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SECOND STATUS REPORT OF THE IIASA PROJECT ON ENERGY SYSTEMS 1975

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PREFACE

This is the written version of the second status report of the IIASA Project on Energy Systems. (The oral version was presented in October in Laxenburg, Austria, and later in Varna, Bulgaria.) By its nature, it is intended as an insight into the present status of the work of the energy project, not as a comprehensive book or a set of results that are final in one way or other.

The IIASA energy project began in the summer of 1973 and we expect it to continue until the end of 1978. Thus nearly half of the time available to us has elapsed. During this first period we focused on the conceptualization of the systems aspects of the energy problem. Now, the energy project is beginning to concentrate on a number of more specific and operational tasks.

The Introduction provides both an explanation of the overall approach and the frame for the individual contributions, which cover certain aspects in greater depth. Notwithstanding my overall responsibility as project leader, each author is responsible for his own independent contribution. Yet it is clear that this status report represents the results of the energy team as a whole.

To finish such a comprehensive status report requires much devoted help. We owe thanks to many, particularly to Maria Helm for patiently dealing with each of us and for putting everything together.

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PART 1. INTRODUCTION

Setting the Stage

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THE SCOPE

It took us some time to understand what energy systems are and thus to spell out appropriate objectives for the IIASA Energy Project. This understanding had to grow steadily in order to mature. It is only now, after two years of work, that we can identify in greater detail the various tasks of the Project and their expected synthesis. One should realize that this process of growing understanding and maturing is an inherent part of the work of a project in its early stages; we have our doubts when it is claimed that a complex project was started with sharply defined objectives at the outset.

It is important to note that the IIASA Energy Project should not compete with national groups. Examination reveals that many of these are more near-term-oriented. Project Independence of the U.S.A., for example, originally had a time horizon of up to 1985; similar observations hold for other national projects. After extended reflection and evaluation, we can now state that the IIASA Energy Project concentrates mainly on the time period between 15 and 50 years from now, while including more long-term considerations when necessary. This appears to be the time period for new technological strategies to take effect, and some natural energy resources will decrease during this span. Evaluations for such time periods, however, are made in view of decision-making--be it explicit or implicit--in the near future. One should recall that one also makes a decision by doing nothing at all.

Equally, it is most appropriate for the IIASA Energy Project to emphasize the global aspects of the energy problem, which will probably come to be the predominant features. The oil problem is already global in nature: a major share of the oil supply for large areas comes from one limited area. We are beginning to appreciate the economic and political implications of this fact. The oil problem is but one example; as we shall see, there are others, such as man's impact on the climate and the like. IIASA provides a unique opportunity for the analysis of such global problems.

Before explaining our overall approach to energy systems in greater detail and illustrating what we have achieved in 1975, it is appropriate to identify the kind of outputs we hope to generate. We plan to write a book in 1976 that will comprise the results the Project has obtained so far. In 1973, at the very beginning of our work, we attempted to draw up a picture of the energy problem; now we wish to comprehend the results obtained and put them into perspective, in order to improve and refine that picture. The book will in no sense give final answers, but will serve as a benchmark of our work.

A second output we are trying for is a set of methods and procedures for comparing options for a satisfactory long-range solution of the global energy problem. This effort will be made largely in line with a contract from UNEP and in conjunction with the IAEA and WHO. Such methods and procedures are intended to assist the national or regional decision-makers: what are the implications of opting for coal, nuclear energy or solar energy? How do the associated systems effects compare? What is the best possible energy mix that minimizes the combined effects?

The third output we hope to produce is a model or a set of procedures that allow one to understand and assess implications of regional or national energy policies in view of global constraints. What does it mean to region X if region Y decides to rely on large-scale oil imports? What will the global situation be like if region Z is determined to pursue the coal option? Are these regional decisions globally consistent? To some extent this will be a world trade model, but it will involve more than the features of traditional world trade. The intent is to make it a more general product. Perhaps the world food situation can be dealt with partly by the same or a similar procedure.

THE APPROACH

It is now appropriate to explain our approach to the problem of energy systems in some detail. For this, it is helpful to look at Figure 1. One must consider energy resources and energy demand. While the near-term future will be unsatisfactory in many instances, a number of options will lead to a satisfactory solution in the long run. These options, and particularly their systems implications, must be identified. Interest then focuses on transitions from today's conditions to one option or a combination of options. It is important to consider the constraints for such transitions; if they are understood, the strategies for such transitions can and must be worked out.

Resources

Let us now consider the resource problem in greater detail. Traditionally, the energy problem consisted mainly in the choice between coal and oil. The assessment of resources seems to be a straightforward matter, but is actually a complex systems problem in itself; the series of publications of the World Energy Conference illustrate this. Such data have to be

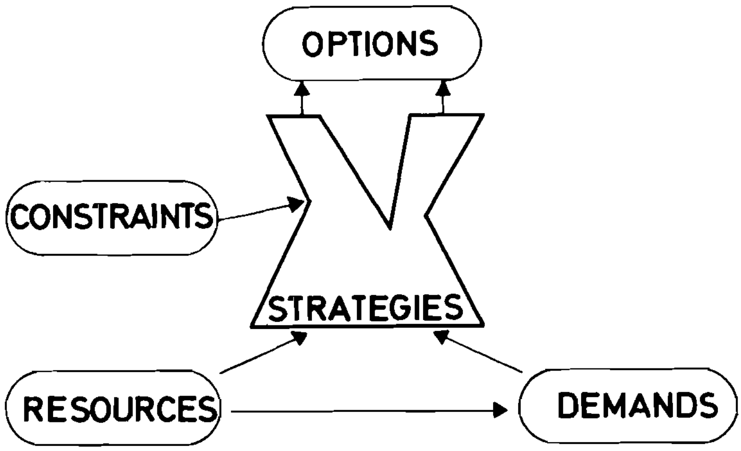

Figure 1. The approach to energy systems.

upgraded continuously, and their classification evolves at the same time. Some time ago, V. McKelvey, Director of the U.S. Geological Survey, proposed a more sophisticated two-dimensional scheme for plotting resource figures. This common classification was finally adopted in 1974, just over a year ago, by the USGS and the U.S. Bureau of Mines, and progressively by other U.S. administrative agencies. In this scheme a distinction is made among various degrees of geological assurance and economic recoverability. Thus reserves become an identifiable subset of resources. In Figure 2 the volume of U.S. coal resources is depicted accordingly. In contrast to the traditional view, for the more distant future the use of coal on a much larger scale must be envisaged--compared to today's circumstances, larger by a factor of perhaps 10. This opens up more than two dimensions of the resource problem. We therefore consider the interaction of mining with the domain of water and with the uses of energy, land, materials and manpower (WELMM matrix). This is illustrated in Figure 3 and Table 1.

Figure 3 indicates the area of land disturbed from surface-mined coal and a solar electric 1,000 MW(e) power plant in middle latitudes, as in Central Europe. After 20 to 30 years, the amount of land required for surface mining compares with that required for a solar power station. Land used for surface mining can in fact be reclaimed. In each case the problems are different, but even so these results are not obvious; this applies also to Table 1.

	IDENTIFIED			UNDISCOVERED	
	DEMONSTRATED		INFERRED	HYPOTHETICAL (IN KNOWN DISTRICTS)	SPECULATIVE (IN UNDISCOVERED DISTRICTS)
	MEASURED	INDICATED			
ECONOMIC	50	147	NONE	1.482	NONE
SUBECONOMIC	63	238	935		

← INCREASING DEGREE OF GEOLOGICAL ASSURANCE

↑ INCREASING DEGREE OF ECONOMIC RECOVERY

Figure 2. Total coal resources of the United States as of January 1, 1974 (x 10^9 metric tons).

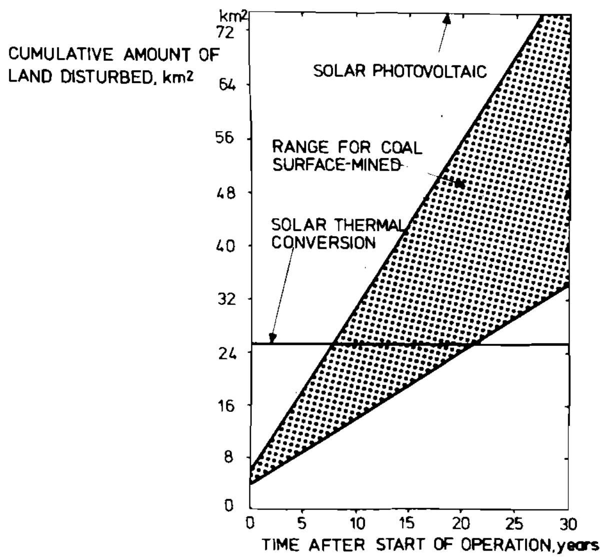

Figure 3. Comparison of land disturbed from surface–mined coal and a solar electric 1,000 MW(e) power plant.

Table 1. Materials requirements for a 1000 MW(e) power plant

Fuel	Weight of Station (10^6t)	Total Flow (10^6t)	Comments
Coal	0.3 - 0.35	50	Coal (25 years)
Nuclear	0.5 - 0.6 LWR FBR	2.5 - 75 0.04-1.2	U 0.2% - U Shale (25 years)
Solar (Tower)	0.35 (Conversion) 0.3-3 (Heliostat)	1 - 30	Mineral Ores (~5-7 years)

In 25 years the materials flow with coal, nuclear and solar will be roughly comparable; only the case of the fast breeder reactor differs significantly. With coal, it is the materials flow for the fuel with some overburden that leads to 50 million tons; with the light-water reactor (LWR), it is the overburden involved in getting a little uranium fuel, and with solar energy, the material to build the facilities.

These figures merely illustrate the kind of work we have done. M. Grenon treated these questions in greater detail when we held a conference on the systems aspects of energy resources in May, 1975. Participation was excellent and stimulating. The conference proceedings are being prepared and edited by M. Grenon and will be published early in 1976. In June 1976 we plan to hold a similar conference on the implications of large-scale uses of hydrocarbons such as shale oil. We are pursuing this jointly with UNITAR, a U.N. group in New York, in the hope that the conference will mark the beginning of an extensive cooperation. There are indications that we might also cooperate with oil industries in this and similar areas. Such opportunities are important, since IIASA activities can bear fruit only through broad interactions of this kind. It should be pointed out here that the methodology of studying energy resources almost automatically becomes general, and thereby applicable to other, non-energy resource problems. Such an evolutionary process is clearly intentional and in the spirit of systems analysis studies at IIASA.

Demand

The counterpart of the fuel resource problem is the probl of energy demand and its systems implications. Traditionally, this did not receive much attention; a given demand was accept and the goal was to find the best way of meeting it by a certain combination of primary energy sources. With today's limitations and constraints, it becomes mandatory to understar energy demand in much greater detail. Energy conservation is closely connected with this.

In the IIASA Energy Project, we are pursuing this problem along three lines. The first involves econometric studies. W.D. Nordhaus and P. Tsvetanov have developed a procedure to relate the per capita net energy consumption, the relative net price of energy and the per capita gross domestic product of market economies (see below).

Specification: $$Q_{t,i} = e^{\alpha i} \cdot \prod_{\Theta=0}^{4} P_{t-\Theta,i}^{0.2\beta} \cdot \prod_{\Theta=0}^{1} Y_{t-\Theta,i}^{0.5\gamma}$$

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where: $Q_{t,i}$ = per capita net energy consumption

$P_{t,i}$ = relative net price of energy

$Y_{t,i}$ = per capita real GDP

α_i = individual-country effects

β = common long-run price elasticity

γ = common long-run income elasticity

The aim is to apply this procedure to both market and planned economies and thereby to understand similarities and differences in these economies. In Table 2 results are given for a number of market-economy countries.

It is quite remarkable to see that price and income elasticities could be considered as common to countries with the same kind of economy; only the absolute price and income levels vary across countries. It is also interesting to note that the explanatory power of developed models with dummy country variables is between 95 and 99 percent of the variance of the time series; they can therefore be recommended for short- and medium-term forecasting. We are in the process of establishing and completing such an evaluation for the planned-economy countries.

Using econometric analysis with prices and incomes implicitly refers to economic equilibria; they determine the prices. We therefore relate a time horizon of perhaps 10 years

Table 2. Results for pooled data: aggregate energy consumption function.

$$q_{t,i} = \alpha i - \underset{(.10)}{.85} \left[\sum_{\Theta=0}^{4} 0.2 p_{t-\Theta,i}\right] + \underset{(0.08)}{0.79} \left[\sum_{\Theta=0}^{1} 0.5 y_{t-\Theta,i}\right]$$

	D_i					
α U.S.A.	U.K.	F.R.G.	B	NL	F	I
4.70	.03	-.09	.13	-.25	-.35	-.35
(.18)	(.03)	(.03)	(.14)	(.03)	(.04)	(.04)

D_i = Dummy Country Variables NL = Netherlands

UK = United Kingdom B = Belgium

FRG = Fed. Rep. of Germany F = France

B = Belgium I = Italy

but not much longer to such studies. This is not really the time period in which we are most interested; however, this econometric approach to understanding energy demand does give us the necessary interface with other energy studies, for example, Project Independence of the U.S., whose language is mostly econometric. Also, the energy conservation problem seems to be more one of price relations than of technology. For this reason, too, we need to pursue these studies.

A neighbor of the econometric approach is energy analysis, which considers the energy content of industrial goods and services, as exemplified in Table 3. This represents our second line of investigation. J.-P. Charpentier studied energy analysis in some detail, and a number of papers are being completed. Both lines of investigation were dealt with at the IIASA conference on energy demand in May, 1975. The proceedings of this conference are being prepared by W.D. Nordhaus with the help of a grant from the Ford Foundation; they will be published within the next few months.

With the help of both approaches, it will be possible to draw life-style scenarios and life-style descriptions in terms of energy demand. Such scenarios are a major input for a more global forecast. One must realize that 75 percent of the

Table 3. Total energy consumed per $ final output in French industry, 1971 (kWh(th); $1 = 4.5F).

Sector	Total Energy Consumed per $ Output
Food Industry	2.20
Building Industry	16.07
Glass Industry	16.03
Steel Industry	34.85
Non-Steel Industry	33.16
First Metal Process	11.44
Electr. & Mech. Industry	6.01
Chemical Industry	11.41
Cloth Industry	2.92
Paper Industry	5.62
Miscellaneous	4.93

world's countries have a per capita consumption of less than 2 kW, while the consumption of 3 percent of the countries is larger than 7 kW. Figure 4 outlines this in greater detail. It is obvious that this distribution will not prevail in the future, and that the distribution of energy demand across countries will become a political issue. This leads to the third line of investigation in the field of energy demand; that is, global scenarios for the evolution of global energy demand, with special reference to world population growth. We are only at the beginning of these studies, but the underlying issue is fundamental: will there be a diffusion of one life style with suitable adaptations to regional conditions such as climate, or a basic life-style dichotomy between two or more parts of the globe?

Again, it should be noted that this methodology for studying energy demand is more general and so of broader use. At present, we are trying to extend it to problems of water demand, and again we intend to evolve beyond energy.

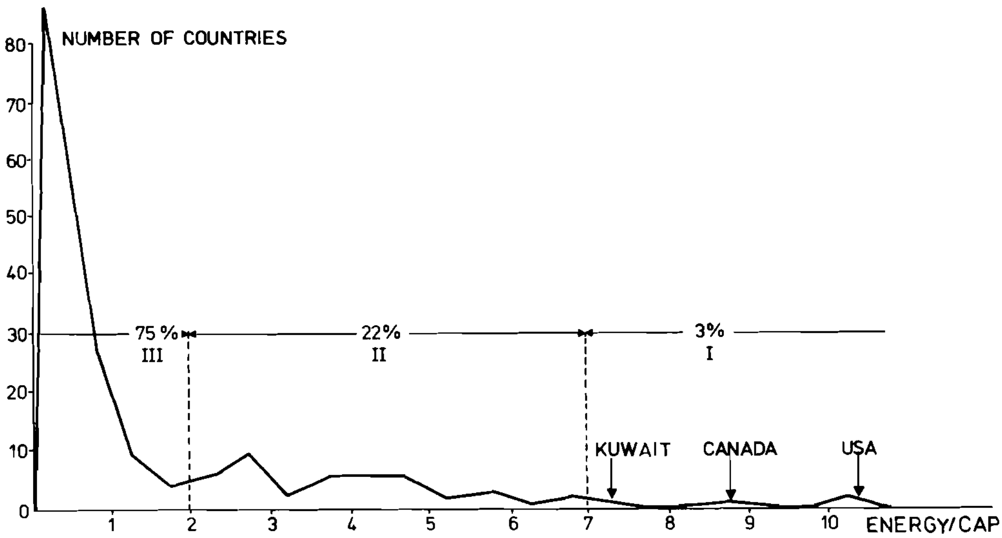

Figure 4. Distribution of world energy consumption, 1971 (178 countries) (After: UN World Energy Supplies 1968–1971).

Before proceeding, we should mention here the survey work on energy models that was done by J.-P. Charpentier. While it relates to energy demand, it can be applied much more widely and thus has attracted considerable interest. This work is a product of IIASA's role as a clearinghouse. Since the first survey on energy models in 1973, it became a more sophisticated and larger venture in 1975. The second review, published recently, treats more countries and models than the first and comes closer to our goal of providing a balanced representation of Eastern and Western countries. The selection of models is based on model criteria such as fuel types and techniques. By computer storage of the models we hope to make our information service more efficient. The survey was done in close cooperation with the Nuclear Reactor Center at Jülich, F.R.G., who were also kind enough to assist with its computerization. We expect to continue this work in collaboration with the IAEA in Vienna.

The Options

Consistently with our approach, one message of the IIASA Energy Project has been that, as far as technology and resources are concerned, there are several options for an unlimited supply of energy. Thus, we are not resource-limited; and in this regard we do not accord with certain branches of the Club of

Rome. There are indications that the more general resource problem can be greatly alleviated if energy is available in virtually unlimited amounts. It is therefore important to identify these options, and in particular their systems implications--that is, the side effects that become predominant if these options are deployed in a truly large-scale fashion.

The case of nuclear energy is really to the point. The handling of the tail end of the fuel cycle and the problem of ultimate waste storage become constraints, while the provision of resources for the fast breeder reactor is of practically negligible concern. Therefore, the nuclear energy option was studied in the early stages of the IIASA Energy Project. A major paper treating the large-scale deployment of the nuclear fuel cycle was written during 1974 and 1975 and published recently. Also, a task force for the comparison of fission and fusion breeders has been established to study systems effects in these two areas.

This might be the moment to say something about task forces. We found it helpful to put together teams that meet at IIASA for about a week, and to organize joint seminars at Moscow and elsewhere. At these sessions, the approach to a given problem is discussed and the groundwork is laid. The team then disassembles and its members pursue the subject of common interest at their home institutions. After a time they meet again, and finally a major report is produced. This format allows outside experts to participate intimately in the work of IIASA without encountering the problems of a more extended stay away from their home institutions.

At present there are two task forces: one deals with the topic, mentioned above, of comparing fusion and fission breeders, and the other is concerned with the coal option. As coal will be or already is a pressing problem for many governments, work on the coal option was started in 1975. It centers around the following question: what are the implications of going back to coal on a truly large scale? Poland, for example, is pursuing a very aggressive forward-looking coal policy. Its participation in IIASA's coal task force is therefore vital to our studies. The U.K. is represented by the National Coal Board and the Federal Republic of Germany by the Gesamtverband des deutschen Steinkohlenbergbaus and by Bergbauforschung, both at Essen. From the Energy Project, M. Grenon and W. Sassin are actively involved. Although results of the coal task force will not be worked out until 1976, two important preliminary results have already been achieved. First, the NBC has set up a similar task force, which illustrates the relevance of our efforts to decision-making bodies; and second, NBC and IIASA members have jointly developed a research model for coal.

During 1975, primarily the solar option was studied, with J. Weingart as leader. The first question was the feasibility of solar power for European latitudes, and in particular for Austria, which is an illustrative example. There was a strong interaction with the Austrian authorities, who provided data on unused land, insolation and other aspects. The unexpected result was that solar power has a finite chance to take over a certain share of primary energy production in Austria. Figure 5 gives some indication of this.

By operating a solar power station of the tower concept, for example, it would be possible to lower the oil consumption in a fossil power plant during sunshine and thus to reduce the oil cost. Let us assume that the solar receiver investments are at $\$30/m^2$ and the insolation is almost 1,200 kWh/m^2 per year, and let us further assume a level of \$10/bbl of the oil costs and, for instance, an interest rate of 12 percent. This then would imply a payback time of 22 years. Without further details it becomes clear that oil prices below \$3/bbl, which prevailed in the sixties, would rule out solar power in Austria at the outset. Such a clear-cut statement cannot be made for costs at \$10/bbl, and further investigations are required. Quite obviously, integrating bits and pieces of electrical power into an existing grid is the significant question. This immediately points to the problem of energy storage. Austria is in a special position with its many water dams. In 1976, the integration of solar power into an existing grid, its relation to energy storage and other technical and non-technical parameters will be studied in greater detail. Along with this goes a study of local space heating by solar power, and related systems implications such as market penetration periods. We also expect a contract from the German Ministry for Scientific Research and Technology for a study of these questions as they apply to the F.R.G.

