two Benchmark Scenarios

Two benchmark scenarios have been elaborated in great detail. These are labeled "high" and "low," the former referring to a situation in which the demand for energy is relatively high, the latter to a situation in which the demand is relatively low. These scenarios allow for a certain inter- and extrapolation and thus leave the reader with a choice; both scenarios result in a mix of energy sources. Three alternative scenarios were also investigated: one in which there is a worldwide nuclear moratorium, one in which there is an all-out effort to develop nuclear energy, and one incorporating very strong energy conservation measures. Here attention will be given to the high and the low scenarios.

Table 1. Historical and projected growth rates of gross domestic product (GDP), by region, for the high and low scenarios (percentage per year).

Region	Historical		Scenario projection			
	1950 to 1960	1960 to 1975	1975 to 1985	1985 to 2000	2000 to 2015	2015 to 2030
			High scenario			
I	3.3	3.4	4.3	3.3	2.4	2.0
II	10.4	6.5	5.0	4.0	3.5	3.5
III	5.0	5.2	4.3	3.4	2.5	2.0
IV	5.0	6.1	6.2	4.9	3.7	3.3
V	3.9	5.5	5.8	4.8	3.8	3.4
VI	7.0	9.8	7.2	5.9	4.2	3.8
VII	8.0	6.1	5.0	4.0	3.5	3.0
World	5.0	5.0	4.7	3.8	3.0	2.7
I + III*	4.2	4.4	4.3	3.4	2.5	2.0
IV + V + VI*	4.7	6.5	6.3	5.1	3.9	3.5
			Low scenario			
I	3.3	3.4	3.1	2.0	1.1	1.0
II	10.4	6.5	4.5	3.5	2.5	2.0
III	5.0	5.2	3.2	2.1	1.5	1.2
IV	5.0	6.1	4.7	3.6	3.0	3.0
V	3.9	5.5	4.8	3.6	2.8	2.4
VI	7.0	9.8	5.6	4.6	2.7	2.1
VII	8.0	6.1	3.3	3.0	2.5	2.0
World	5.0	5.0	3.6	2.7	1.9	1.7
I + III*	4.2	4.4	3.1	2.1	1.3	1.1
IV + V + VI*	4.7	6.5	5.0	3.8	2.9	2.6

*Presented for purposes of comparison with data in (*18*) and other global studies which exclude centrally planned economies. Note: Historical and projected values of GDP in constant (1975) U.S. dollars are given in Chant (*19*).

Table 2. Final energy (in the year 2030) in the two scenarios compared to final energy calculated with historical elasticities.

Region	High scenario (GW-year/year)	With historical ϵ_f* (GW-year/year)	Difference† (%)	Low scenario (GW-year/year)	With historical ϵ_f* (GW-year/year)	Difference† (%)
I	3,665	6,921	47	2,636	4,036	35
II	4,114	5,355	23	2,952	3,850	23
III	4,375	6,037	28	2,987	3,761	21
IV	2,641	4,385	40	1,656	2,481	33
V	3,175	6,900	54	1,876	3,121	40
VI	1,620	2,590	37	850	1,015	16
VII	3,196	8,849	64	1,589	3,536	55
World	22,786	41,037	44	14,546	21,800	33

*Calculated by using historical (1950 to 1975) final energy-to-GDP elasticity (ϵ_f) for each region. †Calculated as final energy using historical ϵ_f minus IIASA scenario projection divided by final energy using historical ϵ_f.

Energy Demand

Population growth, economic growth, technological progress, and structural evolution are the four principal determinants of energy demand. According to Keyfitz (*6*), an overall population growth from 4 billion today to 8 billion by the year 2030 has been considered, and the disaggregated numbers for the seven world regions were used in the analysis described here. Eight billion is a conservative estimate, since it implies that by the year 2015 the average family will have only two children, the age structure then prevailing being the cause of world population growth even after 2015. Although one can make estimates of population growth, it is impossible to predict economic growth rates, because these are strongly influenced by innovations, know-how, and skills of all kinds. Instead, one has to make assumptions. We intended to be conservative and therefore assumed declining economic growth rates throughout. Further, we recognized that developing countries would be limited in their growth potential to one or two percentage points above the growth rates of the developed countries (*7*). This implies that for the next few decades the developing countries will still be tied to the rest of the world economy through trade and other relations. It is unrealistic to assume a high growth rate in the developing part of the world while the OECD countries have a low or zero growth rate. When constructing the scenarios we found that growth rates are generally restricted by the conditions required for interregional consistency and the balance of energy demand and supply. Thus, if one connects the 1975 and 2030 points by an exponential curve (the decline of growth rates therefore not being expressed) one obtains a 3.4 percent rate of economic growth for the high scenario and 2.4 percent rate of growth for the low scenario. Disaggregated in time and space the picture is as explained in Table 1.

On the basis of these assumptions we estimated the related energy demands. It is particularly important to distinguish between primary and final energy, the former being crude oil or coal, for example, the latter gasoline or electricity. For the long-range and globally comprehensive scenarios it is not feasible to base an evaluation on prices and elasticities. It is more appropriate to consider, and account for, the physical end uses of energy. Such accounting has been formalized in the MEDEE model (*8*) and pioneered by the Grenoble group (*9*), among others. It calls for the identification of life-style, as well as economic and technical parameters related to energy end uses. A problem associated with the MEDEE model is internal consistency. Usually one can force such consistency by relying on an input-output approach, for example. But when we consider the evolution of energy infrastructures we ask for the evolution of input-output coefficients and therefore only shift the problem somewhere else. Thus the results obtained are subject to debate, but so is the future of the economies in question. Generally it was assumed that a significant degree of energy conservation would take place.

Table 2 shows the aggregate results for the seven world regions and their differences with respect to historical trends. The high scenario provides for a higher degree of conservation because higher economic growth rates usually allow for more innovation and structural change. Physically, even higher degrees of energy conservation are possible. Energy consumption can be restrained either by not meeting needs or by substituting many of the services that come from energy with services that come from capital or labor. However, related to this are problems of the structure of the economies in question. For example, it may not be possible to maintain high levels of productivity if there is a substantial increase in the number of people seeking employment in the service sector. Such an increase could also have geopolitical implications, particularly in the case of larger nations. In fact, these problems reach far beyond the domain of energy. Here we chose not to make extreme assumptions. It was then legitimate to look for an overall indication of the nature of the two demand scenarios. Figure 3 shows the ratio of energy to gross domestic product, or, in other words, the overall energy intensiveness in the past and in the two scenarios. A certain regularity is evident, pointing to a decreasing energy intensiveness in general. It is felt that such regularity is one of the characteristics of the demand scenarios.

There is a major observation in connection with analyzing energy demand that is quite robust against parameter variations. In view of the balance between energy demand and supply, we found it necessary in our scenario writings to restrict the uses of hydrocarbons to those where substitution is difficult, for example, as chemical feedstocks. The transportation sector was also assumed to need hydrocarbons, because other end-use technologies (which could, for example, use hydrogen instead) will penetrate too slowly to make a worldwide difference before 2030. It was then not surprising to find that in region II, long-range planning indeed requires the use of liquid hydrocarbons exclusively for chemical and transportation purposes. But this approach is not imperative. Chemical feedstock could also come from synthesis gas and more electricity might be used in the transportation sector. But scenario writing requires that we make such considerations explicit.

A demand for final energy leads to a demand for primary energy and therefore implies a combination of energy conversion processes. Such combinations result from the availability of fossil and nuclear fuels, from build-up rates of new conversion technologies, such as coal liquefaction, and from cost optimization. A linear programming model, MESSAGE, was used to identify optimal combinations (*10*). Actually, discounted costs were optimized and this led to the usual question about the appropriateness of such optimization. However, the results obtained were characterized more by the constraints than by the type of the objective function. Indeed, a linear programming procedure accomplishes two things: it optimizes and it handles the many constraints that must necessarily be considered in an orderly fashion. In our scenarios the window of feasibility turned out to be small, that is, the problem was feasibility, not optimality.

Thus the required primary energy supplies are given in Table 3 disaggregated by regions. By the year 2030 the total global demand for primary energy is roughly 36 terawatt-year per year for the high scenario, and 22 TW-year per year for the low scenario (*11*). This compares with 8.2 TW-year per year today. Thus, between 1975 and 2030, the demand for primary energy increases by a factor of 4.4 and 2.7, respectively, for the high and low scenarios; on a per capita basis there is a 2.2- and 1.35-fold increase, respectively, in primary energy demand. It

Table 3. Two supply scenarios, primary energy by region, 1975 to 2030 (terawatt-year per year).

Region	1975	High scenario		Low scenario	
		2000	2030	2000	2030
I	2.65	3.89	6.02	3.31	4.37
II	1.84	3.69	7.33	3.31	5.00
III	2.26	4.29	7.14	3.39	4.54
IV	0.34	1.34	3.68	0.97	2.31
V	0.33	1.43	4.65	1.07	2.66
VI	0.13	0.77	2.38	0.56	1.23
VII	0.46	1.44	4.45	0.98	2.29
Total*	8.21†	16.84	35.65	13.59	22.39

*Columns may not sum to totals because of rounding. †Includes 0.21 TW-year per year of bunker fuel oil.