The policy of the Project is to investigate the nuclear, the coal and the solar options in greater depth, and the geothermal option to some extent. A beginning was made in 1975 in cooperating with the French Institut Economique et Juridique de l'Energie, Grenoble, and the Bureau de Recherches Géologiques et Minières, Orléans.

Constraints

Besides identifying objectives for a strategy, it is important--perhaps even more important--to understand what its constraints are. Since we began our energy studies, we have continually stressed the problem of large amounts of waste heat and their possible impacts on the climate. Starting with the early numerical experiments of W. Washington at NCAR, we considered the hypothetical case where $1.5 \cdot 10^{14}$ W would be released into the atmosphere at two places on the globe. In the numerical experiment IIASA-1, these places were west of England and east of Japan. In IIASA-2, the place west of England was lowered to equatorial regions west of Africa (see Figures 6 and 7). The BMO was kind enough to make their global

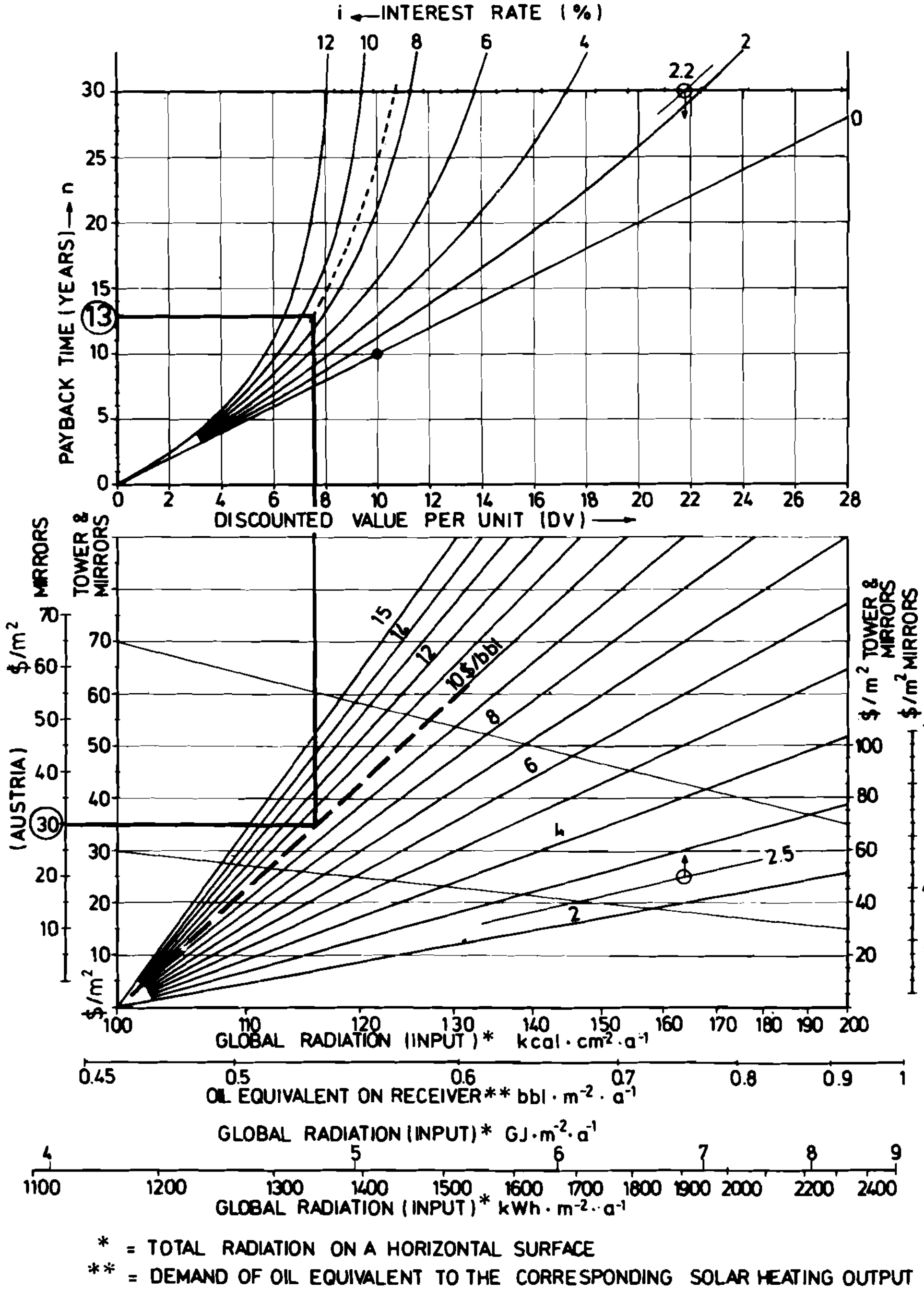

Figure 5. A view into Austria's future. Top: a 13–year payback time at the usual loan interest of 8.5% means 17 years without fuel costs in the average lifetime of a solar power plant. Bottom: Economic mirrors at $\$30/m^2$ after learning effect.

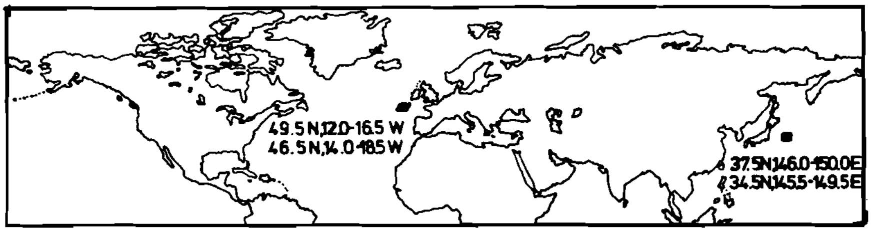

Figure 6. Locations of nuclear parks in Experiment IIASA–1.

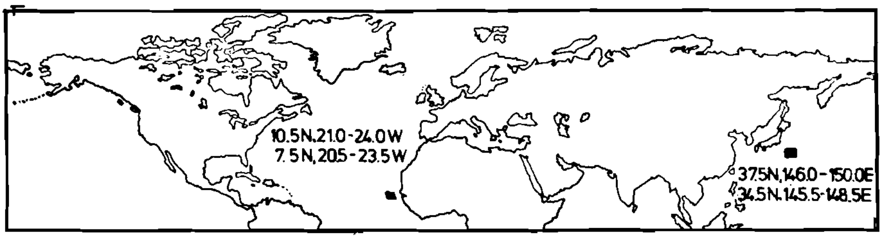

Figure 7. Locations of nuclear parks in Experiment IIASA–2.

circulation model (GCM) available to IIASA, and the Nuclear Research Center at Karlsruhe made it possible to run these very large computer programs at its computer center. It is hard to overestimate the amount of data that must be handled; one numerical experiment has an output of four million numbers. In a workshop at the end of April 1975, a small group of experts discussed the results obtained so far. (The proceedings are in preparation.) Only after the workshop was it possible to establish a σ^2 value that was sufficiently significant (and small) to allow a meaningful interpretation of the experiments IIASA-1 and IIASA-2. The results are due to A.H. Murphy, who conducted these studies at IIASA, and A. Gilchrist of the BMO. For the experiment IIASA-1, the changes in the rates and patterns of precipitation and surface pressure respectively are given in Figures 8 and 9. Within the limits of the GCM there is an

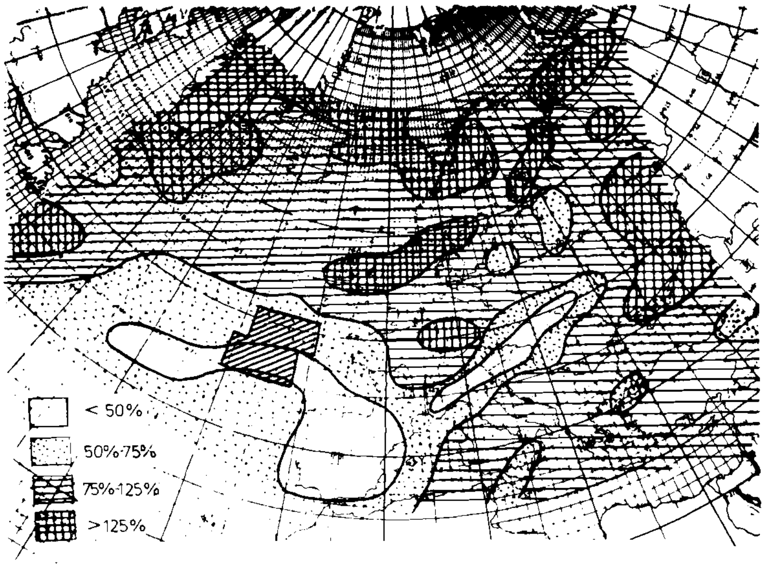

Figure 8. Ratio of rainfall with Atlantic Park (IIASA–1) and mean rainfall for three control integrations (day 41–80).

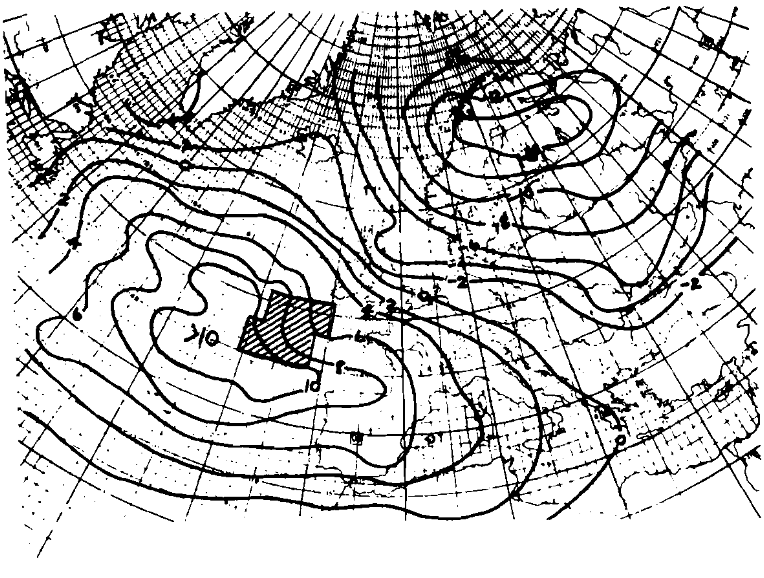

Figure 9. Surface pressure difference (mb) (Atlantic Park Experiment IIASA–1) with respect to average of controls (72,90,96).

obvious impact of waste heat of weather patterns. The IIASA Energy Project has received a contract from UNEP allowing us to continue and extend these investigations.

A consideration that becomes increasingly important is the large release of CO_2 into the atmosphere. This concern is related only to fossil power, but it is also in line with the climate considerations mentioned above. Recently, W. Häfele and W. Sassin considered a scenario of world population growth that is based on data from the UN Conference at Bucharest in 1974. It assumes a population growth from today's four billion to twelve billion. It is further assumed that provision must be made for an average energy consumption of 5 kW per capita. If only oil and gas were consumed at first and coal thereafter, the releases of CO_2 would significantly increase the CO_2 level in the atmosphere. In a scenario where 200 percent additional CO_2 (above normal) is considered a limit, on account of the greenhouse effect and the related temperature increases, the use of coal is curtailed to 20 percent of the world coal resources assumed at present. This is outlined in Figure 10. A remarkable feature of this scenario is that hitting such a ceiling is highly insensitive to various technological and economic assumptions. These investigations also provide a background for climatological studies and obviously extend beyond the 15-to-50-year period; they provide the appropriate bracket within which the studies must be made.

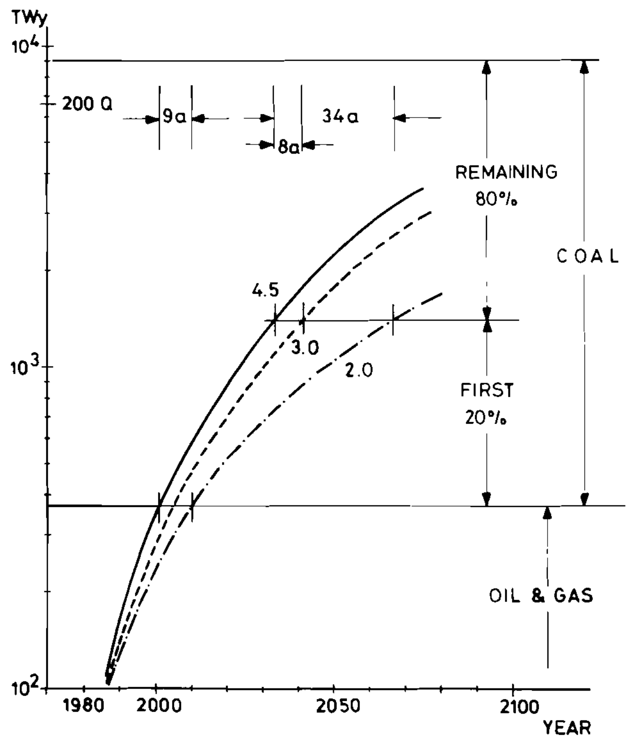

Figure 10. Fossil energy reserves and cumulated energy consumption.

In a manner similar to that employed in the climate case, the problem of market penetration was also intensively studied in the Energy Project. According to C. Marchetti, market penetration is largely governed by the logistic curve that represents the (exponential) growth in a limited environment. These studies have been pursued further, as illustrated in Figure 11. Energy market penetrations for the whole world seem to follow the Fisher/Pry model[1] as extended by C. Marchetti, and seem not to exceed a certain rate of introduction. If confirmed, this would indeed constitute a major constraint. The Energy Project is expecting a grant from the German Volkswagenwerk Foundation for further investigation of these relations.

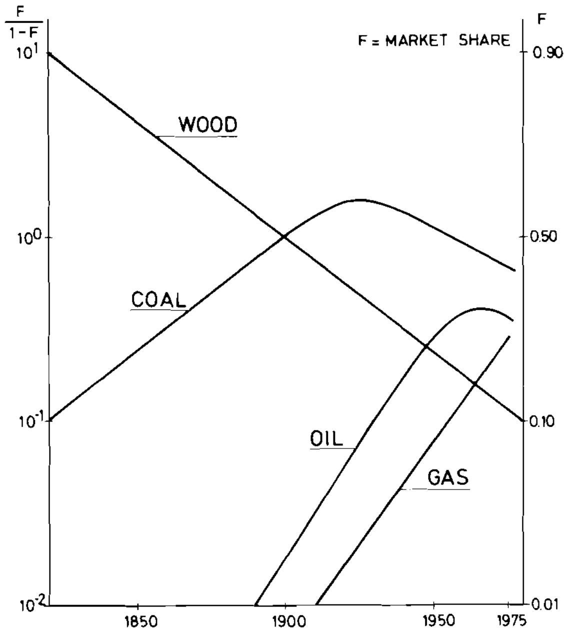

Figure 11. Energy market penetrations: world.

[1]J.C. Fisher and R.H. Pry, "A Simple Substitution Model of Technological Change," Report 70-C-215, Technical Information Series, General Electric Research and Development Center, Schenectady, N.Y., 1970.

Other constraints seem to come from society's perception of certain risks. Safety problems and, in particular, nuclear safety problems are heavily debated today. Since 1974, we have had a joint IIASA/IAEA subgroup on risk assessment, which does research into problems of public acceptance and the establishment of standards. Figure 12 is helpful in explaining these relations. The traditional approach in dealing with the unknown is to anticipate certain events and to make provisions against them by engineering measures. As all engineering measures are finite in nature, the anticipated events against which one wishes to design must be finite in scope; in other words, the anticipation is within limits. Today, society wants to anticipate events without limits. This may have been induced partly by the fact that modern technologies, deployed on a truly large scale, may have global consequences. The CO_2 releases and their conceivable impacts on the climate have served as an example. Anticipated events without limits therefore necessarily lead to the consideration of residual risks. These residual risks can be made smaller than any conceived limit, but not zero. The next logical step is to embed residual risks in a spectrum of natural risks such as earthquakes, lightning, and the like. This is done in terms of objective risk evaluations. But the perception of objective risks is quite a different matter which has yet to be fully understood. This then leads to decision-making under uncertainty if standards or regulatory steps for the acceptance of residual risks are at stake; and still more so in the domain of hypothetical considerations, that is, in the absence of the traditional trial and error approach. For example, one cannot apply the trial and error approach to the climate or similar global effects. If the question: "How safe is safe enough?" is answered, the next step is reliability control: to assure that the envisaged engineering measures are adequate. The recent Rasmussen report[2] on the safety of light-water reactors is very much a case in point. It brings us back to engineering measures against the unknown, although the procedures proposed are quite different from the traditional ones.

Strategies

We now have the elements we need to design and understand strategies. A first step was the work of A.S. Manne and W. Häfele elaborating a linear programming (LP) model for the transition from fossil to nuclear fuels. This model has been generalized in the past year, mainly by A. Suzuki and L. Schrattenholzer. It is assumed that a model society with enough oil and gas for only 60 years wants to overcome this fuel situation. Substitutions can be made by engaging solar power, nuclear energy or coal.

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[2] "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," Wash-1400, U.S. National Research Council, Washington, D.C., 1975.

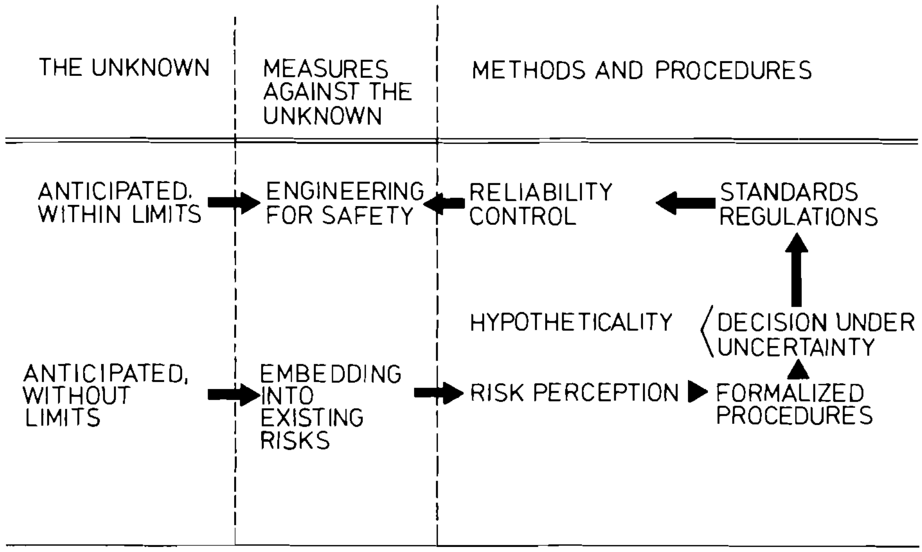

Figure 12. How to deal with the unknown.

Figures 13 and 14 illustrate transitions which were quantified with the help of the LP model. Note the share of solar electric hydrogen (SHYD) in Figure 13. Figure 14 presents results in relation to coal contributions. In the case of a society with oil and gas for only 40 more years and at a coal price of $20/kW(th) per year, 50 percent of the electricity would be provided by coal; for societies with 60 or more years of oil and gas, the contribution of coal would be drastically lower, that is, between 15 and 20 percent.

Such programs do two things. They observe constraints and they optimize within them. In the LP model mentioned, the discounted costs were optimized. For some time we have been trying to generalize these programs. An important step is the inclusion of abatement measures in regard to environmental control; during the past year, the most important input data were gathered and the program was adapted. In the coming year, the generalized version of our LP-strategy program will help us to establish shadow prices for abatement measures. A related aspect is that of establishing standards; the standards to be considered in this context are those for emission and ambient dose rate.

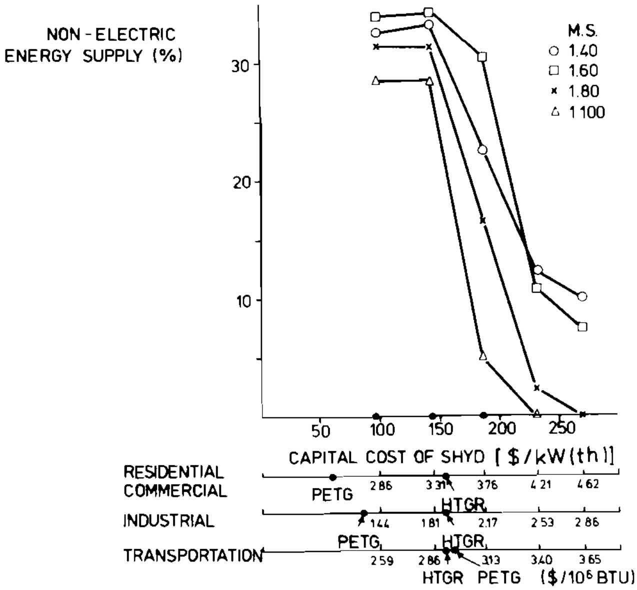

Figure 13. Contribution of solar hydrogen for non–electric energy supply (%) as a function of assumed capital costs for solar hydrogen.