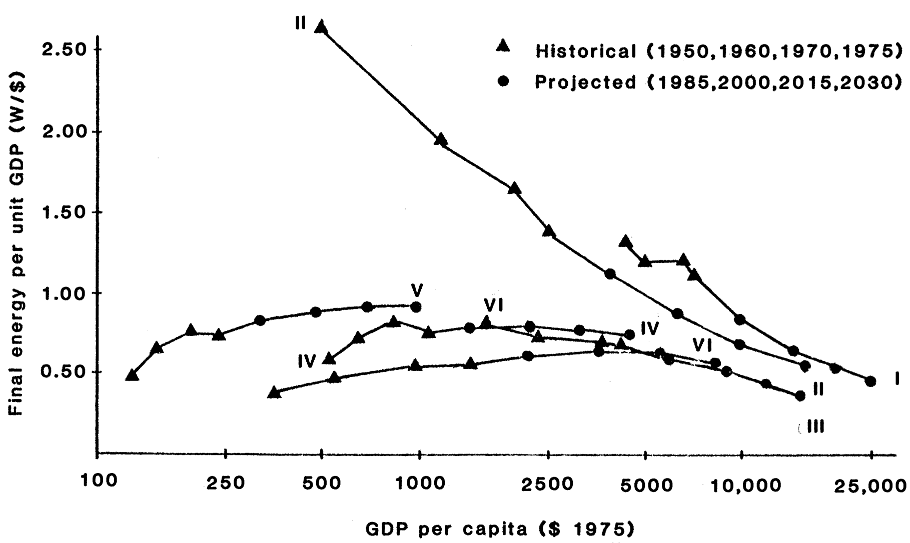

Fig. 3. Energy intensiveness in different world regions.

should be noted that the supply of energy continues to be very uneven. The ratio of energy supply in regions IV + V + VI + VII (the South) compared with regions I + II + III (the North) shows only a slight improvement. The ratio improves by a factor of 3 from 0.23 to 0.75 in the high scenario, and by a factor of 2.6 from 0.23 to 0.6 in the low scenario. Realistically, one must expect the growth of energy demand, at least in regions IV, V, VI, and VII, to continue increasing beyond the year 2030, for reasons of population growth as well as reasons of economic growth. Thus, supply options must be evaluated against a yardstick of 2 to 3 TW-year per year if a contribution of about 10 percent of the 20 to 30 TW-year per year of the total global demand is to be envisaged.

Energy Supply and Related Technologies

Let us now turn to the disaggregation by source. This was done for each region separately, and here I only give such disaggregation for the world as a whole because space is limited. Figure 4 refers to the high scenario and gives the relative shares; the pattern for the low scenario is quite similar.

There is a somewhat constant share of gas and a decline in the share of oil. This is because synthetic liquids from coal are used as substitutes. Coal therefore has to be set aside for this purpose, and this in turn becomes possible because nuclear power takes over large portions of electricity generation. Hydropower has a somewhat constant share, while the other renewables have a rather low share. This is more an outcome of the cost optimization routine than a statement of the potential or desirability of such renewable resources. More will be said about this below. What must be emphasized here is the advent of two major technologies in the year 2000: synliquids and the fast breeder reactor. Synliquids should be interpreted as synthetic hydrocarbons of any kind, for example, methanol, gasoline, or even methane. But in the scenarios the demand for energy in liquid form was particularly pressing, and thus it was labeled as synliquid. It was assumed that the processes in question would be autothermal. (In autothermal gasification and liquefaction schemes both the process heat and the required hydrogen come from the coal itself, in addition to what is needed for the chemical coal content of the synfuels. This means a difference of a factor of 3 to 4 between autothermal and allothermal processes. In an allothermal process, the process heat and the required hydrogen are supplied exogenously, preferably by means of either nuclear or solar power.) To have synliquids and the fast breeder reactor in use by the year 2000 would mean an installed capacity of dozens of gigawatt-thermal or, what is equivalent, dozens of million tons of coal (tce). It would not be sufficient to have one or two demonstration plants by this time. Although there are regional differences in these requirements, this means that aggressive action in an overall context is required now.