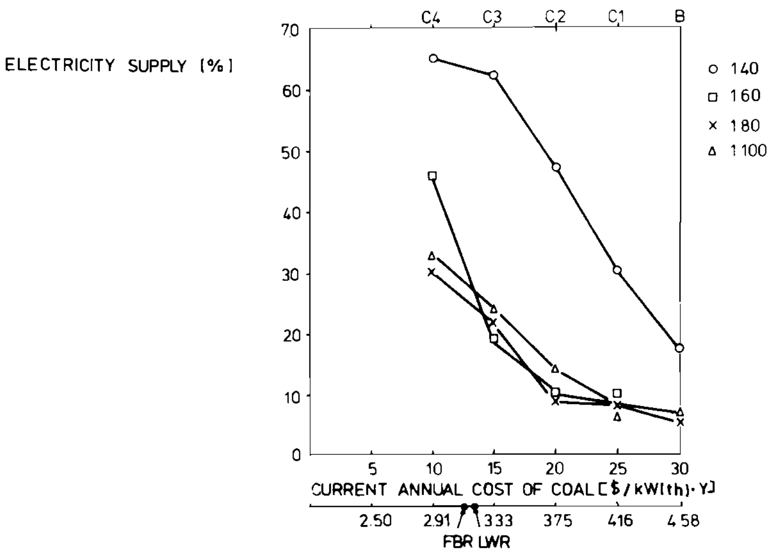

Figure 14. Contribution of coal for electricity supply (%) as a function of current annual cost of coal.

A more complex generalization is the striving for resilience. As mentioned earlier, we are primarily interested in the time period between 15 and 50 years from now. Conceivably, one might be looking for the resilience of a civilization more than for the last percent of a cost optimum. This work has been greatly influenced by the work of C.S. Holling and his colleagues of the Ecology Group at IIASA. This, of course, requires putting resilience into mathematical form; the approach involves the study of the dynamical behavior of a few fundamental (nonlinear) equations in their respective phase space. There it is mainly the phenomenon of separating manifolds that subdivide the phase space under consideration into various distinct basins. Crossing a basin boundary by accident will not immediately be noticeable from local considerations, but it drastically changes the long-range evolution of the system. Work along these lines has to be basic, as there are no established techniques. The Methodology Project, in conjunction with the Ecology and Energy Projects, held a workshop on such basic research in July of 1975. This workshop was chaired by T.C. Koopmans and had strong assistance from H.R. Grümm. Economists, ecologists and climatologists participated in the workshop; they considered differential topology as a common basis for understanding global phenomena in these and other areas.

We now see that this approach not only would allow for an additional objective function to play with, but also may be helpful in judging strategies as a whole. We will try to represent a given strategy (or more generally, development) as a trajectory in a phase space and to consider its relations to the structure of the phase space in terms of separatrices, attractors, basins, etc. It is hoped that Thom's catastrophe theory can be applied to certain aspects of this work.

The approach discussed is meant to provide one set of procedures for making judgments on strategies. This is very interesting, but there must be more than that. One must realize, for instance, that an energy strategy competes with a variety of investments such as those for biomedical systems, urban systems, and so forth. It is necessary, therefore, to consider the problem in a broader perspective that includes global aspects. Thus we intend to complement that approach with a second endeavor: a model for the relations between some five regions in the world in terms of their trade in primary and secondary energy. Other fields, such as food, might be included in addition to energy. The model must take global constraints and conflicts into account. The aim is to consider the consistency or inconsistency of regional energy policies. During 1975, W.D. Nordhaus completed and employed his world energy allocation model, which we consider to be a first step in this direction. Another line of econometric analysis of relevance here deals with econometric demand models in overall energy models. It is oriented towards the description of world and regional energy mechanisms and strategies. This work has already been started and will be developed in the coming years.

Let us return to Figure 1. It is now clearer what the various parts of the figure mean. Resources and demand refer mostly to a situation that would prevail if no large and possibly world-wide strategies were pursued. The options correspond to a set of feasible goal or objectives. The constraints reflect the realities of a limited world. Strategies then stand for a conscious transition into a meaningful future. This observation implies that the perspective of the transition must be the main characteristic of the near-term and medium-term future. It is transition and not equilibrium, also not the equilibrium of markets.

And After the 15-to-50-Year Period?

To imagine future life conditions requires fresh thinking and the breaking of mental blocks. We feel that by going through the process conceived above we will learn much about energy systems. It is then natural to ask for examples of synthesis. One important point is that, as far as technology is concerned, it is possible to provide for the production and handling of an amount of energy that is enough even for 12 billion people. One scheme of related engineering is that of energy islands as proposed and pursued by C. Marchetti at IIASA. The starting point is his observation that the embedding of the production of large amounts of energy into the sociosphere is particularly difficult; the embedding into the hydrosphere, atmosphere and ecosphere is difficult enough. Most of the constraints as envisaged in Figure 1 result from the problem of embedding. Marchetti proposes a radical decoupling of the large-scale production of energy, and doing the embedding in less restrictive areas of the globe, such as Canton Island. This is one of a group of Pacific islands at 171^{0} western longitude slightly south of the Equator that are passed by the ocean current going from South America to Indonesia. The idea is to install large-scale nuclear power there on the basis of the breeder principle. This would allow for the meaningful harvesting of uranium from the sea waters of the passing ocean current. The product would be hydrogen or ammonia, that is a type of synthetic secondary energy that can be stored and transported by tankers, much like oil. The huge waste heat losses would be given to the passing ocean current by sucking cold water from greater depths and delivering it at sea surface temperature. The geography of such islands allows for the mounting of the power production facilities on large barges and thereby for doing much of the construction work in home ports. (See Figure 15.) In view of laws of scale, a size of several hundreds Gigawatts is considered. In such a scheme Canton Island would become an artificial oil field. There are other schemes like this; for instance, that of rigorously following the observation that civilization needs negentropy rather than energy; or that of providing for deep sea CO_2 waste disposal without passing through the atmosphere.

We want to pursue this line of investigation in the future.

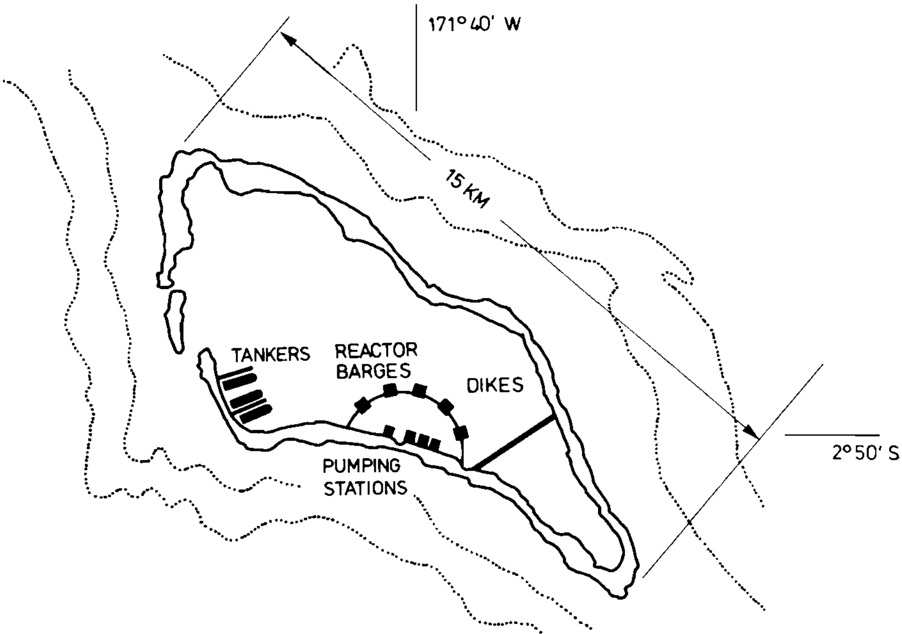

Figure 15. Canton "Energy Island."

Part 2: ENERGY RESOURCES

2.1 Coal: Resources and Constraints

Michel Grenon

2.2 A Bayesian Approach to Discrimination Among Models for Exploring Geological Bodies

Jacques G. Gros

PART 2. ENERGY RESOURCES

2.1 Coal: Resources and Constraints

Michel Grenon

INTRODUCTION

One of the major tasks of the Energy Project is to assess and compare long-term energy options--nuclear fission, nuclear fusion, geothermal and solar--and to study the related transition from the present fossil fuel economy to a future non-fossil fuel economy. Two questions, among others, can be raised:

1) What must or can be the speed of transition? That is to say, what is the exact value of the fossil fuel resources on which to base such a strategy, taking due account of the environmental and even social problems associated with fossil fuel utilization (for example, the long term CO_2 problem, or social aspects of manpower requirements for coal mining)?

2) During this transition--which can take from some decades to possibly a few centuries--what can be the role of coal, the resources of which are considered very large and equivalent to a few thousand years of today's consumption? Will coal continue its progressive relative decline, or will it be "revived" and reach an absolute (and relative) maximum?

It is to explore the latter possibility that we have recently started a Coal Task Force at IIASA, closely associating the staff of the Energy Project and representatives of various national coal organizations, such as the British National Coal Board, the West German Gesamtverband des Deutschen Steinkohlenbergbaus, the Polish Chief Mining Study and Design Office, Czechoslovakian coal representatives, etc.

The purpose of this presentation is to outline where we are in the Energy Project at the point of starting this Coal Task Force.

WORLD COAL RESOURCES

Many classifications have been proposed for mineral and/or fuel resources; in general, the more classifications, the longer has the resource been used. This is especially true in the case of coal compared to oil (which quickly became an international commodity), or to uranium, which appeared only recently on the energy scene. One of the most recent--and most interesting--is the so-called Canadian classification [1], which distinguishes among three resource categories (Figure 1):

- The reserves (economic now; discovered and delineated);
- The resources (of economic interest within the next 25-year period; discovered and undiscovered);
- The resource base (economic aspects irrelevant; discovered and undiscovered).

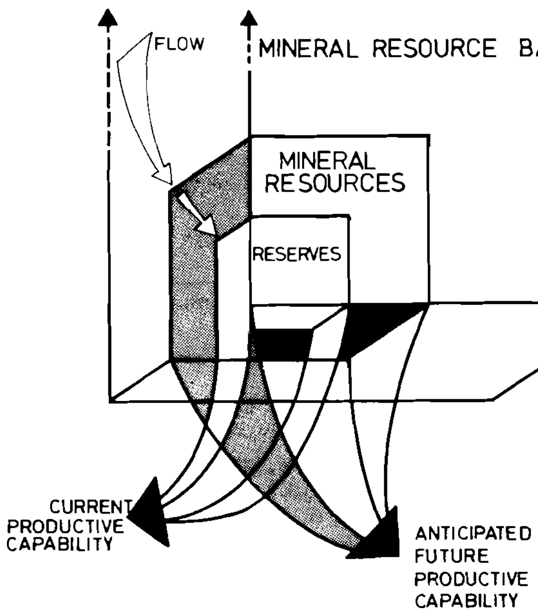

Figure 1. Mineral resources (Source: Ref. [1]).

However, this classification is mainly of interest for resources that are in short or relatively short supply, or for which technological developments in the next 50 years (or, at any rate, for a period longer than 25 years) can be reasonably predicted. We consider that this is at present not the case for coal. We generally prefer to use the "McKelvey diagram" (Figure 2) recently agreed upon by the U.S. Geological Survey (USGS) and the U.S.

Bureau of Mines,[1] although, as a rule, we do not use the division between paramarginal (1 to 1.5 times the maximum economic cost) and submarginal (more than 1.5 times the economic cost).

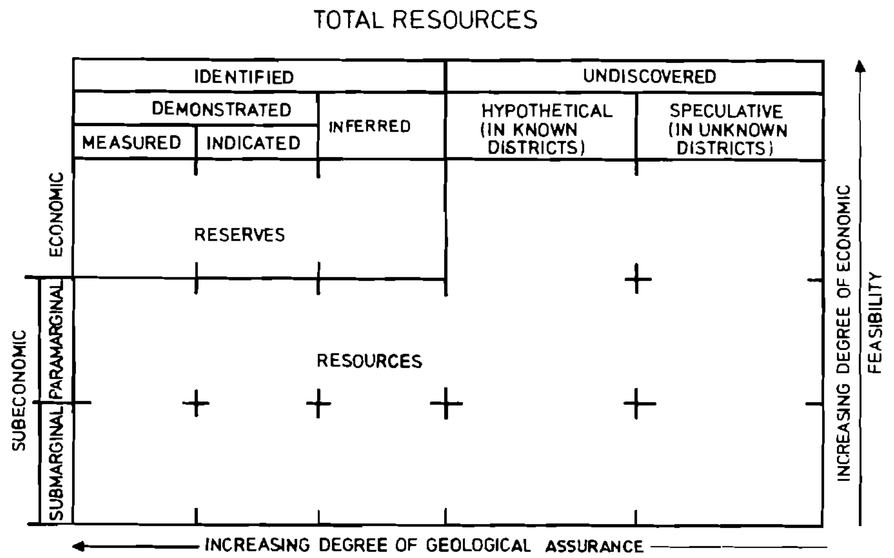

Figure 2. USGS–USBM reserves/resources classification, 1974.

In Figure 3, the categories are specified by geological evidence. These definitions are not universally used, which raises many problems when comparing world coal resources; but they give a fairly good indication for the various resource categories. One of the main problems is, of course, to enter figures in the various blocks of the McKelvey diagram--remembering the comment of King Hubbert [3] that the farther removed we are from the upper lefthand corner, the more uncertain are the available data: so much so that the uncertainty in the lower righthand corner can easily be one order of magnitude greater than the figure in the upper lefthand corner!

As an example, Figure 4 shows the coal resources of the U.S.A. as of January 1, 1974 [4]. (Note that Englund, of the USGS, has also used the single division of subeconomic resources, and not the subdivisions of paramarginal and submarginal mentioned earlier.) Of a total resource of almost 3,000 billion metric tons, only 50

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[1] For a very detailed analysis of this classification, see e.g. [2].

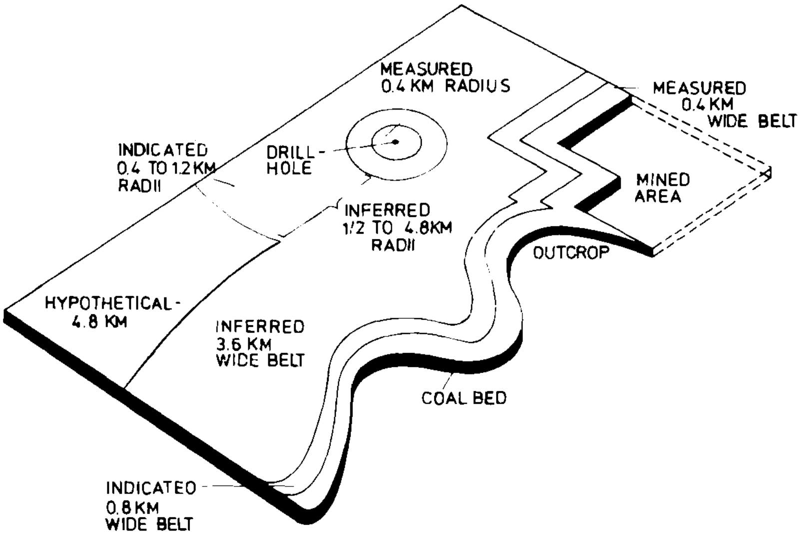

Figure 3. Coal resource categories based on density and proximity of data (Source: Ref. [4]).

	IDENTIFIED			UNDISCOVERED	
	DEMONSTRATED		INFERRED	HYPOTHETICAL (IN KNOWN DISTRICTS)	SPECULATIVE (IN UNDISCOVERED DISTRICTS)
	MEASURED	INDICATED			
ECONOMIC	50	147	NONE	1.482	NONE
SUBECONOMIC	63	238	935		

← INCREASING DEGREE OF GEOLOGICAL ASSURANCE

INCREASING DEGREE OF ECONOMIC RECOVERY ↑

Figure 4. Total coal resources of the United States as of January 1, 1974 (x 10^{12} metric tons) (Source: Ref. [4]).

billion (1.7 percent) have really been measured, and 197 billion only (6.5 percent) are considered as economical reserves. In fact, we can presume that a good part of the subeconomic identified resources are economical to mine today because of the boost in oil (and nuclear and coal) prices, although such reassessments are always difficult to achieve.[2] It is also interesting to comment that there are no resources in the speculative (undiscovered districts) category, due to the intensiveness of mineral exploration throughout the U.S. territory. The reverse is probably true for many regions in the world, as we will see later.

Whilst bearing King Hubbert's comment in mind, at IIASA we are interested essentially in the totality of such a diagram, that is, in knowing the overall total of world coal resources possibly available. Independently of this desire, the diagram also shows the direction of efforts to shift coal resources from one category to another: from badly known or non-economic resources to economically recoverable reserves, through better geologic knowledge (a world exploration program is badly needed in this sector) and/or through improved extraction and recovery technologies.

With a coal decline in the last two decades, much attention has been paid to the more economically recoverable reserves, and very little to the resources, which is understandable from an industrial point of view. That is, most of the statistics on world coal resources date back to a few decades ago--sometimes to the beginning of the century--and in most countries have not been seriously revised or up-dated.

Regarding world coal resources, we can say that they are very badly known at best. First, classification is not standardized. The last World Energy Conference Survey of Energy Resources in 1974 could divide world coal resources into two categories only: proven recoverable reserves, and all additional resources. Second, many data are poor because of insufficient exploration. It is clear that, compared to oil, there has been very little effort on a world-wide basis to search for coal. The majority of known coal fields were found due to their outcrops, and/or as extensions of fields already discovered.

According to the 1974 World Energy Conference Survey, world coal resources in the ground amount to 10,754 billion metric tons (all kinds of coal mixed together, from anthracite of 8,000 kcal/kg to lignite or brown coal of 3,500 kcal/kg or less; peat excluded in principle), or roughly 8,400 billion metric tons of coal equivalent to 7,000 kcal/kg.

This is an impressive figure, but we do not wholly trust it

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[2]The same is true for U.S. and/or world oil reserves, which have not yet really "reacted" to the quadrupling of oil prices.

at IIASA; we have decided to try to reassess this figure and the related national figures, and to obtain a better understanding of them.[3] This task, begun a few months ago, fits in very well with the goals and general program of our Coal Task Force. The following preliminary comments can be made at this stage.

1) If we look at the geographical distribution of total world coal resources (Table 1), we observe that there are still fewer "giants" than for oil, a fact apparently not favorable to a "global coal option." Three countries--the U.S.S.R., the U.S.A. and China[4]--own almost 90 percent of world coal resources, each having more than 1,000 billion metric tons. Four other countries--the F.R.G., Australia, the U.K. and Canada--each have between 100 and 1,000 billion metric tons, although most of those in the F.R.G. are deeper than 1,200 m; this depth, while raising many problems, is already being mined (in Lorraine for instance). Eight countries--India, Poland, South Africa, Finland (mostly peat), the G.D.R. (mostly brown coal), Yugoslavia (mostly lignite), Czechoslovakia and Mexico--each own between 10 and 100 billion metric tons of coal,[5] equivalent in most cases to oil reserves of the largest oil producers of the Middle East. And finally, 21 countries each own more than 1 billion metric tons of coal, with muted enthusiasm about the fact. It is clear that the geographical distribution of coal resources is more highly correlated to white settlement and/or colonization than to geology.

2) It is the opinion of the resource group of the IIASA Energy Project that more coal resources may exist than are reported, and especially so in vast little-explored areas such as South America, Africa, and part of Asia. This can be inferred from the U.S.S.R., where resources are assumed to be still higher than reported. As mentioned above, no systematic search for coal has really been made, not even in some industrialized countries.

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[3]For instance, we are exploring the possibilities of using for resource assessment some of the methods developed for oil, which were discussed extensively at the IIASA Energy Resources Conference at Laxenburg in 1975 (to be published).

[4]For China, the figures are highly unreliable, having for many years--or even decades--been around 1,000 billion tons.

[5]These figures, like many others of the WEC Survey, must, in any case, be treated with care, since they generally refer to tonnages, and not to heat content or coal equivalent. We have prepared a revised table based on heat content for our own use.

This opinion does not contradict others claiming that coal resources are "not so abundant"...[5].

Table 1. Distribution of total world coal resources.

Number of Countries	Class of Resources (10^9 t)	Amount	Percent of World Total
3	>1,000	9,638	89.0
4	100-1,000	757	7.0
8	10-100	305	2.8
21	1-10	88	0.8

3) This raises the question of economic recovery. It is clear that present trends are opposed to resource conservation; during the past few decades the U.K.--and others--have converted reserves into resources in order to be able to compete with the low prices of hydrocarbons. If we are to speak of a "coal option," this trend must be reversed.

An additional comment is aimed at comparing coal with nuclear energy. Although the light water reactor is now commercially operational, and some geologists (e.g., Brinck [6]) are relatively optimistic about world uranium resources at low prices, tens and possibly hundreds of billions of dollars are being spent on developing the breeder. The only justification for this, as far as we know, is that it will lead to a better utilization of world uranium resources. By comparison, very little money is spent on improving coal extraction technology.

4) If we are right about the occurrence of coal resources and reserves in little-explored areas (in most cases corresponding to developing countries), there is an interesting line to explore in connection with possible "decision trees" for regional and/or global coal options [7]. Many developed countries such as Japan, France and Belgium, which are now high-energy importers and also had a considerable and technologically advanced coal industry, may have the choice of reviving their own resource potential (sometimes at the social cost of importing guest workers) and/or starting exploration and further production in host countries (by exporting

technology and coal specialists, analogously to production-sharing agreements for oil).

SYSTEMS ASPECTS OF LARGE-SCALE PRIMARY ENERGY PRODUCTION

Resources in the ground are one thing. Extracting them--quite apart from their use, which is analyzed elsewhere in this Status Report--is quite another. For our purpose, it is interesting to compare the problems of coal production--especially production on a very large scale, possibly 10 or more times the present annual world production of about 3 billion metric tons--to the production of other energy resources.

In this report, we will concentrate mainly on primary energy production problems, which will lead us to consideration of the more general problem of world mining of mineral resources (global mining). We have developed a systems analysis tool referred to as WELMM:[6]

Water

Energy

Land

Materials

Manpower.

Here, we will focus on energy, land and materials problems and requirements for coal as compared with other long-term energy options (nuclear and solar, and to a lesser extent oil shales).

Energy Analysis

Let us first consider the scale of the gross energy content of various primary energy resources (Figure 5), i.e., the amount of raw material containing the same amount of energy (heat content) as one metric ton of coal equivalent.[7] This scale immediately gives a rough idea of the magnitude of the mining problem for the various energy commodities; it extends over 10 orders of magnitude, from uranium in sea water for non-breeder reactors (LWR type) to pure uranium used in breeder reactors (the "mine," in this case, is the stock-pile of depleted

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[6]Although it was developed quite independently, the WELMM approach is somewhat similar to the MERES (Matrix of Environmental Residuals for Energy Systems) developed for the U.S. Council on Environmental Quality [8].

[7]Comparison of the energy content of fossil and fissile fuels is a difficult problem. We have used here the conversion factors of the 1974 World Energy Conference Survey, in which 1 kg U nat, used in non-breeder reactors, equals 29.35 t.c.e.

uranium). Of primary interest for the time being are the four or five decades around coal, fossil fuels being on the left of the scale and fissile on the right.

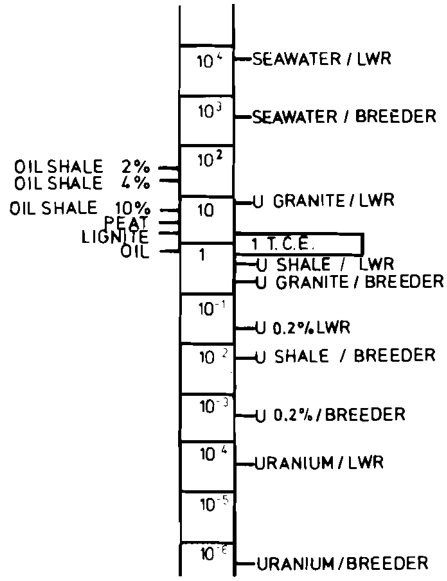

Figure 5. Gross energy content and mining scale.

Of the fossil fuels, only oil has a higher heat content per ton than coal when it can be obtained as free oil. Lignite and peat contain between 3 and 5 times less energy per ton than coal, and so the amount of raw material which must be handled for the same gross heat content is 3 to 5 times greater. One ton of oil shale at 10 percent oil content by weight (Colorado shale contains up to 13-14 percent, French oil shale around 4 percent) contains about 7 times less energy than one ton of coal, and oil shale at 4 percent about 17 times less. Roughly, the problem of handling fuel material is multiplied by a factor of between 5 and 20 when considering oil shale as an energy resource.

The situation is completely different for fissile fuels. One ton of uranium ore at 0.2 percent uranium content contains about as much energy as 60 tons of coal if used in a non-breeder reactor of LWR type, and about 3,600 as much with the breeder, apparently decreasing the mining problem by the same ratio. But the picture changes progressively as we proceed to lower and lower ore contents. Uranium shale (at 60 ppm) is still 100 times better than coal with the breeder, but is similar to oil--or only 1.5 times better than coal--when used with the LWR. This shows that "burning the rocks," as suggested by Alvin Weinberg, will not necessarily eliminate the mining problem. "Burning the sea" may be simpler, however great the tonnages of water to handle may be.

But of course the mining problem is not restricted to raw materials; other materials (overburden, refuse, etc.) are mined at the same time, as will be discussed. This could constitute another advantage of mining the sea.

So far, we have spoken of gross energy content. In fact, we must consider the "net" energy content. Moreover, for our purpose in the Energy Project, such an analysis must be made for the whole length of the energy chain, from resources in the ground to final consumer use, as explored by Charpentier for nuclear energy and the LWR fuel cycle [9].

We will consider here only the beginning of such energy chains, restricting ourselves to the mining and milling steps. One of the difficulties of such an energy analysis is to define the system considered and its frontiers (Figure 6), depending on whether we deal only with direct energy expenditures (for which the data are more easily obtained) or include indirect or even "investment" energy. Of the two methods used, Input/Output and Direct Accounting, we have chosen the second, and we are now collecting data at IIASA in cooperation with other organizations.[8]

For mining and milling, it is generally considered that energy expenditures can be separated into two parts, one independent of tonnage or grade (relative to one ton of product, for instance) and one a function of tonnage, say inversely proportional to grade (Figure 7). Such curves have been established for various minerals, such as titanium, iron, aluminum, copper. (The last of these is interesting for a comparison with uranium because of its low grade, as suggested by Mabile [10] some 10 years ago.)

If this analysis is applied to the various fuels in Figure 5, their positions relative to coal can be changed. It is well known that little energy is spent for the production of coal itself: generally less than 1 percent of its gross energy content (for ancillary--direct--energy, 0.4 to 0.6 percent for underground mining, about 0.5 percent for area mining and possibly 1.4 percent for contour mining in the U.S. [7]). For uranium, our preliminary results are that energy expenditures are only a small fraction of 1 percent of the energy content, with uranium ores at 0.2 percent. Let us recall that this applies only to mining and milling, and not to the other steps of the fuel cycle, some of them, like enrichment, being very energy-intensive); for

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[8] Such as the French Bureau de Recherches Géologiques et Minières and the French Commissariat à l'Energie Atomique.

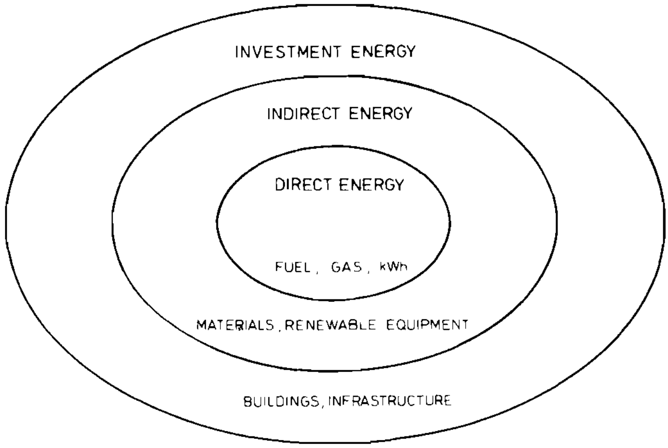

Figure 6. Energy analysis. Two main applications: conservation of energy and comparison of options.

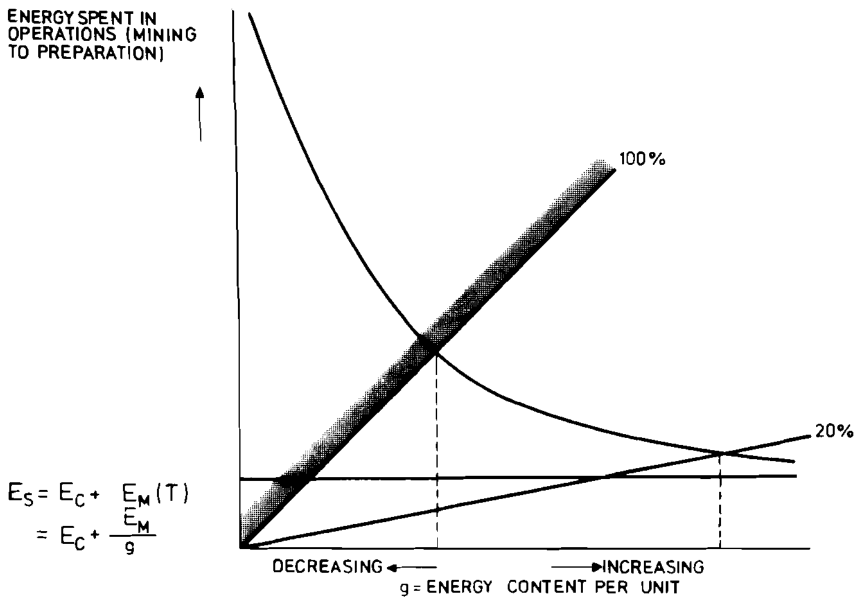

Figure 7. Theoretical energy expenses in mining.

uranium shale, it would approach 1 percent [11] and become significant only for lower contents, and for uranium granite (used with the LWR) it would exceed 10 percent.

The situation is quite different for oil shale, because of its lower energy content. Moreover, the retorting process, with temperatures between 400 and 500°/C, is also energy-intensive. This is illustrated by a recent study [12] (see Figures 8, 9 and 10). The situation will be still worse with oil shale of lower content. Another study [13], carried out in France, generally considers that only 50 percent of initial energy can finally be recovered from about 4 percent shale; compared to coal, this means that about 35 tons of raw material must be mined to obtain the same net energy content as from one ton of coal (based only on direct energy costs).

E_o: Total Energy Out (as Oil, Coke, Other Fuel)

E_1: External Energy In

E_2: Fuel-Energy Derived from Shale Oil Used in Processing

E_3: Internal Energy Not Recovered by the Primary Recovery Process

$$R_1 = \frac{E_o}{E_1} \qquad R_2 = \frac{E_o}{E_1 + E_2} \qquad R_3 = \frac{E_o}{E_1 + E_2 + E_3}$$

Figure 8. Net energy ratios for oil shale.

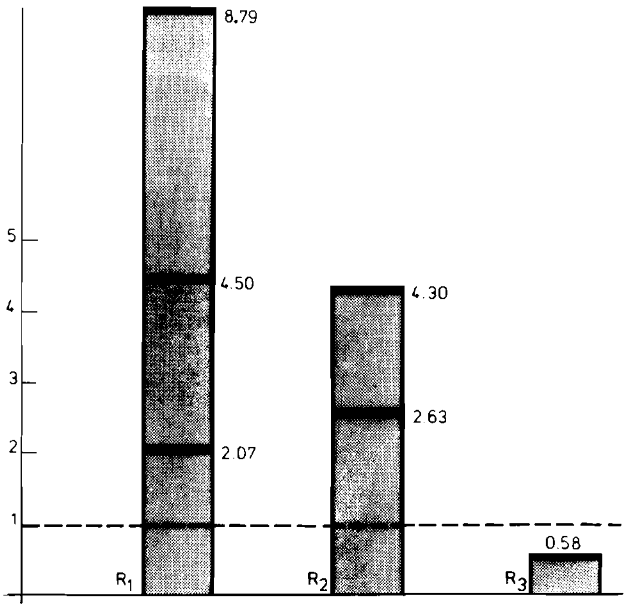

Figure 9. Net energy ratios for oil shale (shale–oil recovery, processing plant of 5 million tons per year).

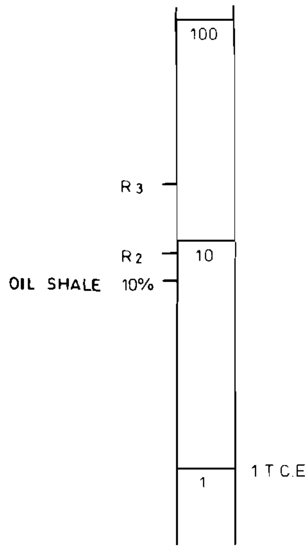

Figure 10. Net energy content and mining scale (oil shale at 10%).

Mining Trends and Prospects

We consider that land and material handling problems associated with mining are closely related. A major development of the last decades was the progressive increase of surface mining. For U.S. coal, surface mining constituted less than 10 percent at the end of the Second World War. Now, 30 years later, it reached more than 50 percent (Figure 11). This ratio, however, does not correspond to the distribution of the resources as shown in Figure 12, where 68 percent of the reserves are underground and only 32 percent near the surface.

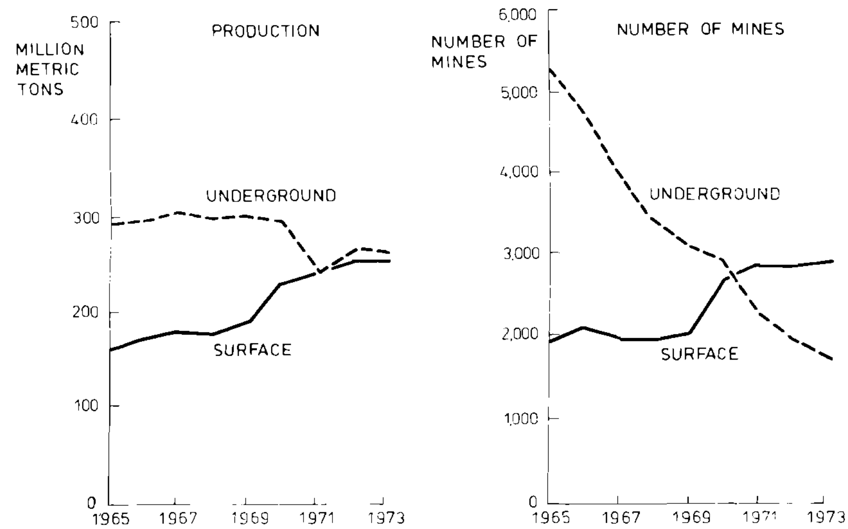

Figure 11. U.S. coal trends, 1965–73 (bituminous coal and lignite).

The same comment applies to uranium. In the U.S. in 1973, of 175 uranium sources 70 percent were underground mines and 19 percent open pit. But the surface mines accounted for 62 percent of production, and deep mines for only 36 percent. The percentage was still higher for copper, where surface mines accounted for 83 percent of production.

This is a general trend which merits a few supplementary comments. The main reason for the development of surface mining is the progress made in mechanical handling equipment; for instance, bucket-wheel excavator capacities of 100,000 m^3/day a few years ago have now increased to 260,000 m^3/day, and the same applies to the associated transportation equipment. This has led to impressive parallel increases in yields: 40 to 50 tons per man-shift for U.S. Western coal, and 60 tons of raw lignite per man-shift (equivalent to 15.5 tons of hard coal) in the Rhine area--roughly 5 to 8 times the average output of the European hard coal underground mining industry.

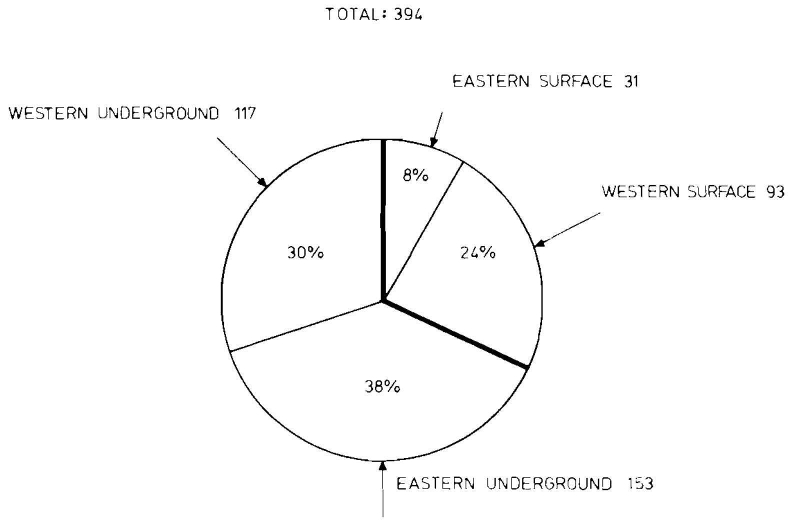

Figure 12. U.S. demonstrated coal reserve base, January 1974 (billions of metric tons).

Surface mining changes the manpower problem appreciably. If we consider the need to mine minerals--not only mineral fuels, but also metals and so on--in the next 25 years or so, and the manpower trends in the mining industries, this is clearly a very big problem which can lead to a serious bottleneck. Even in fully mechanized mines, people are increasingly reluctant to work underground; working time is becoming shorter and shorter, and efficiency is low.

Surface mining, when feasible, is one of the most obvious and fastest solutions to the large increases in mineral production in coming decades. U.S. and U.S.S.R. coal developments rely heavily on it, and we think that it will become a major technique. But one day it will reach its own limit of practical depth and/or land availability. Where natural conditions do not favor it for shallow deposits, surface mining must therefore be considered as a transition; one day we must again, and perhaps almost exclusively, rely on deep mining. In other words, the time gained through surface mining must be used to improve conventional underground mining techniques and to develop new ones.

New underground mining techniques may be broadly divided into two categories: solid handling and in situ fluidization. The former include increased automation, remote control and possibly teleoperation (as used in nuclear energy, with the operator staying in a safe and clean area), aiming to increase both yield and recovery factor. In situ fluidization (which can be applied as a secondary recovery) includes gasification and liquefaction.[9] We believe that these techniques could, and probably would, benefit from petroleum technology (secondary and tertiary oil recovery, fracturation for tight gas formations, etc.) and possibly also from geothermal developments (fracturation again, apparently one of the key technologies of underground exploitation). Conversely, the petroleum mining industry is partially shifting to solid mining of oil shale, tar sand, heavy oils, and so on. We believe that there will be a mutually profitable cross-fertilization of technologies. This could be institutionally favored by the entry of oil companies into the coal industry, as has happened during the last decade in the U.S. and elsewhere; and by the interest of some coal organizations in oil research and production (for instance, that of the British National Coal Board in the North Sea).[10]

The two major problems involved in surface mining are land and materials management.

Land

Figure 13 shows the cumulative land use for bituminous coal mining in the U.S. from 1930 to 1971. Although underground production during this period largely exceeded surface production, it can be seen that more than 90 percent of the surface disturbance was due to surface mining.

In fact, surface mining techniques have evolved dramatically with time, and their "devastating" effect has been increasingly counterbalanced by the requirement (now generally imposed by law) to reclaim land; that is, restoring the ground to its initial condition if it is fertile, as in the lignite Rhine area, or to a condition suitable for further industrial or social uses (vacation areas). Today most of the perturbed areas are so only temporarily. But to what extent restoration of the surface also reestablishes underground equilibrium is not yet fully known. One major problem is that of underground water equilibrium; as is known, underground water represents 97 percent of man's fresh water reserves.

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[9] An example of liquefaction is copper leaching, but at present recovery is poor (about 50 percent) and selective (copper only, and no other minerals--such as gold, molybdenum, selenium--usually recovered in conventional mining and processing).

[10] This is in line with what we have called the development of a global "carbon option."

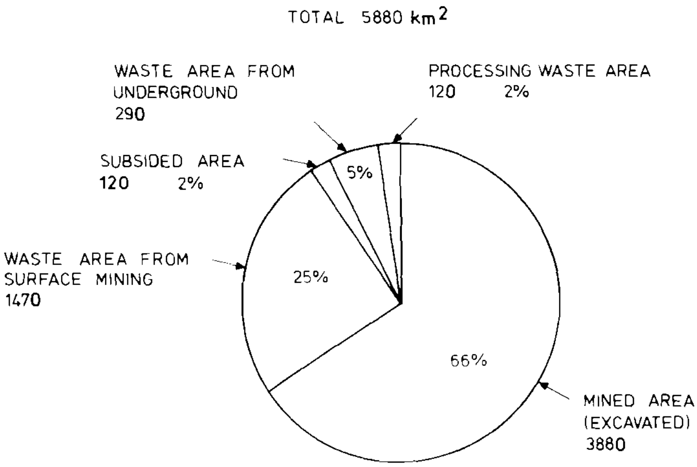

Figure 13. U.S. cumulative land use, bituminous coal mining, 1930–71.

The evolution of reclamation of land used by the U.S. bituminous coal industry is illustrated below. Note that between 1930 and 1971, 68 percent of the land disturbed was reclaimed. In 1971, more land was reclaimed than disturbed.