Of particular interest is the disaggregation by source in absolute terms as given in Table 4. What is striking is the increase in oil use. This means a transition to ever higher production costs and, consequently, a transition to oil shale and tar sands. Also the production of gas increases. Perhaps most indicative is the case of coal. Many may argue that an increase of up to 12 TW-year per year (high scenario) is impossible. This may indeed be the case. But if we are to be globally comprehensive we must then ask: What will we have instead? The low scenario? More solar? Indeed, it was our intent in this scenario analysis to seek answers to such questions. Nuclear power takes on a medium-size share. It should be noted that all the numbers refer to thermal energy production per year; for example, the figure for light-water reactor plus fast breeder reactor in the low scenario is 5.17 TW-per year. This relates roughly to an installed capacity of 3000 gigawatt-electric by the year 2030, which is quite close to the results obtained in a recent study on the future of nu-

Table 4. Two supply scenarios, global primary energy by source, 1975 to 2030 (terawatt-year per year).

Primary source*	Base year 1975	High scenario		Low scenario	
		2000	2030	2000	2030
Oil	3.62	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light-water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar†	0	0.10	0.49	0.09	0.30
Other‡	0.21	0.22	0.81	0.17	0.52
Total§	8.21	16.84	35.65	13.59	22.39

*Primary fuels production or primary fuels as inputs to conversion or refining processes; for example, coal used to make synthetic liquid fuel is counted in coal figures. †Includes mostly "soft" solar, that is, individual rooftop collectors; also small amounts of centralized solar electricity. ‡"Other" includes biogas, geothermal energy, commercial wood use, as well as bunker fuel oil; for 2000 and 2030, bunker fuel is not estimated. §Columns may not sum to total because of rounding.

Table 5. Region VI (Middle East and Northern Africa) oil production rates and capacity and assumed production ceiling (million barrels of oil per day). Non-region VI OPEC countries are Venezuela, Ecuador, Nigeria, Gabon, and Indonesia. Eight OPEC member countries are in region VI; six in the Middle East (Saudi Arabia, Kuwait, United Arab Emirates, Iran, Iraq, and Qatar) and two in Northern Africa (Algeria and Libya).

Region or country	1975	1977
Production rates		
OPEC member countries	27.19	31.53
Minus non-region VI OPEC member countries	− 5.82	− 6.52
OPEC and region VI countries	21.37	25.01
Plus non-OPEC region VI countries*	+ 1.05	+ 0.99
Region VI	22.42	26.00
Of which exported	21.23	24.64
Production capacities†		
Saudi Arabia	10.7	10.8
Iran	6.5	6.8
Iraq	3.0	2.6
Kuwait	2.9	3.0
Libya	2.3	2.5
United Arab Emirates	2.3	2.3
Algeria	1.3	1.0
Qatar	0.6	0.7
Estimate of other region VI countries‡	1.4	1.4
Region VI	31.0	31.8
Estimated long-term region VI "ceiling": 33.6		

*Seven countries in the Middle East: Bahrain, Jordan, Lebanon, Oman, Syria, North Yemen, and South Yemen, and one in Northern Africa (Egypt). †Production capacities are estimates from the Department of Energy (20) for 1975 and from *Petroleum Intelligence Weekly* (21) for 1977. ‡IIASA estimate.

clear power on a worldwide basis (*12*). Solar power here refers to local, or "soft," uses of solar power.

More Oil

The most important aspect of Table 4 is the increase of what is labeled as oil. How could this be achieved? Both production and resource constraints must be considered. Figure 5 shows production requirements for the world excluding centrally planned economies. Indeed, by the year 2010 production from known reserves of conventional oil will be approaching exhaustion. New reserves were accounted for in the analysis. Cases like Mexico illustrate the point. But more is required. Unconventional oil such as that obtained from tar sands, oil shales, heavy crudes, and enhanced recovery take over an ever larger share. After the year 2000 it becomes necessary to add coal liquefaction, yielding a total oil production outside region VI that still does not meet the minimum demand of liquids required for chemical feedstocks and transportation. Continued imports from region VI are necessary, and it is indeed one of the crucial assumptions in the analysis that region VI would continue to have a production ceiling of 33 million barrels of oil per day. This ceiling is 50 percent greater than the 1975 oil production of this region, and about 30 percent above its 1977 production rate. Region VI is not the OPEC (Table 5 explains the relation between these two entities). So the conclusion is that the worldwide struggle for oil will continue; only some time after the year 2030 could this situation change. Obviously, one also has to envisage lower production ceilings in region VI. This leads quickly to very awkward situations. More unconventional sources of energy would be required and even more coal liquefaction. We studied the consequences of having a ceiling of 30 million barrels of oil per day and found them tough. In view of the general lack of elasticity in the oil market, adjustments of demand will also be tough. Reduced economical growth rates are a most likely consequence.