Land Utilized (km^2)	
1930-1971	5,880
1971	293
Land Reclaimed (km^2)	
1930-1971	4,000
1971	378
Land Reclaimed (%)	
1930-1971	68
1971	129

It is possible to correlate land disturbance with our previous table (Figure 5) of gross and/or net energy content and with seam thickness, as shown in Figure 14 for theoretical values. In order to mine one million tons of coal equivalent in Northern Appalachia, where seam thickness is about 1.2 m, .5 km^2 is disturbed, and about 6 to 8 times less in the Northwest, where seams are about 12 m thick but the coal has a lower heat value. In the Rhine area, lignite seams reach 45 to 100 m, and the area disturbed per million tons of coal equivalent is roughly 0.1 km^2. The uranium shale of Tennessee, with 5 m seam thickness at outcrops, would necessitate disturbing about 0.1 km^2 (if considering gross energy values), a value similar to those for coal.

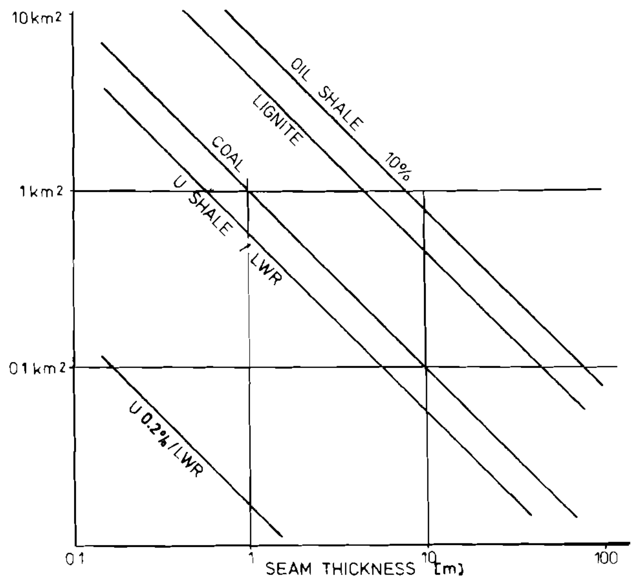

Figure 14. Land disturbed for producing 10^6 t.c.e.

These values can be used for a rough comparison of various energy alternatives. It is clear that such comparisons must include all sectors of the energy chain, from raw material production to final (secondary) energy distribution and use. We are in the process of making comparisons of this kind; for illustrative purposes here, we will limit ourselves to a few simple data for a 1,000 MW(e) power plant (Table 2). It can be seen that areas associated with various energy options may be comparable. Sites for coal and nuclear stations are, of course, relatively small compared to those for solar. But coal, if strip-mined, requires temporary use of a large area, as mentioned above. The area for uranium ores at 0.2 percent is relatively small (a calculation of the U.S. Council for Environmental Quality gives about 5 km^2 per 25 years per 1,000 MW(e) under 1974 conditions), but would increase with decreasing ore content to 10-40 km^2 when exploiting uranium shale. In the case of both coal and nuclear, land disturbance is only temporary (reclamation periods are from three to five years in temperate climates, and up to ten years or more in dry zones) and stretches over a 25- to 30-year period.[11] For solar, land occupancy can be considered as permanent; this is illustrated by Figure 15 (taken from the U.S. Atomic Energy Commission and based on somewhat different assumptions).

Table 2. Land requirements for a 1,000 MW(e) power plant.

Fuel	Attribute	Specification	Area km^2	Comment
Coal	Strip Mine (+ high-voltage line)	2 m Seam 10 m Seam	25 5	Temporary
Solar	Tower Concept	4 kWh/m^2/day 2 = 0.2	30	Permanent
Nuclear	Site		0.08-0.5	
	LWR-U Shale	2 m Seam 10 m Seam	37 7.5	Temporary
	(High-Voltage Line)		(20)	(Non-Exclusive)

The problem of land disturbance, even if minimized through reclamation laws and procedures, is nevertheless serious and will become more so with growing population densities, even if, on a global basis, it remains modest. It has been calculated that up to 1965, all open-cast mines in the U.S. occupied 12,400 km^2 plus about 1,300 km^2 for access roads and exploratory work; this represents less than 0.2 percent of the total surface of the U.S.

It is our opinion that land management will become a major problem and may present an almost insurmountable obstacle to surface mining, independently of the fact that most of the good shallow deposits will by then have been mined. If this is the case, land management can really be employed, from a systems point of view, to reshape the landscape during the period of use. Two possibilities are worth mentioning. The first is recreation

[11]For nuclear, we have mentioned the area covered by high-voltage lines (although, in principle, it does not exclude other uses, such as farming and possibly housing), assuming the location of power parks on sea shores or in remote areas.

areas, which will be in increasing demand; the second, pumping sites for peaking or storage plants, which will probably be necessary for both nuclear and solar power. In both cases, the land can be used--as is proposed in the Rhine area--for fresh water storage. This systems aspect of water, energy and land management will be studied in further detail in the coming months.

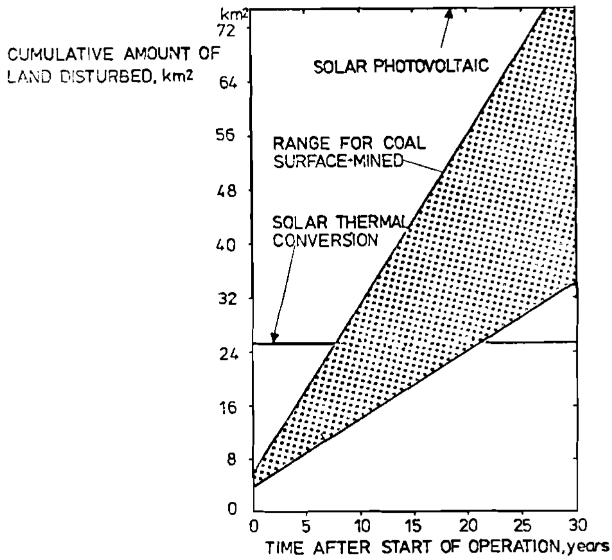

Figure 15. Comparison of land disturbed from surface-mined coal and solar electric 1,000 MW(e) power plant.

Materials

The materials balance problem is of no lesser importance. By way of comparison, we again present some data for a 1,000 MW(e) station (Table 3). The weight of the station is generally small compared to the amount of materials "flowing" through it during their active life in the case of fossil and nuclear plants, but becomes the main item in the case of solar plants.

For coal, we have assumed an average of 2 million tons per year (a value that is somewhat low but takes into account a decreasing load factor with time). For nuclear, we considered only the flow of uranium ore--for a U content of 0.2 percent and for uranium shale of 60 ppm--for the LWR and for the breeder reactors. With U at 0.2 percent for the LWR, the flow of ore is an order of magnitude below that for coal. If uranium ores of lower content were mined, tonnages would increase accordingly and become comparable to coal, with an ore content of about 0.01

percent or 100 ppm.[12] In the case of both coal and uranium, overburden is not included because it does not really participate in the flow. For a solar power plant, we have considered the tower concept and used the figures provided by J. Weingart of IIASA, say between 10 kg/m^2 (which is probably too low) and 100 kg/m^2 (somewhat high) for the heliostat, which means a total mass of 0.6 to 3.3 million tons, not including concrete, etc. This is the mass for equipment, that is to say, for elaborated materials. Upstream up to the mine, assuming a conservative ratio of 3 to 4 (probably too low, depending on the materials) between ore and extracted metal, we arrive at a balance between 1 and 12 million tons, to capture the "immaterial" solar flux of energy. Moreover, the flows for coal and uranium ore are spread over the lifetime of the plant, say 25 years; for solar, it has to be mined during the construction period of the plant.

Table 3. Materials requirements for a 1,000 MW(e) power plant.

Fuel	Weight of Station (10^6 t)	Total Flow (10^6 t)	Comments
Coal	0.3 - 0.35	50	Coal (25 years)
Nuclear	0.5 - 0.6 LWR FBR	2.5 - 75 0.04 - 1.2	U 0.2% - U Shale (25 years)
Solar (Tower)	0.35 (Conversion) 0.3-3 (Heliostat)	1 - 30	Mineral Ores (~ 5-7 years)

Turning to the problem of materials associated with mining, especially surface mining, we would like to consider the example of an open-pit mine in the lignite Rhine district: Garsdorf, which began operation about 15 years ago and which represents a benchmark in mining. Garsdorf may be considered as an outcome of the evolution of open-cast technology in the Rhine Valley: a decrease in the number of mines by a factor of 4 in 25 years, from 23 to 6; increased monthly production; and an eightfold increase in the amount of overburden, from 10 to 80 million m^3 per year. Garsdorf thus constitutes some kind of beginning of a new era in mining.

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[12] Detailed material balances are being established for various energy sectors. Cooperation is being developed with the Electricité de France for the nuclear sector.

Technical data are given below.

Garsdorf Lignite Mine	
Reserves	10^9 t
Total Area	26 km^2
Seam Thickness	45-60 m
Maximum Depth	300 m
Capacity of Bucket-Wheel Excavators	130,000 m^3/day

Table 4 shows roughly the material balance of the Garsdorf mine. Garsdorf is, in fact, firstly a mine of water (.5 percent of the Rhine flow rate), then of overburden, and finally of lignite, in the ratio 23.3 to 15 to 1, which again illustrates the systems aspect of water, energy, land and materials management.

Table 4. Material balance for Garsdorf mine.

Material	Output	Comments
Lignite	$15 \cdot 10^6$t per year	Maximum (30-35) $\cdot 10^6$t
Overburden	$226 \cdot 10^6 m^3$ in 1974	Estimated total $2 \cdot 10^9 m^3$ for 40 years
Water	$350 \cdot 10^6 m^3$ per year	Total for 13 years, $4.6 \cdot 10^9 m^3$

Garsdorf will not, however, be the deepest open-pit mine. A new mine in the Rhineland is planned for opening in 1978-1979: Hambach, with coal reserves of 4.5 billion tons, which will reach depths of approximately 500 m, with an overburden-to-coal ratio of more than 6 to 1.

It is interesting to compare the 300 m of Garsdorf and, still better, the 500 m of Hambach with present usage for U.S. surface coal mining, which is generally restricted to depths of less than 50 m (but with overburden-to-coal ratios up to 30 to 1).

Figure 16 shows the distribution of total estimated U.S. coal resources according to the thickness of overburden; note that about 80 percent of these resources could be strip-mined with Garsdorf and Hambach technology--a measure of its possible importance and impact.

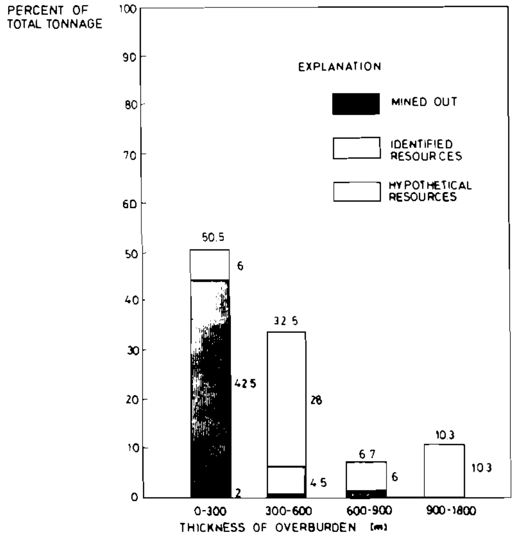

Figure 16. Probable distribution of total estimated U.S. coal resources according to thickness of overburden.

In Garsdorf, the energy expenditures for pumping the water and for handling and transporting the overburden and the coal amount to less than 5 percent of the energy extracted. Most of the equipment is powered by electricity, and the total power installed on the site is 280 MVA.

The handling of growing amounts of overburden is not, of course, restricted to coal. Figure 17 gives some data for U.S. copper production;[13] due to a continuous decrease in grade, from 4 percent to about 0.6 percent in 70 years, the amount of ore mined has increased much faster than production itself. A partial materials balance for 1968 and the year 2000--the latter calculated from the USBM forecasts for domestic production--are shown below (in 10^6 t). We have assumed that the ratio of waste material to ore extracted would remain unchanged, say 2.88 to 1.

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[13] Interesting also for comparisons with uranium, as mentioned previously.

	1968	2000
Smelted Copper Production	1.1	4.5 - 7.2
Average Grade	0.66	0.30
Copper Ore Extraction 83% Strip-Mined	170	1500 - 2400
Waste Material Discarded	490	4300 - 7000

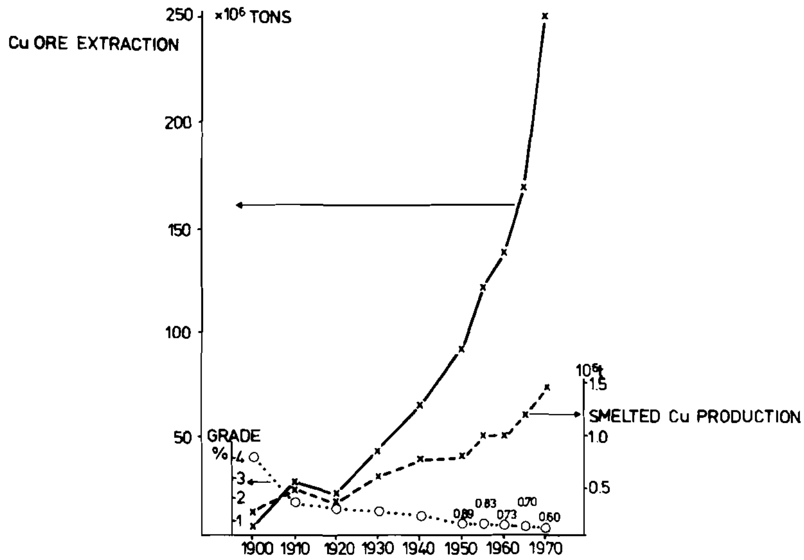

Figure 17. U.S. copper production.

Even when used to refill the open cut, the overburden and/or refuse materials raise many problems, either because their volume is greater after processing or because of concern for the environment. The concentration of solids in run-off water can reach 1,600 ppm suspended and more than 800 ppm dissolved, either basic or acidic, depending on the rocks. Air pollution through particulates is also a problem: for coal, Hittman [14] has calculated an emission of 0.5 kg per ton of overburden (with 33 tons of overburden per ton of Eastern surface coal, and 13 tons per ton of Western coal); Battelle gives even higher figures.[14]

As an illustration of this "spoilite" problem, Table 5 summarizes a few data for uranium ores of various contents, from the present 0.2 percent average to the 60 ppm of uranium shale and the 4 ppm of some uranium granites. In fact, in the U.S., the average grade is 0.27 percent in underground mines and only 0.17 percent in open-pit mines. A study of the USAEC [15] mentioned that for mining 100,000 tons of uranium, about 2.7 million tons of overburden were produced, so that our figures of 5 and 10 are very conservative. Once again, this shows that "burning the rocks" is not necessarily so easy.

Table 5. Wastes for uranium ores of low content (in tons, for one ton of uranium).

	Ore	Overburden	
		5 × ore wt.	10 × ore wt.
U 0.2%	500	2,500	5,000
U Shale (60 ppm)	16,700	83,000	167,000
U Granite (4 ppm)	250,000	1,250,000	2,500,000

Finally, we have applied these figures to two global scenarios, one for the year 2000 using projections of the USAEC, and one for a hypothetical world of 10 billion people consuming 15 kW(th)/capita (Table 6). For the year 2000, with uranium ore at 0.2 percent, 210 million tons of ore will be needed, with 1 or 2 billion tons of overburden (6 billion with the USAEC figure). For the hypothetical world, assuming the "burning" of granite, 30 billion tons will have to be mined annually (probably about twice as much as all materials being mined today, including building stone, sand and gravels) and 150 to 300 billion tons of overburden (the value of a few Semmering mountains).

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[14]According to [8].

Table 6. "Spoilite" for nuclear scenarios (10^9 t).

	Nature of Resource	Ore	Overburden	
			5 × ore wt.	10 × ore wt.
World				
"Year 2000,"	U 0.2%, LWR	0.21	1.05	2.1
3,620,000 MW(e)	U Shale, LWR	7	35	70
World				
10^{10} People 15 kW(th)/cap	U Granite, Breeder	30	150	300

CONCLUSION

We have briefly explored some systems aspects of primary energy production, and have tentatively shown that coal is not at a disadvantage when compared to other fuels. In the case of a real coal revival, it could happen that the main problems would be psychological (lack of dynamism--or of confidence in the future--of coal organizations) or institutional, rather than physical or industrial.

If we were to head for large-scale utilization of coal, world production could increase within a short space of time through surface mining in many countries. In other countries, the production level could and should be used to develop new methods of coal mining. This period could also be used by old coal countries to develop joint ventures and a world coal market. In any case, it will be interesting to see how the interrelations of the coal and oil industries can benefit or modify carbon fuel technology.

Finally, we have tried to emphasize that one of the main future technological problems may be to learn how to make holes, and refill them, or, in a few cases, use them for integrated development. Hole technology or global mining--one possible sector of geoengineering--would be needed for liquid or solid hydrocarbons as well as for geothermal, for nuclear, and for mineral production. After the civilization of homo sapiens and that of homo economicus, we now have to shift progressively to the civilization of the intelligent mole.

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2.2 A Bayesian Approach to Discrimination Among Models for Exploring Geological Bodies

Jacques G. Gros

Frequently, alternative models are proposed as aids to exploring geological bodies. They are characterized by different sets of relevant parameters; exploration data are used to obtain values for these parameters. The data can be reused to rank and to aggregate the models. A description is given of the use of Bayes' theorem for this analysis; an application is made for "trending" geological bodies.

The word trending describes bodies whose planar shape can be approximated by lines or by low-order curves, as for example shoestring sands, buried reefs, some mineralizations, and high-permeability channels of subsurface flows. Linear, quadratic, and cubic curves can be used to describe the centerline. By applying standard procedures (Zellner [1]), prior probabilities on the parameters of these curves can be updated to yield posterior probabilities, based on the likelihood of observations (exploration data). Normally, only one of these models would be considered and used in the analysis. But, in addition to the uncertainties inherent in estimating model parameters, there are uncertainties about which centerline model to use; these uncertainties can be a substantial component of total uncertainty and, in practice, are often not treated.

Bayes' theorem can be used to include model uncertainty in the analysis. The set of alternative hypotheses, H_i, is the shape of the centerline: linear, quadratic, cubic. We assume that an a priori degree-of-belief can be assigned to each of the hypotheses denoted by $p^o(H_i)$. This is the probability that the hypothesis is correct before the (drilling) exploration data are obtained. These prior probabilities can be obtained by considering relevant geomorphological information, crossbedding orientations in core samples, grain-size changes, etc. Given a set of drilling observations $\underline{Z}$, by Bayes' theorem the a posteriori degree-of-belief of each of the hypotheses is:

$$p'(H_i \mid \underline{Z}) = \frac{p^o(H_i)L(\underline{Z} \mid H_i)}{\sum_{i=1}^{3} p^o(H_i)L(\underline{Z} \mid H_i)} .$$

The term $L(\underline{Z} \mid H_i)$ is the likelihood of the observations conditioned on H_i, that is, the probability of observing $\underline{Z}$ given that hypothesis H_i is correct. The influence of the prior probabilities decreases rapidly as the number of observations increase. The denominator is a normalizing constant, chosen so that the posterior probabilities have all the properties of probabilities. These probabilities are the posterior model probabilities used in forming the weighted or composite model for predictions. The usual application of Bayes' theorem involves the updating of parameters of probability distributions; in our application, the hypotheses are different models.

An application of the technique is found in Baecher and Gros [2]. The goal of their analysis was to determine in a probabilistic sense whether points in an unexplored region were or were not within the trending body. To keep these computations simple, they assumed that probability density of width around the centerline was a Maxwell distribution and that borings intersecting the body were randomly distributed across the body width. This results in a Normal distribution for the error in locating the centerline. This in turn means that the well-known and documented Normal Bayesian regression techniques can be used to estimate parameters of the centerline. Given uniformed priors, the result is that the centerline is distributed as a univariate Student t; the likelihood function is Student t with degrees of freedom depending on the number of drillings and on the order of the curve. Bayes' theorem can be used to find the posterior model probabilities and the associated composite model. An example of prediction is shown in Figure 1.