But what about the availability of resources? An attempt to explain this is made in Table 6. One should note the difference between 837 TW-year for the grand total and 281 TW-year for the conventional resources (281 TW-year relates roughly to 200 billion tons of oil equivalent). The difference between 837 and 281 TW-year is made up by unconventional resources (see also Fig. 5). For example, in region I the 126 TW-

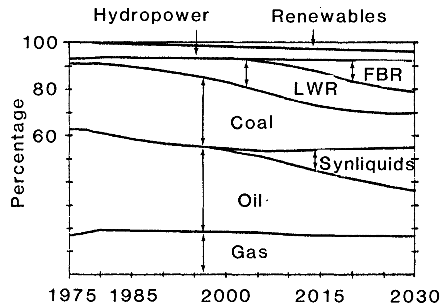

Fig. 4. Global primary energy, high scenario, 1975 to 2030.

year of oil shale and tar sands refers to deposits in such areas as Colorado in the United States and Athabaska in Canada; the 178 TW-year refers mostly to the Orinoco area in Venezuela. The potential of these areas is equal to or larger than that of the Persian Gulf. But the necessity to use these resources, as is indicated in Fig. 5, implies tremendous environmental consequences. Despite all the environmental analysis already performed today, this situation provides a new dimension of its own that requires more work and imagination. A natural reaction would be to declare the use of these deposits undesirable and perhaps infeasible. But the overall global balance between demand and supply must be kept in mind. It is particularly region III that would have to look for alternatives. One such alternative would be gas from region II and perhaps region VI—with all the geopolitical consequences; this requires a separate consideration (*13*).

World Oil Exports

How are these exports of region VI allocated to the other regions? The answer to this question requires a major study

Table 6. Ultimately recoverable oil resources (all numbers in terawatt-years).

Region	Conventional	Unconventional: Deep offshore and polar areas	Unconventional: Enhanced recovery	Unconventional: Oil shale and tar sands	Total
I	26	12	10	126	174
II	43	12	20	76	151
III	15	7	6	13	41
IV	23		8	178*	210
V	23	13	7	20	63
VI	139		†	20‡	159
VII	12	8	5	14	39
Total§	281	52	56	447	837

*Includes 170 TW-year of heavy crude oil. †Region VI is not expected, within the next 50 years, to make extensive use of tertiary recovery techniques. ‡Includes heavy crude oil and some possibly deep offshore oil. §The analysis of region VII is necessarily rough, because few published data are available.

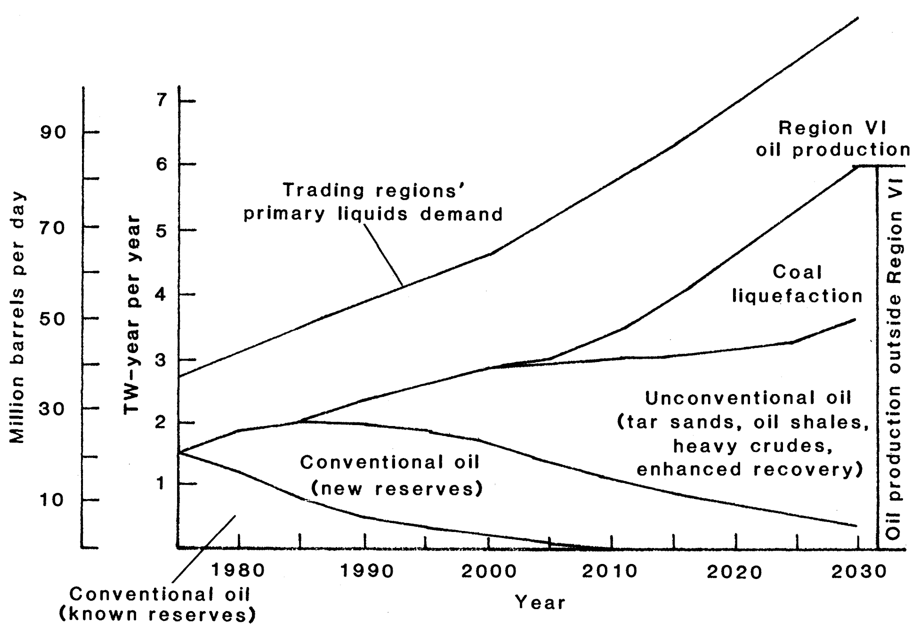

Fig. 5. Oil supply and demand, 1975 to 2030 for the world, excluding centrally planned economies, high scenario.