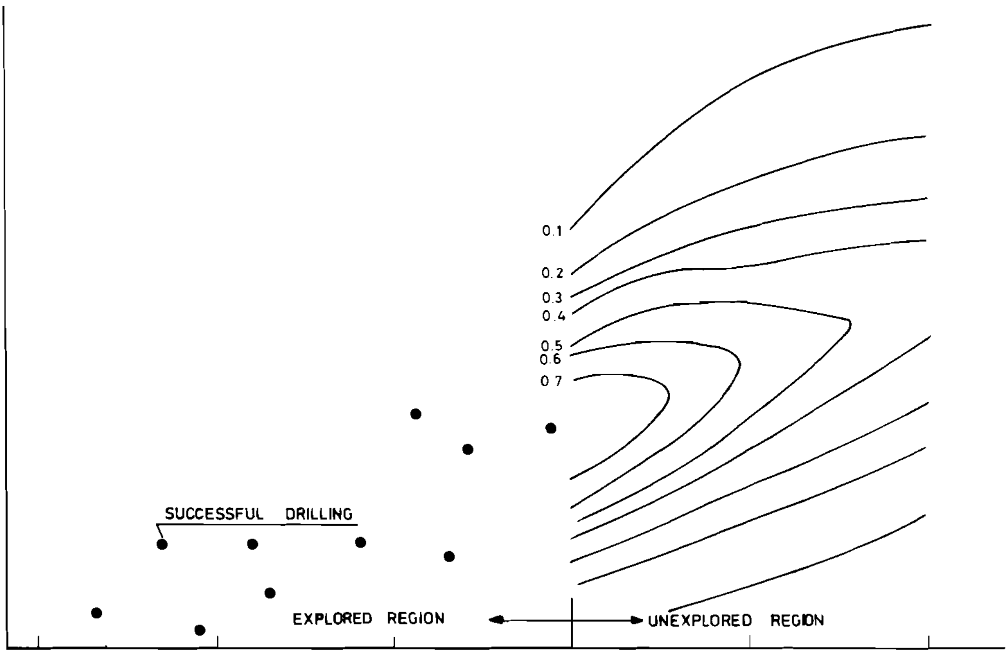

Figure 1. Results using the composite model: curves of equal probability in the unexplored region.

Bayes' theorem is a powerful tool for solving problems with model uncertainty. Its usefulness is not limited to solving problems with straightforward calculations, such as the one described. The theorem's main requirements are a set of hypotheses, the probabilities that these hypotheses are correct before exploration, and a procedure for finding the probability of obtaining the exploration observations, given the various hypotheses.

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Part 3: ENERGY DEMAND

PART 3. ENERGY DEMAND

3.1 Econometric Analysis of Energy Demand at IIASA

Plamen Tsvetanov

The study of energy demand, one of the principal variables linking the energy systems with society, is carried out at IIASA along three general lines: econometric analysis, energy analysis and global scenario of energy demand. This paper briefly discusses the two principal directions of investigations in the field of econometric analysis: conceptual problems and international econometric analysis of energy demand.

CONCEPTUAL PROBLEMS: ENERGY DEMAND IN ENERGY SECTOR MODELS

The first direction concerns conceptual problems of energy demand as a derived and final demand. There are two groups of important factors to consider: those determining the demand for final products, and those of competing inputs into the productive process. The technique outlined in this study specifies the way in which demand and technology interact so as to give a final derived demand for energy inputs. The bases for the estimates are the production function and the preference function for final goods. The detailed mathematical derivation and the results of this work are given in [1]. We will only indicate the general framework of the study.

Consider an economy with the primary factors labor L, energy E, and capital K, and with produced goods $Q_1,\ldots,Q_n$.

The production function for the goods is

$$Q_i = F(Q_{ie},\ldots,Q_{ni},L_i,K_i,E_i,T) \quad .$$

Cost functions exist as dual functions of the production function of price (P). That is,

$$C = F(P_1,P_e,P_k,T) \quad .$$

We have assumed that society's preferences can be represented by a well-behaved function over the final products of the society,

$$U = U(Q_1,\ldots,Q_n) \quad ,$$

and can be derived either from market demand functions for the decentralized economies or sectors, or from the preferences of planners in centralized economies or sectors.

The demand function of the economy can be represented as

$$Q_1 = D^i(P_1, \ldots, P_n, Y) \quad ,$$

where P_i represents prices, and Y is the total income.

Other variables (weather, income distribution, form of government) are built into the D function.

By approximating these functions by polynomial equations and solving them for energy, we can find the energy response function. After some simplifications, assuming that all variables are independent of the disturbances in the equation, the energy response function could be used for econometric analysis.

A subsequent development of this general approach to energy demand [2] deals with how energy demand models provide the necessary information to analyze the future development of overall energy balances, utilization and policy. Section two describes the general concepts underlying the work now under way at IIASA.

Consider an economy with K produced goods, and m non-produced goods of which $(x_1, \ldots, x_k)$ is the vector of gross outputs, $(q_1, \ldots, q_n)$ is the vector of final demands, and $(r_1, \ldots, r_m)$ is a vector of resource endowments or non-produced goods.

To keep the discussion simple, we assume that the technology can be represented by linear inequalities which relate the final demands to gross outputs and resource endowments. Thus we have:

$$q \leq Ax$$

$$q \leq Br$$

where the inequalities represent the constraints under which the economy or region must operate.

In addition, there is a preference function for the economy. The preference function may be the market demand functions in the case of a market economy, or the plan in the case of a planned economy, or some mixture of the two in a mixed economy. The economic problem can be seen as maximizing the preference function $U(q_1, \ldots, q_n)$ subject to the constraints of the technology:

$$\max U(q_1, \ldots, q_n) \quad ,$$

subject to

$$q \leq Ax$$

$$q \leq Br \quad .$$

I should like to remark:

- When considering the preference function for an individual sector, such as energy, it is important to note that the determination of the preference function is one of the most difficult parts of the problem of projecting future resource needs or of making policy analysis.

- In both planned and unplanned economies, the preference function reflects the relative valuation (or tradeoff) between different final goods which the economy can produce, and differences in the tradeoff will lead to different patterns of resource utilization.

- The two important final goods--the value of environmental quality and the value of energy consumption--may have different relative valuation in different economies. Based on this, very different results will be found for the utilization of different technologies, for emission control, or for the location of an industry.

Without going into details of the determination of the preference function, I shall indicate that for the countries with market economies it is possible mathematically to integrate a set of market demand functions where the quantities demanded are a function of prices, income, tax and institutional structure. That is,

$$V = V(q_1,\ldots,q_n) \quad .$$

The planning problem for a market economy using the market revealed preference function as a preference function is expressed as:

$$\max V(q_1,\ldots,q_n) \quad ,$$

subject to

$$q \leq Ax$$

$$q \leq Br \quad .$$

For goods allocated by central planning, the preference function is formulated by the planners. Nevertheless, a large share of the final goods is allocated in part by decisions of individual consumers or firms. The knowledge of the individual decisions is essential for guiding the planning process, and could be represented by a consumer response function which relates the desired quantity of final goods to the income of the individual consumers or firms and to the relative price of different consumer goods. That is,

$$q \leq f(y,p) \quad ,$$

where q represents the purchases of the final demand sector, y is the income, and p is the vector of prices of final goods, including taxes, costs, etc. We then have a modified problem:

$$\max W(q_1,\ldots,q_n) \quad ,$$

subject to

$$q \leq f(y,p)$$

$$q \leq Ax$$

$$q \leq Br \quad .$$

To summarize, we feel that the preference functions play an important role in the energy field. They are an essential element in making projections for the future, in performing policy analysis and in understanding the evaluation of energy systems. In particular they could be useful for comparing energy options and for modelling international and interregional energy trade.

INTERNATIONAL ECONOMETRIC ANALYSIS OF ENERGY DEMANDS

General Specification

The second direction is a series of studies mainly oriented toward countires with developed market economies and the Eastern European countries with planned economies. The work covers the aggregate energy demand and the energy demand in the domestic, transportation, industry (except energy) and energy sectors as a function of income, price, population and other determining factors.

These studies consist of three steps: an analysis of individual countries; a cross-section analysis of countries with the same type of economy and an international analysis of countries with planned and market economies.

The purposes of the studies are: to analyze factors and methods of forecasting; to choose the structure of models for different economies; to determine short- and long-run elasticities for different sectors and countries, and groups of countries; to recommend models for short- and medium-run forecasting of energy demand for different groups of countries; and to carry out an international analysis of the energy demand in planned and market economies. A future step would be to combine the determinant of energy demand with the models of economic growth of these countries.

This international approach causes some problems:

a) Gathering adequate data is a crucial and difficult task; prices and consumption figures of different fuels are not available or are not complete for some countries. On the other hand, the regression analysis needs a larger number of initial variables than are normally used in many models of energy demand.

b) In many empirical studies, a constant elasticity model is specified. Although the constant elasticity model is a useful first step, it is desirable to allow variable elasticities. For the purpose of the cross-section analysis, a variable elasticity model (VEM) would allow for some degrees of heterogeneity among countries. In the VEM, the value of the elasticity for a particular factor depends on the level of the factor.

c) The correct specifications of the model should also allow for the gradual adjustment of demand through time, in response to changes in the casual factors. This lagged response affects the relationships between the use of fuel and existing stocks of equipment and appliances. The size of these stocks depends on past as well as current decisions, and consequently on the past and current levels of explanatory factors. Two main difficulties have arisen. First, the time response is long (5-10 years) with respect to the sample periods for an individual country (15-20 years). Secondly, the choice of the lag structure is difficult since it is related to the lag of all variables, to the autocorrelations between the errors, to relationships between the length of the lag, to the degree that the polynomial has to be investigated, etc.

We obtained preliminary results from data mainly for the countries in Western Europe. For the countries of Eastern Europe, including the U.S.S.R., we are collecting available data and making a preliminary analysis of the factors and the methods of forecasting. This work is in progress.

ECONOMETRIC ANALYSIS OF SELECTED WESTERN COUNTRIES[1]

Methodological remarks

The econometric analysis of market economy countries includes two levels of investigation: individual country analysis, and pooling of data of the following seven countries: Belgium, the F.R.G., France, Italy, the Netherlands, the U.K., and the U.S.A.

The study considers the total consumption of fuel in each sector and neglects the composition (or breakdown) of the total consumption between fuels. The important difference between this and earlier studies is that we have considered the demand of net energy. The fundamental hypothesis is that within each sector there is a subclass of fuels that are perfect substitutes; for equal levels of non-fuel cost (equipment, appliances, labor etc.), interfuel competition will be determined by the relative net prices of fuel. The efficiency of each fuel in each sector is used to render this definition operational.

Income, price and population are considered determining factors of energy consumption. Gross domestic product (GDP) is taken to be the aggregate income measure, and the aggregate price index is the GDP deflator. Per capita variables refer to total population.

Individual Country Analysis

As a first step, a constant elasticity model is used. Two specifications are tested: a geometric lag, and two variants (B_1 and B_2) of an equation with polynomial lag structure.

$$\text{(A)} \quad Q_t = e^{a_o} P_t^{a_1} Y_t^{a_2} Q_{t-1}^{a_3} \quad ,$$

$$\text{(B)} \quad Q_t = e^{b_o} \prod_{T_o}^{T_1} W_i P_{t-i}^{b_1} Y_t^{b_2} , \ \Sigma W_i = 1 \quad ,$$

where

$$(B_1) \quad T_o = 0, \ T_1 = 3, \ W_i \text{ quadratic}, \ W_4 = 0 \quad ,$$

$$(B_2) \quad T_o = 0, \ T_1 = 5, \ W_i \text{ quadratic}, \ W_6 = 0 \quad ,$$

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[1] This work was headed by W.D.Nordhaus. For more information about results see [1].

and

Q_t = per capita net energy consumption,

P_t = relative net price of energy,

Y_t = per capita real GDP.

In terms of these specifications the short-run elasticity is a_1 and a_2 in equation (A), and b_1W_o in equation (B). The long-run elasticity (LRE) is $a_1/(1-a_3)$ or $a_2/(1-a_3)$ in equation (A), and b_2 or B_2 in equation (B).

Results of the short- and long-run elasticities are given in [1]. Here we shall focus only on the long-run elasticities of the specification B_1, which gave the lowest standard errors. (Long-run elasticity is defined as percentage change in net energy demand per year after the entire lag is included, divided by the percentage change of the explanatory factor during the current year.) Since the LRE's characterize the final response of the energy demand to the change of a determining factor, they are the main task of the investigation. If a sector has an absolute value of LRE (for example, income or price) greater than unity, we say that the energy consumption of this sector is income (or price) elastic: if less, inelastic.

Let us now proceed to the results. The results for the aggregate (the economy of a country as a whole) and for the four consumer sectors are given in Table 1. It is possible to calculate a composite statistic for the sample countries[2] based on the assumption that the coefficients are samples from normal distribution with common mean ($\bar{M}$) and differing variance--the variance differing because the range of the independent variables differs. Composite statistics are also given in Table 1. We will not analyze the results since this has been done in [1]. However, we will briefly assess these results; this will be done with the aid of Figures 1, 2, and 3.

For the aggregate economy the income elasticities differ significantly across different countries. Three countries have high income elasticities, and three have low elasticities. There is no clear indication whether energy demand tends to grow faster or slower than income.

The price elasticities are highly variable and not well determined: three countries (Italy, the Netherlands and the U.S.A.)

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[2]On the individual country level, results for Belgium are not complete.

Table 1. Individual countries, long-run elasticities, β_1 specification.

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

Notes: Comp. = composite estimate of coefficients.
Upper figures = estimated coefficients.
Lower figures in parenthesis = standard errors.
Underlined figures = elastic coefficients (absolute value > unity).
On the individual country level, results for Belgium are not complete.

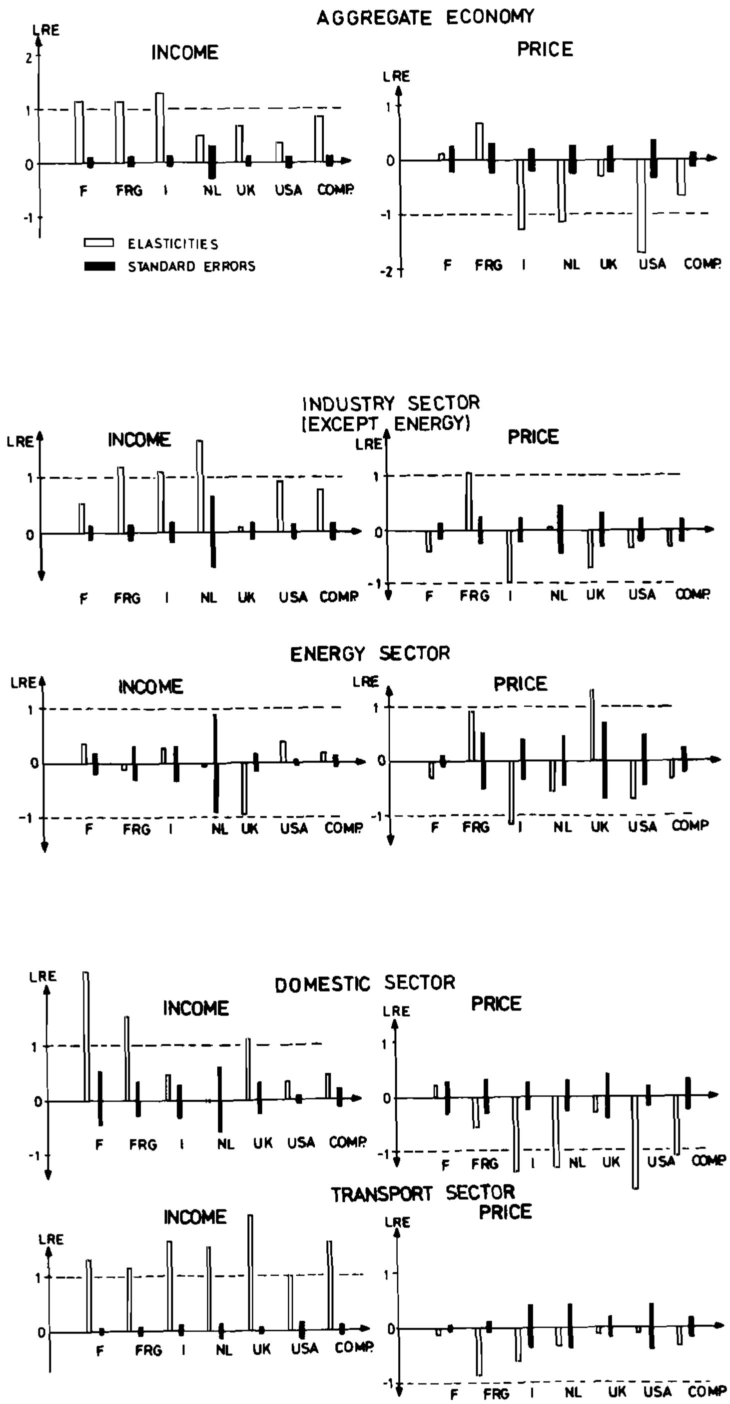

Figure 1. Individual countries, long–run elasticities, B1 specification.

are price elastic, two countries (France and the F.R.G.) have incorrect (positive) signs.

Domestic sector. The income elasticities are positive, but show some irregularity across the samples. The price elasticities are consistently negative (except for France). The composite statistics--greater than unity--indicate that the sector is price elastic.

Transportation sector; highly income elastic. All six countries have income elasticity greater than unity. For high income countries--i.e., the U.S.A. and the F.R.G.--the income elasticity is close to unity, while the medium and low income countries--especially Italy and the U.K.--have very high income elasticities. The overall impression is that the transport demand is price elastic.

Industry (except energy) sector. Income elasticities scattered around demand unity are well-determined. Price elasticities show a pattern of instability.

Energy sector. This sector has a different character from that of the other sectors. In reality energy consumption is energy consumed in the transformation of one energy form into another, or in the extraction or upgrading of fuels. The energy sector exhibits very low income elasticities. The price elasticities are mixed.

The results obtained from the analysis of individual countries are not encouraging since price and income are highly colinear for an individual country and therefore the data cannot determine the coefficients with great precision. The next step taken was to combine or pool the data into a single relationship.

Pooling of the Country Data

Briefly, our approach is based on the following assumptions:

- All countries have similar preference functions and production functions, but differences in incomes and relative prices lead to different energy-intensiveness in different sectors.

- In addition to the systematic effects of prices and incomes, there may be other omitted variables that are crucial to the determination of energy demand. For example, weather is important in determining domestic heating demands; the road network is important in determining automotive demand. We have assumed that these effects, which can be called country effects, are multiplicative and do not vary systematically over time. This implies that we can simply use country dummy variables in our logarithmic specification to represent the effects for individual countries. Thus the specification for the pooled model is that countries have different levels of energy demand, but the elasticities or responses to prices and incomes are constrained to be the same.

- The current and lagged income terms which appeared to have the same sized coefficients are constrained to be equal; the length of the lag for price is four years and the lag is linear over a five-year period.

The specification based on these assumptions is as follows:

$$Q_{t,i} = e^{\alpha_i} \cdot \prod_{\theta=0}^{4} P_{t-\theta,i}^{0.2\beta} \cdot \prod_{\theta=0}^{1} Y_{t-\theta,i}^{0.5\gamma} ,$$

where

$Q_{t,i}$ = per capita net energy consumption ,

$P_{t,i}$ = relative net price of energy ,

$Y_{t,i}$ = per capita real GDP ,

α_i = individual country effects ,

β = common long-run price elasticity ,

γ = common long-run income elasticity.

The major difficulty in pooling countries revolves around the question of the appropriate conversions of different currencies. The usual procedure is to use market exchange rates, but these are seriously deficient. A superior method of measuring real incomes is to use purchasing power parity rates which compare the purchasing power of incomes of different countries. Since these indices will differ according to the group of goods used, we took as the geometric mean the purchasing power exchange rates according to the U.S.A. and to local composition of GDP with 1960 as a base year. These rates are used to translate each currency into a "universal" standard of value for a given year; domestic GDP deflators are then used to indicate changes over time. In general, purchasing power parity exchange rates lead to a lower inequality of income distribution across countries than have existing exchange rates.

The results for pooled data, the aggregate function, and the energy consumption functions for the four consumer sectors are shown in Tables 2 and 3.

The aggregate consumption function concerns the energy demand for a country as a whole. All seven countries have common price and income long-run elasticities; the dummy variable indicates whether the country differs in these factors from the U.S.A. The price and the income elasticities are moderate and well-determined. The ranking of economies by energy intensiveness is as follows: Belgium, the U.K., the U.S.A., the F.R.G., the Netherlands, France and Italy; however, the pattern of results varies for different sectors.

The energy consumption function concerns the four consumer sectors. The price and income elasticities vary from sector to sector and are all well-determined. The income elasticities for the transportation sector are very high. Since this sector consists of largely road transport, which is highly income elastic, the income elasticity for transportation is not surprising. The result for the energy sector indicates that the transformation processes of energy are not related to income.

For the price elasticities, in all four consumer sectors the price elasticities have the right (negative) sign. The magnitudes of the elasticities indicate that the long-run response of energy consumption to price is moderate. They indicate that the most inelastic is the transportation sector, which is plausible, since there is probably less possibility for technological substitution in this sector.

Conclusion

We have presented briefly the preliminary results of a study of a series of investigations of energy demand, from an international perspective. The major differences between this and earlier studies are that our study attempts to estimate the demand for net energy in four major sectors of the economy, without regard at this stage to the breakdown between the different fuels; it also attempts to compare the energy demand functions of seven different Western countries over the period 1955-1972, both by individual estimation and by pooling of data.