on the future of world trade. Such a study has not yet been possible at IIASA, because it requires more economical than energy-analytical skills. It has been possible, however, to sketch a trading scenario by using an interregional gaming routine developed by the Siberian Power Institute at Irkutsk. For this routine it is assumed that region VI dominates the market and that region VI wants to maximize its revenues within the production ceiling of 33 million barrels of oil per day, using it for both export from the region and domestic consumption in the region. Limiting factors are the synfuels as produced in the importing regions. The result is given in Fig. 6. The scenarios point to a situation where regions I, II, IV, and VII are self-sufficient in 2030. This means that the exports from region VI are going only to two regions: II and V. Western Europe and Japan must compete with the developing countries of region V, and region III must reduce its oil imports to let region V have its share. Again one must point to the geopolitical implications (*13*).

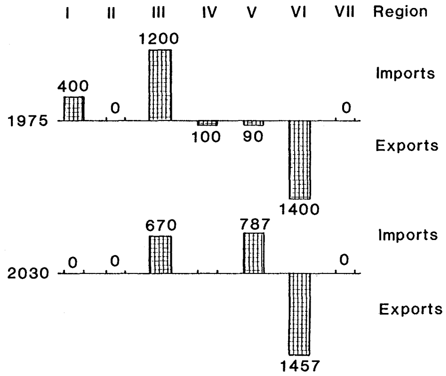

Fig. 6. Oil trading between regions in 1975 and 2030, high scenario (gigawatt-year per year; 1 GW-year per year = 14,000 barrels of oil per day).

Coal and Nuclear Power

Coal can be considered in a similar manner. Unusually high figures for yearly productions have to be assumed: in region I up to 2700 million tce per year, in region II up to 3500 million tce per year, and in region III up to 1000 million tce per year. Both regions I and II are asked in the scenarios to assume an export function for coal much in the same sense as region VI is asked to export oil. An indicative figure for regions I and II in the high scenario is 600 million tce each by the year 2030. All this comes on top of the above considered production of oil from shale oils and tar sands. Today this appears inconceivable, but the global energy problem is just of that dimension. In any event, one has to expect coal to be in short supply after the year 2000. While it seems natural to go into autothermal coal liquefaction and gasification schemes today, such shortages of coal supply after the year 2000 may force the use of allothermal liquefaction and gasification schemes, because these would reduce the demand for coal used for synfuels by a factor of roughly 3 to 4. Apart from coal supply, there is the problem of carbon dioxide production from fossil fuels, which might equally demand the use of allothermal schemes. However, the two reference scenarios imply autothermal liquefaction schemes. For these two scenarios the related CO_2 buildup is given in Fig. 7, according to Niehaus' model (*14*). Even today the situation looks serious.

Nuclear power in the supply scenarios is represented on a medium scale. As mentioned earlier, the 5.17 TW-year per year of the low scenario relate to 3000 GW-electric of installed capacity by the year 2030. In the high scenario the respective figures are 8.09 TW-year per year and 4800 GW-electric. In the analysis it was concluded that not more than 10,000 GW-electric could be installed by the year 2030 even if there were a worldwide and lasting effort to develop nuclear power. However, some additional nuclear potential may exist that could be used when obtaining fossil power—from unconventional fields—becomes too cumbersome. The generation of hydrogen by electrolytic or thermolytic means could, for instance, facilitate the allothermal schemes of coal liquefaction or gasification. If nuclear power were to be installed on such a scale, it would be necessary in any event to base it on the principle of breeding, because the integrated demand for uranium comes close to 8.5 million tons in our high scenario. In practice it is not intended to restrict the use of nuclear power to light-water reactors and fast breeders. All prudent reactor strategies, including the high-temperature and the heavy-water reactors, should be employed as long as the global supply conditions for natural uranium (and thorium) are kept in mind. There have been many studies on this subject, for example, those of INFCE (International Fuel Cycle Evaluation), so it is unnecessary to go into greater detail here. However, a word on fusion must be added. Strategically, fusion can substitute for the breeder reactor because it produces primarily electricity and is de facto decoupled from the resource question. There are also many other similarities between the fusion and the fast breeder reactor (*15*). But it is considered unlikely that a fusion capacity greater than, say, 1000 GW-electric could be installed before the year 2030. Although its strategic potential might be utilized, essentially this will be after the year 2030.

Hard and Soft Solar Power

It is necessary to distinguish between hard and soft solar power. Hard solar power refers to large solar power fields that might be installed, for instance, in the Sahara or in other sunny desert areas. Assuming an effective density of 20 watts per square meter for the production of solar electricity, it would take only 500,000 square kilometers to install a capacity of 10 TW-electric. Such an amount of land is not unreasonable; one may recall, for example, that all agricultural land on earth adds up to about 13 million square kilometers. However, the production of solar energy requires that the land put aside for this purpose be covered with materials, regardless of the particular solar technology to be used. The materials installed may amount to 100 kilograms per square meter (*16*), if one includes the hardware used to protect the solar collectors from the elements. These are typical systems effects that are often not taken into account when a new technology is first being considered. Only when the technology reaches a later stage of development do such effects come into view and then tend to dominate. If it is assumed that each year, 500 million tons of materials would have to be set aside just for solar power installations, this would imply a buildup rate of 100 GW-electric per year. It must be emphasized that 500 million tons per year is a large figure; today's world production of cement and steel amount to about 700 million tons per year. This leads us to the conclusion that the production capacity of solar power could not reach a dozen terawatt-year per year or so until after the year 2030, as is the case for fusion. And in both cases we have disregarded the question of costs.

What is left is the soft version, or local use, of solar power. Such power might very well be of local significance; however, on a global scale its contribution is limited. For example, the total roof area per capita may amount to 40 square meters, but only one-fourth of this area might be suitable for collecting solar power. With 40 watts per square meter of effective solar power being harnessed in the low-temperature domain, one would obtain 400 watts per capita, or, for 8 billion people, a total of 3.2 TW-year per year. This back-of-an-envelope calculation does not take into account such problems as low-temperature storage or costs or special local conditions. But the argument is sufficiently robust to conclude that such soft solar power does not match the scale of global energy demand. It turns out to be a valuable but limited contribution. In the scenarios, both high and low, the contributions of soft solar may be somewhat too small. In a linear programming approach, which optimizes discounted costs, it is difficult to arrive at meaningful estimates for the year 2030 and the seven world regions of the whole globe. But is is maintained that the contribution from soft solar energy will be a few terawatt-year per year, not a few dozens of terawatt-year per year.

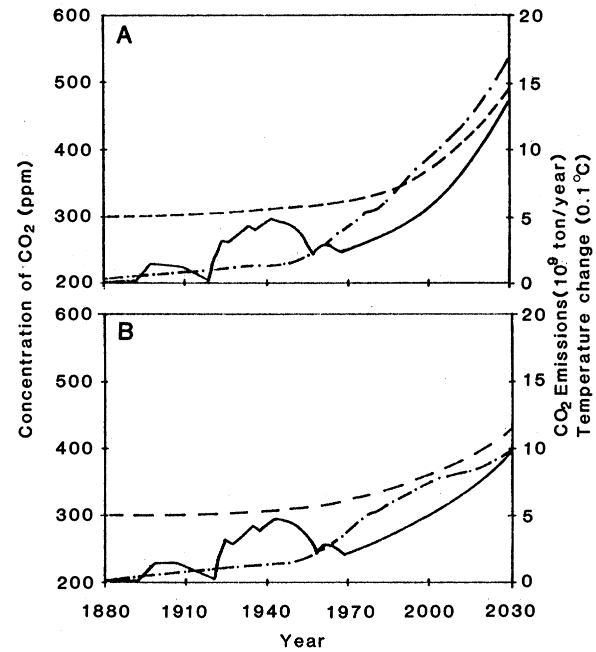

Fig. 7. Carbon dioxide emissions (—·—) (measured as tons of carbon per year), atmospheric CO_2 concentration (— —), and temperature change (———). (A) High scenario. (B) Low scenario.

Other Renewables

In addition to solar power there are the renewable energy sources with a somewhat local character that invite special consideration. Indeed, because local conditions are different and sometimes special, there are important local opportunities that do not become explicit in a global study. Often these sources are referred to as "soft"; however, it is interesting to make estimates of the global potential of such local, renewable sources. Hydropower seems to have a potential of 2.2 TW-electric of generating capacity (*17*), and this figure is hardly disputed. The renewables that remain include biomass, geothermal, and wind energy. In the analysis that underlies this article, it is concluded that the energy from these sources might add up to 2 or 3 TW-year per year. These upper limits are not well defined and therefore are potentially controversial. However, it should be kept in mind that soft energy sources become harder as the scale on which they are produced increases. Therefore there is agreement with proponents of soft energy paths that the soft renewables could have a global total potential in the order of 8 TW-year per year. Hard solar power is to be added to this figure.