The results of our study are somewhat mixed. On an individual country level, the regression results show considerable lack of precision, as well as a certain number of contradictory conclusions. We have surmised from these results that it is extremely difficult, even for a time period of twenty years, to obtain reliable estimates of energy demand functions using the specification mentioned in this paper.

When data for the seven countries are pooled (along with country dummy variables), the results are more encouraging. The price elasticities are all of the correct sign (negative) and are

Table 2. Results of pooled data: aggregate energy consumption functions.

$$q_{t,i} = \alpha_i - \underset{(.10)}{.85} \left[\sum_{\Theta=0}^{4} 0.2 p_{t-\Theta,i} \right] + \underset{(0.08)}{0.79} \left[\sum_{\Theta=0}^{1} 0.5 y_{t-\Theta,i} \right]$$

$\alpha_{U.S.A.}$	D_i					
	U.K.	F.R.G.	B	NL	F	I
4.70	.03	-.09	.13	-.25	-.35	-.35
(.18)	(.03)	(.03)	(.14)	(.03)	(.04)	(.04)

Notes:

$q_{t,i}$ = per capita net energy consumption.

$p_{t,i}$ = relative net price of energy.

$y_{t,i}$ = per capita real GDP.

$q_{t,i}$, $p_{t,i}$, $y_{t,i}$ -- in natural logarithms.

$\alpha_i = \alpha_{U.S.A.} + D_i$.

D_i = dummy country variables.

Upper figures = estimated coefficients.

Lower figures in parenthesis = standard errors.

Underlined figures = elastic coefficients (absolute value > unity).

Table 3. Results of pooled data: energy consumption functions.

$$q_{ti}=\alpha_i+\beta\left[\sum_{\Theta=0}^{4} 0.2p_{t-\Theta,i}\right]+\gamma\left[\sum_{\theta=0}^{1} 0.5y_{t-\Theta,i}\right]$$

$\alpha_i=\alpha_{U.S.A.}+D_i$	β	γ	$\alpha_{U.S.A.}$	D_i					
				U.K.	F.R.G.	B	NL	F	I
Industry (except energy)	-.52 (.17)	.76 (.16)	<u>2.98</u> (.10)	.08 (.19)	.28 (.06)	.19 (.07)	-.34 (.05)	-.19 (.05)	-.11 (.08)
Energy	-.58 (.12)	.05 (.12)	<u>3.12</u> (.12)	-.37 (.06)	-.21 (.07)	-.60 (.06)	-.63 (.04)	-.91 (.07)	-1.41 (.06)
Transportation	-.36 (.12)	<u>1.34</u> (.80)	<u>1.84</u> (.23)	-.37 (.06)	-.63 (.05)	-.59 (.06)	-.44 (.05)	-0.74 (.09)	-.35 (.06)
Domestic	-.79 (.08)	<u>1.08</u> (.12)	<u>3.31</u> (.20)	.24 (.03)	-.05 (.07)	.11 (.03)	-.09 (.05)	-.39 (.04)	-.46 (.07)

Notes:

$q_{t,i}$ = per capita net energy consumption.

$p_{t,i}$ = relative net price of energy.

$y_{t,i}$ = per capita real GDP.

$q_{t,i}$, $p_{t,i}$, $y_{t,i}$--in natural logarithms.

$\alpha_i = \alpha_{U.S.A.} + D_i$.

D_i = dummy country variables.

Upper figures = estimated coefficients.

Lower figures in parenthesis = standard errors.

Underlined figures = elastic coefficients (absolute errors value > unity).

inelastic (i.e. they are less than one in absolute value). The results indicate a moderate but slow reaction of energy demand to the price of energy products. The major surprise was that the income elasticity of energy demand tends to be relatively low. In three of the four sectors--energy, industry (except energy) and domestic--the estimated income elasticities were between zero and one, which indicates that with relative prices of energy to other goods constant, per capita net energy demand tends to grow slower than per capita income.

Another important conclusion is that for market economy countries the net energy consumption of the aggregate economies, as well as of different sectors, is relatively well-explained by population, per capita income, and relative prices. Without dummy variables, between 60 and 96 percent of the variance of the sample is explained by these factors; country dummy variables raise the explanatory power to 95 to 99 percent of the variance. An important application of the final results of this study is the forecasting of the growth of energy demand over the short and medium term. Very preliminary projections were made for the U.S.A. Emphasis was placed on the uncertainty of these results. It was concluded that the statistical uncertainty of the projection of energy demand at the end of the twentieth century is equally due to uncertainties about price and income and to the uncertainty about the structure of the equation.

ON THE FUTURE WORK ON ECONOMETRIC ANALYSIS AT IIASA

Corresponding to the goals of the IIASA Energy Project, the work on econometric analysis is expected to evolve in the following two directions: the energy demand in overall models of energy systems; and the international econometric analysis of the countries of market and planned economies.

The first direction will be oriented toward describing world energy mechanisms and strategies and will correspond to the line of synthesis of all studies of energy systems undertaken by the Energy Project. It will deal both with the general problems of complex models of this kind and with aggregated regionalized models of energy systems. The main concerns of the first (general) part of this study are the following: the problem orientation of the integrated energy submodels; the regionalization reflecting different development and problems in different parts of the world; the stratification of the energy systems as a method of describing system behavior; and the main concepts and variables, constraints and procedures for the scenario analysis.

The regional models would be oriented toward: the design of regional macroeconomic models, consumption factors and parameters; life-style constraints; policy options (population fertility rates, desired economic growth, fuel price , energy conservation, relative cost of substitution); and indicators (populations, gross regional product, environmental qualities, interregional trade, etc.)

The international econometric analysis now under way should be seen as a part of these regional models. It must then continue along the lines of an in-depth study of general problems of process and parametric estimations, distributed lags and multicolinearity in energy demand analysis. This will help to improve the statistical accuracy of the models, the gathering of data and the analysis of energy demand for the countries with planned economies, and will enhance the international comparison of energy demand of countries with planned and market economies.

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[2] Tsvetanov, P.S. and W.D. Nordhaus, "Problems of Energy Demand Analysis," in Proceedings of the Workshop on Energy Demand, May 22-23, 1975, CP-76-1, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

3.2 A Global Scenario

Wolfgang Sassin

INTRODUCTION

The question how much energy will have to be supplied in the future, and what for, has been asked many times. And no doubt there are many ways to find an answer. A large number of models, some highly sophisticated, are available now to explain energy consumption as a function of other parameters and to project future demand. Some detailed examples are presented in this status report. P. Tsvetanov specifically elaborates on an econometric approach designed for analyzing possible developments in the near- and medium-term future. An extensive survey of energy models has been published [1], and modelling is a continuing effort of the IIASA Energy Project.

Despite the new analytic tools which came up in the last few years, the global energy future never seemed less certain than today. It is evident that we are all reorienting our goals in the field of energy. As a consequence, instead of extrapolating past trends, assumptions have to be made on which of the dominating supply objectives, economic optimization principles, energy technologies or simply consumption habits of today will prevail and which new ones might enter the picture.

Within the IIASA Energy Project we felt the need to improve the conditional basis of further modelling efforts which is formed by a set of the assumptions just mentioned. This is the more important because of the sensitivity of long-term developments to new goals and new supply possibilities.

This paper reports on some of the results obtained in analyzing the conditional basis. Here I will largely rely on the work of J.P. Charpentier. Then I will briefly describe how we built a global energy scenario by summarizing a group of demand projections.

PRESENT GLOBAL ENERGY CONSUMPTION

Before looking some 50 years ahead, let us first consider what happens today on a global scale.

Figure 1 gives the fractions of primary energy that were consumed in the past in the form of wood, coal, mineral oil and

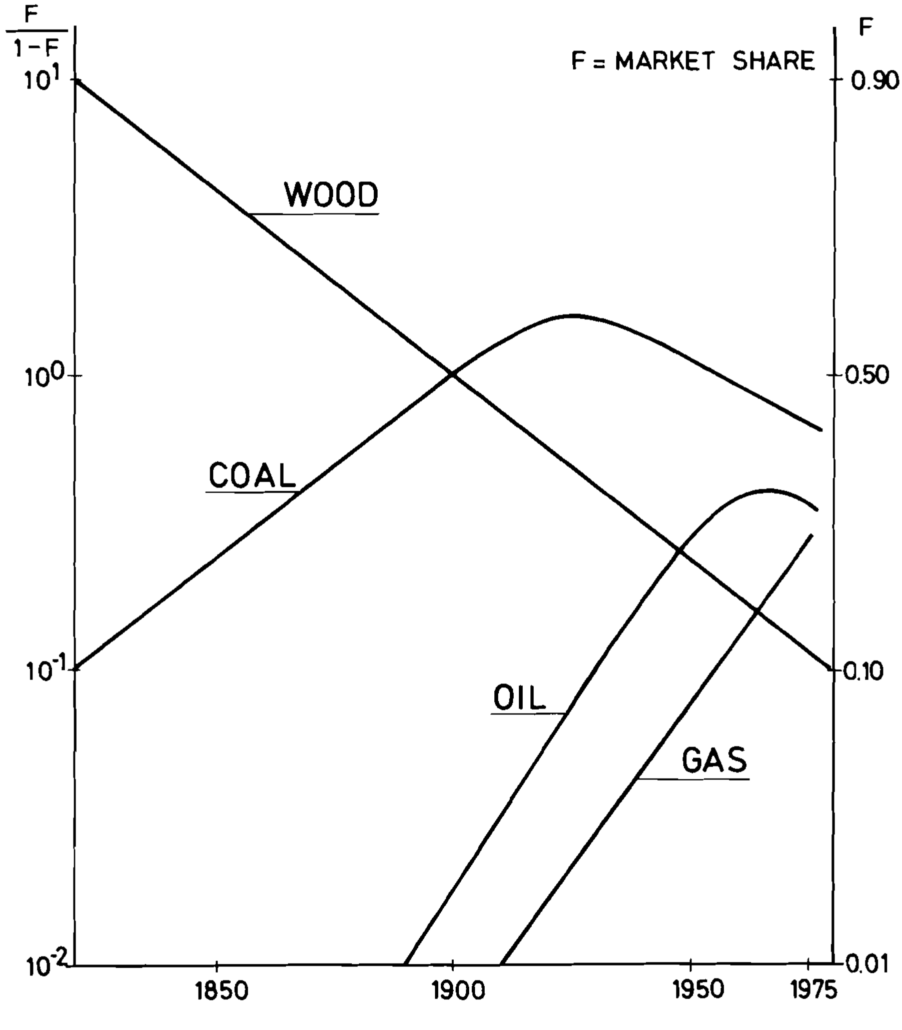

Figure 1. Energy market penetrations: world
(Source: Marchetti, IIASA).

natural gas. The global energy system has undergone a process of modernization: wood was replaced by coal, which in turn declined during the last 50 years with the advent of oil and later with natural gas. Coal still holds the largest share. Rather similar figures were derived from the statistical data for single countries [2], and it is interesting to note that in industrialized nations with large coal resources, such as the U.S.A. or the F.R.G., this substitution process has proceeded even further. Thus an anticipated scarcity in natural gas and mineral oil is first of all a challenge for those countries whose energy system is most advanced. This leads us to regional aspects and to the question, who uses this energy?

Figure 2 shows the number of countries that have achieved a certain level of primary energy consumption. The distribution function in the figure would be quite similar if the number of people at a certain energy consumption level were used instead of the number of countries. The majority--75 percent of the world population--consume less than 2 kW(th) years per year and capita of primary energy, the largest fraction having a consumption level around 0.2 kW(th)/cap. Group III in Figure 2 comprises developing countries in Asia, Africa and Central and South America. Group II contains mainly the European countries, the Soviet Union and Japan, with an energy consumption between 2 kW(th)/cap and 7 kW(th)/cap and 22 percent of the global population. The United States, Canada, Sweden and Kuwait, totaling 3 percent of the global population, consume more than 7 kW(th)/cap. One should note that the use of energy in the U.S.A. is 50 times that of the countries at the maximum of the distribution function, but also that there is a factor of 10 difference between the main group and the developing countries at the upper end of group III in Figure 2. Before trying to interpret such a dramatic difference, it is useful to consider what energy is used for in the three groups of countries.

In Table 1 the energy inputs into the three basic sectors industry, transport, and all other energy consumers--i.e. mainly domestic, agriculture and public services--are listed. The entries are not average values for the groups of Figure 2. They represent typical examples: e.g. the U.S.A. for group I; a number of European countries and Japan which lie at the center of group II; and a number of developing countries with an energy consumption level of about 1 kW(th)/cap, which is a factor of five more than the average in group III. The energy use, as can be seen from the percentage figures, does not vary significantly as a function of the overall consumption level. The similarity of group I and group III should be particularly noted.

This very short survey of the present global energy consumption pattern suggests two conclusions. First, a diffusion process of an identical technological and economic way of life was the driving force for energy consumption.

Table 1. Primary energy consumption of different sectors.

Class	Energy Per Capita kW	Sectors						Σ
		Industry		Transport		Other Sectors Household + Agr		
		%	kW/cap	%	kW/cap	%	kW/cap	kW/cap
I Upper Level of Energy Consumer (e.g. U.S.A.)	$E/cap^{>7}$	42	4.2	22	2.2	36	3.6	10
II Middle Level of Energy Consumer (e.g. Europe, Japan)	$2<E/cap^{>7}$	56	2.5	14	0.6	30	1.3	4.4
III Low Level of Energy Consumer (e.g. Developing Country)	$E/cap^{\leq 2}$	47	0.5	29	0.3	24	0.25	1.05

Average About 1970

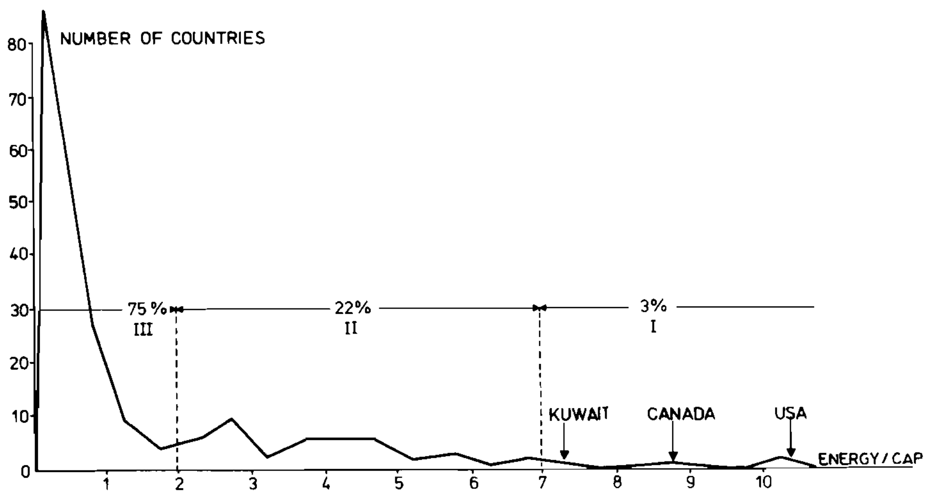

Figure 2. Distribution of world energy consumption, 1971 (178 countries) (Compiled from: UN World Energy Supplies 1968–1971).

Secondly, the most advanced forms of primary energy, such as gas and oil, were introduced mainly by countries with a high energy consumption level.

In order to prove and quantify such conclusions, many studies are under way. They aim at life-style scenarios that are to be based on technological forecasts. Such scenarios, if completed for all relevant regions of the world, will allow calculation of the necessary energy input and will thus provide energy-demand scenarios. Apart from a highly advanced body of information for some specific countries (e.g. [3]), much remains to be done before quantitative demand estimates for the global system can be derived from such an approach.

For the purpose of illustration, Table 2 gives an apportionment of the present energy input to run the technical equipment of typical households. The data were taken for France and compare a better-equipped household with higher investment in an efficient heating system (hypothesis 1) and a less equipped household (hypothesis 2), both in a big city, with a household in the country (hypothesis 3). Together with projections of the construction rate of new houses, the penetration rate of appliances, the process of urbanization and finally assumptions on the build-up of district heating, gas distribution and electricity grids, quite reliable projections of the overall energy demand of this sector can be derived. Unfortunately a sufficient data base and an established framework for economic development are the exception. I should close this part with the observation that by following this kind of analysis, we can expect considerable insight into the mechanisms that result in the demand for energy. On a global scale and in view of long-term development, the lack of detailed data for developing countries is not so much of a hindrance. The uncertainty introduced thereby is somewhat compensated by the fact that from an engineering standpoint it is well known which minimum energy input is needed to run low capital production processes.

Figure 2. Per capita energy consumption for different appliances in the household sector in Europe (kW(th)/cap).

Standard of Living	People Living in Big Cities		People Living in the Country
	Hypothesis 1	Hypothesis 2	Hypothesis 3
Lighting	0.17	0.03	0.01
Water Heater	0.43	0.16	-
Refrigerator	0.08	0.04	0.04
Freezer	0.08	-	-
Cooker	0.20	0.20	0.09
Dishwasher	0.03	-	-
Washing Machine	0.02	0.01	0.01
Dryer	0.01	-	-
Television	0.04	0.02	0.02
Sub-Total	0.97	0.46	0.17
Space Heating	0.37	0.53	0.96
T O T A L	1.34	0.99	1.13

While waiting for further results on energy accounting, energy analysis and life-style scenario writing, we must rely on more general and in principle heuristic approaches to relate energy demand with other controlling variables. Factor analysis is a very simple tool for checking whether there is a correlation between energy consumption and a large variety of parameters describing the basic conditions of a national economy, its inputs and its outputs.

Table 3 lists those parameters for which correlation values were determined based on a set of 35 countries. The parameters refer to the detailed energy consumption, to natural production factors and geographic features, and finally to economic activities and the social structure. There is only one linear combination of these parameters--a so-called eigenvector--for which the variance of the individual country data is considerably reduced. Figure 3 shows a projection of the countries onto that eigenvector, called "degree of development" as it correlates mainly with the features generally considered as indicators of a high level of economic development. Table 4 lists, for illustration, parameters which had a two-by-two correlation greater than 0.83.

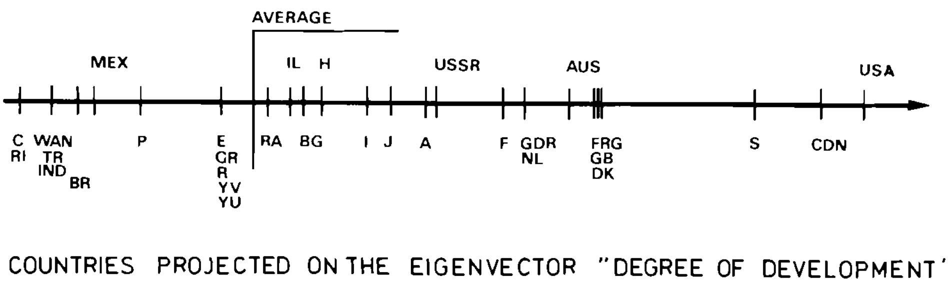

Figure 3. Factor analysis--energy consumption and economic development.

Table 3. Parameters included in an energy factor analysis.

Parameters Related to Energy Consumption	Parameters Related to Geographical and Physical Situation	Parameters Related to Economic and Sociological Aspects	
		Present Level	Growth Rate
Energy/Capita (1970)	Arable Area/Total Area	Urban Population/ Rural Population	Decrease Rural Population (1963-1970)
Fuel Oil/Capita (1970)	Population/Total Area	Students/Population (1970)	Increase Population (1963-1970)
Gas/Capita (1970)	Arable Area/Population	Investment Ratio	Increase Industrial Production (1969-1970)
Electricity/Capita (1970)	Energy Imported/Energy Consumed (1970)	Cars/Capita (1970)	Increase Manufactural Production (Without Mining and Energy Industry)
Electric Industry/ Total Electricity (1970)	Reserves Fossil/Capita (1970)	Newspaper/1000 (1970)	Increase of Production of Electricity (1963-1970)
		Steel/Capita (1970)	Increase GNP/Capita (1967-1970)
		Employment/Capita (1970)	
		Cement/Capita (1970)	
		t x km Transport by Rail/ Capita (1970)	
		t x km Transport by Plane/ Capita (1970)	

Table 4. Factor analysis.

Energy Consumption and Economic Development
Parameters with Correlation Factors > 0.83 (Per Capita Values)
Primary Energy Consumption
Electricity Consumption
Fuel Oil Consumption
Gross National Product
Steel Production
Passenger Cars
Students

The correlations support an earlier conclusion, that a similar economic and technological way of life is adopted within the global system, since otherwise at least a second significant eigenvector should have been found; and clearly indicate that energy has so far been an essential ingredient for economic development.

To stress this point, I want to rephrase it: energy is neither more nor less important for economic development than steel production, or the number of students. Within certain limitations we can therefore state development goals in terms of energy consumption, and I will make use of that in formulating a global energy scenario.