With 8 billion people by the year 2030, 8 TW-year per year would mean 1 kW-year per year per capita as the global average. Today's average is 2 kW-year per year per capita. As mentioned before, it is not physically impossible to live with 1 kW-year per year, especially once capital (and time) is available for the substitution of services from energy with services from capital, labor, and knowhow. But the IIASA analysis also makes it clear that drastic changes of the structure of the economy would be required. This has far-reaching social and political implications and leads to the question of what happens politically when the gross national product of one group of nations consists of 20 percent steel and 80 percent arts, and the gross national product of another group of nations is nominally equal but consists of 80 percent steel and 20 percent arts. In fact, the hard-soft controversy is mostly a political one; the physical science aspects are rather clear.

Energy from Gas

In the reference scenarios, the cautious assumption was made that gas would not be transported intercontinentally. Thus gas is of regional significance only and its contribution, while increasing in absolute terms, remains somewhat constant in relative terms. The resource situation allows for higher energy contributions from gas, but only for a couple of decades given today's knowledge. Where 837 TW-year is the total recoverable oil (see Table 6), 538 TW-year is the total recoverable gas, its share of conventional resources being 267 TW-year.

Given the limited supply opportunities, it is likely that the problems of intercontinental transportation of gas will be solved. The technical problems associated with LNG (liquid natural gas) tankers and large-diameter or high-pressure pipelines, as well as methane-methanol conversions, are not insurmountable. Hydrogen produced by electrolysis or thermolysis using energy from nonfossil sources such as nuclear breeders and solar power would be suitable for an extension of the infrastructure for the transport and distribution of natural gas. It could thus allow for a certain flexibility of energy strategies that might be required in view of the CO_2 problem, or in view of other shortcomings on the supply end of oil and coal.

A Word on Cost Ranges

It is true that the analysis did not start on the side of costs and prices, but nevertheless, that aspect was constantly monitored. On the supply side, oil and natural gas production costs were considered. Note that these were costs and not prices. By definition we arbitrarily eliminated the political and, specifically, the monetary aspects of the problem. Actually, three cost categories were considered: $0 to $12, $12 to $20, and $20 to $25 per barrel of oil equivalent. For coal the categories were: $0 to $25 per ton and $25 to $50 per ton; and for uranium, $80 and $80 to $130 per kilogram of uranium. All figures are in constant 1975 dollars. The linear program then picked resources as necessary. In additon, capital costs were entered into the linear program. They ranged from $170 per kilowatt for gas turbines up to $920 per kilowatt for the fast breeder reactors, up to $1900 per kilowatt for solar central stations in the case of electricity generation, and from $60 to $320 per kilowatt of secondary energy in the case of district heating. The weighted average cost of final energy thus increases by a factor of 2.4 to 3.0 between 1972 and 2030.

Observations

It is not too difficult to envisage a satisfactory energy system for even more than 8 billion people in the long-distance future. As secondary energy, such a system would make use of electricity and hydrogen; as primary energy, nuclear power from fusion or fission breeder reactors would be used as well as solar power. The carbon atom would be used for the most part only insofar as reduced carbon is produced by photosynthesis. In effect this would mean the recycling of CO_2. In this event the problems associated with obtaining fossil resources and disposing of CO_2 would be eliminated. The next 50 years is too brief a period for a complete transition from fossil to nonfossil energy sources. By the year 2030, perhaps 30 percent of primary energy could come from nonfossil resources. But within the period up to 2030 there is another superimposed transition, that is, the transition from conventional and cheap fossil fuels to unconventional and expensive ones. This superimposed transition becomes necessary because even the somewhat modest rates of economic and population growth exceed the rates with which the infrastructure for energy supply and demand can change. We observed above that the most precious resource is time. Indeed, the more time we waste the deeper we have to go into the use of unconventional fossil resources. This is shown in Table 4. In the absence of a proper approach this could have far-reaching environmental consequences, for which appropriate abatement measures should be envisaged. The two transitions should be harmonized; the carbon atom should be used prudently. The use of allothermal coal liquefaction or gasification schemes is a case in point. But the buildup of appropriate infrastructures must also be considered in this context; adapting gas pipelines for the transport of hydrogen is an example.

The intertwining of the two transitions can also be differently expressed: during the next 50 years we will not really be resource-constrained; the constraints will only be developing. However, between 2030 and 2080, the resource constraints will come to the forefront, and then the transition from fossil to nonfossil resources will have to be completed.

Balancing demand and supply on a worldwide basis required the use of all supply and demand opportunities. Coal, oil, and gas, as well as nuclear, were used extensively in the scenarios, together with significant energy conservation. In that sense there are few choices to be made: *all* opportunities must be utilized.

The world energy problem can be solved. But it will require great effort. Besides will power and determination, it will require a strategic view and prudence.

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