GLOBAL ENERGY SCENARIO

I will use a simple synthesis by considering existing projections of world population growth and combining them with a set of per capita energy demand figures.

A considerable effort has been made worldwide to understand and model the mechanisms that resulted in an exponential growth of mankind during the last century. Figure 4 summarizes a report that was given by the Secretary General of the UN World Population Conference held in Bucharest in 1974 [4]. It contains a projection of the world population based on studies conducted for different regions. The increase from $1.6 \cdot 10^9$ people in 1900 to $4 \cdot 10^9$ people in 1975 is due largely to a reduction of mortality rate which started in the developed countries and was gradually achieved also in less developed countries. We are just at a point where the reduction of fertility observed in some of the developed countries begins to influence the overall growth rate. The number of people that will live on the earth under equilibrium conditions depends largely on time that will

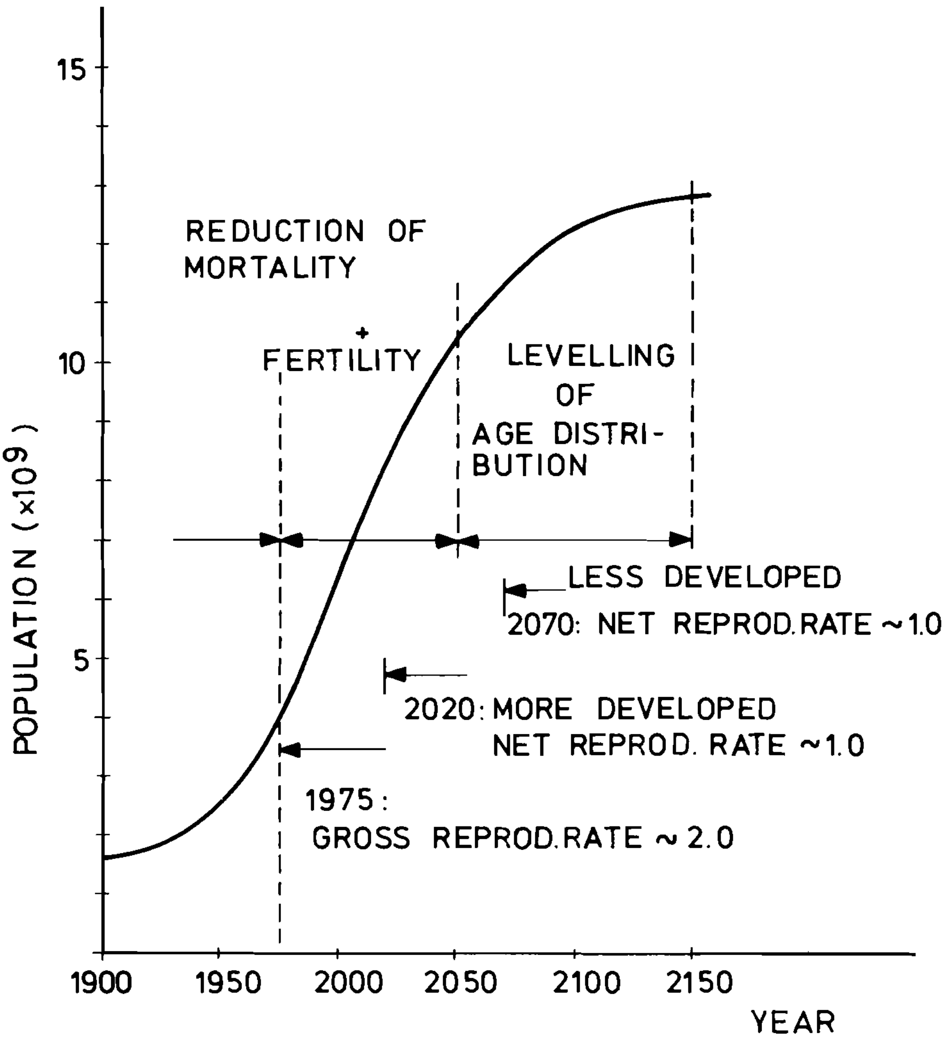

Figure 4. World population growth
(Source: UN World Population Conference, Bucharest, August 1974–Report of the Secretary General).

elapse until, at the level of the average individual, a net reproduction rate of 1.0 can be reached. This means that each couple will give birth to two children who will survive until their reproductive age.

Under optimistic assumptions--and these include a favorable economic development in the third world--the UN report projects a net reproduction rate of 1.0 for the developed nations as a whole in 2020, and for the developing nations in 2070! This would result around 2050 in a world population of approximately $10 \cdot 10^9$ people. A further increase by nearly $3 \cdot 10^9$ people must be expected as a consequence of the leveling-off of the age distribution, which will be heavily distorted at the beginning of the next century. In using such a projection, I am fully aware of the uncertainty that is introduced in an energy-demand scenario. We will return to this point.

Figure 5 quantifies the well-known fact that the population in less-developed regions grows faster than that in the more-developed regions of the world. Whereas in 1960 the ratio between more and less developed was one to three it will be roughly one to eight around 2060, the major change taking place within the next 30 to 40 years. With this rearrangement of weights in mind, I will now try to fix a set of "reasonable" future energy consumption levels. These levels are to be understood as target indicators for a more general economic and social development. I am not suggesting that a precisely quantifiable relationship exists between energy consumption and economic development. Still, one can expect a stronger dependence of economic development on energy supply in a global system than on the scale of a national economy. In the latter case a lower energy input may be compensated by other production factors and by the import of goods which require large amounts of energy. As this work is at an early stage, the focus in setting consumption levels has been mainly on making a good estimate of upper and lower boundaries. It seemed appropriate to operate with average values, thus establishing a first-order scenario that will have to be improved.

In using average consumption values we make the implicit assumption suggested by the findings on which I reported at the beginning, that the penetration of the same technological and economic life style will prevail. A more detailed scenario based on possibly different targets of long-term economic development, and consequently with a different energy demand for different regions of the world, will have to be worked out later.

Table 5 lists a set of objectives chosen to describe a pessimistic and a slightly optimistic future development. In using terms such as "optimistic" and "pessimistic" development, I want to indicate that the objectives were set on the basis of personal judgment. Others certainly will choose different figures. The main point in discussing Table 5 is not to prove that one entry is more probable than another. Instead I will try to show that once one target is set, it has a strong influence on the possible setting of other targets.

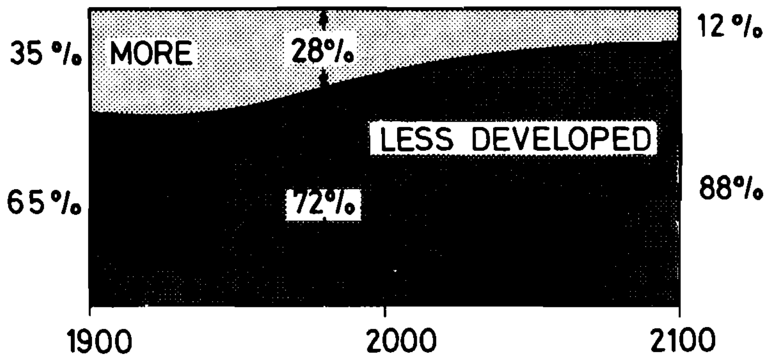

Figure 5. Changes between more and less developed population shares (After: UN Population Projections, March 1974).

Table 5. Global scenario: energy demand.

Objectives: Total Growth % Per Year After 1975	Specific Energy Consumption kW(th)/cap - Target -	Target Achieved Within Generations	Target Compares to Present Status of
4.5	5	2	F.R.G., U.K.
3	5	3-4	
2	2	No Improvement	Spain

The second column in Table 5 list 5 kW(th)/cap and 2 kW(th)/cap as long-term asymptotic energy consumption levels. Introducing the concept of an asymptotic development introduces new questions that cannot be answered here. I will leave this point with the remark that in the context of our work on resilience, we may arrive at some results clarifying whether or not this is a reasonable concept.

Now a primary energy consumption of 5 kW(th)/cap is found today in Great Britain and in the Federal Republic of Germany, both industrialized countries which expect for the medium-term future a considerable further increase in their energy input. In view of less favorable natural conditions for supporting an agreeable life in many parts of the world, 5 kW(th)/cap were taken as a modest long-term energy demand. 2 kW(th)/cap, slightly more than the present average global energy consumption of 1.8 kW(th)/cap, was considered as the minimum long-term supply target. This value compares to a national economy of e.g. Spain. A target of 2 kW(th)/cap is hardly acceptable for political reasons. It would allow only minor improvements of the global economic situation, at least if we do not assume that the industrialized countries would dramatically reduce their present energy consumption. Such a questionable target was introduced in Table 5 only as a reference case that can easily be interpreted, as it reflects the present global energy situation.

The third column in Table 5 states the approximate time periods within which the 5 kW(th)/cap should be achieved. Two cases were introduced: a faster development which would require a time of 50 to 60 years, that is roughly two generations, and a slower one where the third or fourth generation from now would consume 5 kW(th)/cap on an average. Again, for political reasons, we may question whether an individual would support a development policy whose noticeable results would be experienced only by his children or grandchildren. On the other hand, we cannot assume that the global system can develop faster than some of its parts did under very favorable conditions. The global growth rate of the overall energy consumption between World War II and the oil crisis in 1973 was about 4.5%/a. It was determined mainly by the energy consumption of the industrialized nations. This period also was characterized by the penetration of cheap oil and even cheaper natural gas within the global energy market, in retrospect a sort of golden energy age which definitely has passed.

Column 1 of Table 3 contains three different growth rates of 4.5, 3.0 and 2.0%/a for the global energy consumption of the near future; we will see in Figure 6 that they largely predefine the time spans of column 3 within which an improvement on a per capita level can be planned. Here we arrive at the problem of transition modes. Figure 6 displays the effects of alternative transitions from the present energy consumption to the stated objectives of 2 kW(th)/cap and 5 kW(th)/cap.

The horizontal, essentially straight line corresponds to the case where the present average energy consumption of 1.8 kW(th)/cap would be raised only to 2 kW(th)/cap. This implies an overall growth rate of the global energy consumption of 2.0%/a, starting in 1975 and decreasing slightly with the decrease in the population growth rate. The index 2.0 is used to characterize the corresponding near-term growth rate of the overall energy consumption.

Let us now turn to the transitions from 1.8 kW(th)/cap to 5 kW(th)/cap. The dashed lines marked by the indices 4.5 and 3.0 illustrate the effects on the average consumption level of the individual if the overall energy consumption either continued to grow at 4.5%/a or settled around 3%/a from 1975 onwards. They lead to the shortest time spans for achieving the target value of 5 kW(th)/cap. As we cannot assume that a global system could immediately return to almost zero growth, the price for fast improvement would be a reversal experienced by the individual, with all the adverse effects of lowering the energy consumption status achieved.

If a more rational and soft transition were chosen instead, it would take roughly 25 years more to move from 1.8 kW(th)/cap to 5 kW(th)/cap. The solid lines in Figure 6 with the indices 4.5 and 3.0 represent such "smooth transitions." They start with overall energy consumption growth rates of 4.5 and 3.0%/a in 1975. These growth rates, together with the present growth rate of the global population, define the increase in the average per capita consumption level. The simplest assumption now is that a linear growth of this individual level will be maintained until the target of 5 kW(th)/cap is reached. This kind of transition avoids such problems as reducing the consumption of an individual at a time when the overall demand still grows. Finally it corresponds to a gradual reduction of overall growth rates which so far have been considered as basic indicators of welfare or as guiding variables that should not undergo fast variations for the sake of stability of economic systems.

With the choice of a transition mode, we have now created a basis for giving a projection of the future global energy demand. Multiplying the projected world population figures with the projected per capita energy consumption figures of Figure 6 yields a group of global energy demand curves.

The lowest curve in Figure 7 projects the demand for a basically zero growth on the level of the individual. Still the global consumption of 7.6 TW in 1975 would double within the next 40 years, leveling off at 24 TW, three times the present value, around 2100. The two upper curves in Figure 7 differ mainly in the growth rates in the near-term future; the curve starting with 4.5%/a growth will approach the target value of 5 kW(th)/cap around 2030, the curve with a 3.0%/a growth rate would need 30 years more. The asymptotic energy consumption would be 64 TW, that is approximately eight times the present value.

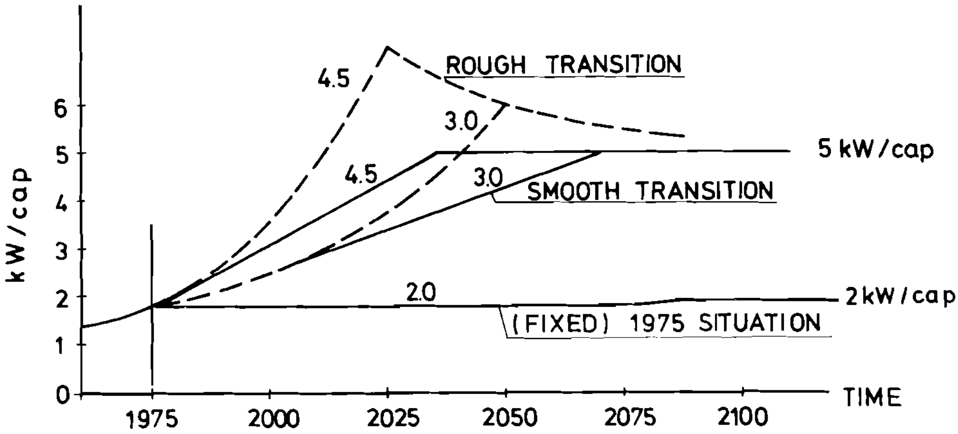

Figure 6. Projected per capita energy consumption (world average) (After: UN Population Projections, March 1974).

SUMMARY AND CONCLUSIONS

Let me summarize where we stand. From investigation of the energy economies in a variety of countries we have concluded that one single economic and technologic life style is diffusing, and that energy consumption is a factor that closely correlates with the level of economic development. Based on the assumption that this diffusion process will continue, 5 kW(th)/cap and 2 kW(th)/cap were chosen as asymptotic energy consumption levels to illustrate two alternative economic developments, the lower serving mainly as a reference case. With the aid of population projections and some very general assumptions on a smooth transition from today's consumption figures to a zero-growth situation, the development of the global energy demand was derived.

How confident can we be in using such forecasts? The largest factor of uncertainty within this scenario is the degree of economic development the third world will try to achieve in the long run. This is directly linked with the uncertainty in the projection of the world population figures. A second important factor of uncertainty would be introduced by a technologically split development, e.g. the use of non-resource-constrained primary energies at the expense of high capital expenditures--a solution that might be accessible only for a limited number of highly developed countries.

As the main focus of our work is directed towards the next 15 to 50 years, the uncertainties just mentioned will not have too much influence on the overall development. The scenario should therefore provide a useful tool to check a variety of possible energy supply strategies.

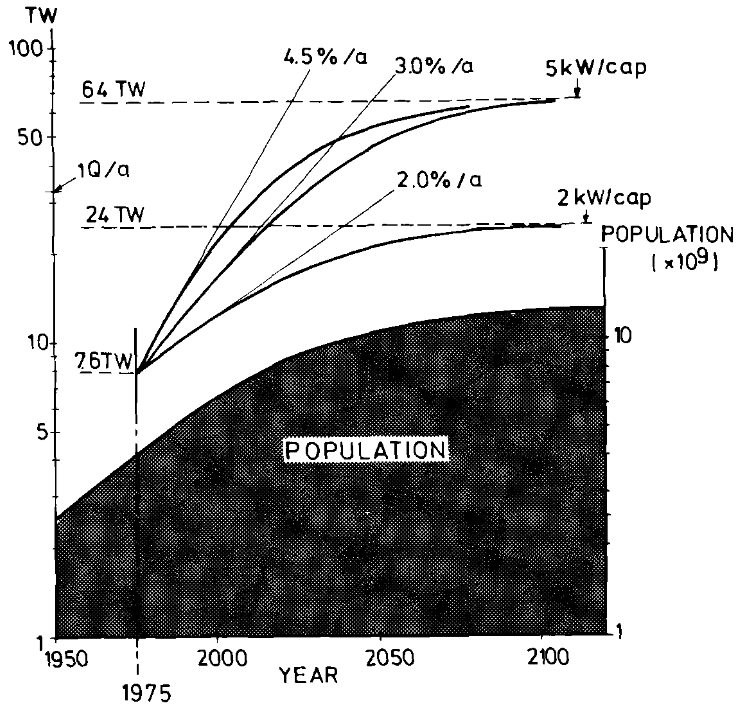

Figure 7. Global energy scenarios.

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Part 4: OPTIONS FOR ENERGY SUPPLY

PART 4. OPTIONS FOR ENERGY SUPPLY

4.1 Solar Energy Systems Consideration

Charles R. Bell

SOLAR ENERGY CONVERSION

The search for a practical method to harness solar energy is gaining momentum as the concerns for the availability of fossil fuels and their impact on environment increase. The need to find timely applications of solar energy, without greatly disturbing the economy and ecology, stipulates careful assessment of solar technology, as well as development of methodology for objective evaluation of solar options with respect to various geographic locations.

A "solar option" is viewed as a solar energy conversion system, capable of transforming sunlight into useful forms of energy, such as heat, shaft horsepower, electricity and synthetic fuels. The two principal categories of solar energy conversion systems are:

a) Indirect conversion via the biosphere (winds, waves, thermal gradients of the oceans, etc.), followed by conversion with man-made machines (windmills, wave-motion rectifiers, ocean-thermal systems, etc.);

b) Direct conversion via thermal collectors, producing heat and/or electricity (e.g., heating water and/or producing steam for turbo-generators), or via photovoltaic cells, producing electricity directly.

The solar energy project at IIASA has initially concentrated on the systems study of direct conversion of solar energy to heat (concentration and absorption) and on a variety of thermodynamic pathways for production of electricity, because these do not require major technological advances and thus offer an earlier application potential for large-scale systems. Photovoltaic (solar cells) concepts were also considered because of their long-term potential. Some significant advances in the development of solar cells mass production are conceivable within a decade; this would permit production of relatively low cost, fully encapsulated arrays which could revolutionalize direct conversion of solar energy into electricity.

The solar insolation (energy input) on the (inhabited) surface of the earth averages from 700 $kWh/m^2 \cdot a$ (e.g., in parts of Northern Europe), to 2300 kWh/m^2·a (e.g., in some desert regions of Africa, and South-west U.S.A.). The overall efficiencies of the evaluated solar options for producing electricity range from about 7 percent (flat plate collectors) to about 22 percent (heliostats and central tower receiver). Design optimizations and improved working fluids for heat transmission may produce some improvements in overall efficiencies. However, the major problems in solar energy conversion evaluation are the differences in fractions of clear sky radiation (sunny days/cloudy days), which for current practical considerations range from about 0.4 (e.g., in parts of Northern Europe) to about 0.8 or better in some desert regions of Africa, Asia and South-west U.S.A. These differences, and the variations of monthly insolation averages, require that the solar options must be carefully optimized for the detailed insolation condition of the locations under consideration, as well as for land availability, materials production, environmental impact and economic considerations.

SOLAR ENERGY PROJECTS AT IIASA

The prime issue is the development of a (periodically) validated data base and methodology concept to permit timely evaluation of potential solar options for desired locations, including all the necessary technical, environmental, social and economic aspects. This will provide quantitative and qualitative information for decision-makers dealing with solar energy utilization potential. To approach this objective, the solar energy project at IIASA is conducting the following studies:

a) Acquisition and delineation of solar insolation data;

b) State-of-the-art review of solar technology and projections thereof;

c) Identification of solar energy conversion systems for short-, mid-, and long-term utilization potential, including derivation of potential energy mix concepts;

d) Identification of technological, material, environmental, social and economic constraints for principal solar options;

e) Delineation of possible strategies for gradual introduction of large-scale solar energy utilization; solar embedding studies; and

f) Organization of workshops, seminars and conferences for acquisition, exchange and validation of solar technology and related data.

These studies are receiving cooperative assistance from other groups within the IIASA Energy organization, and from all IIASA scientific staff, as needed. The projects evolving from the solar energy conversion studies are:

a) Austrian case study (solar-electric), identifying areas of adequate solar insolation for large-scale conversion of solar energy and all the related technology assessment issues;

b) Proposal for large-scale solar energy utilization in F.R.G. (contract award pending early in 1976);

c) Development of cooperative solar evaluation methodology programs and regional case studies with IIASA member countries: Austria, Bulgaria, France, the F.R.G., the G.D.R. and the U.S.A., as well as with the Commission of the European Communities, Brussels. It is anticipated that other member countries will join during 1976.

SOLAR ENERGY TECHNOLOGY REVIEW

Continuing data acquisition and validation process has created information resources on a global scale and established working relations with key institutions. IIASA library has made valuable contributions to this effort. While a reasonable preliminary data base has been established, the variations of data on many critical subjects indicate a need to dedicate more resources to the validation of the acquired data, and to the establishment of the relationship between the theoretical, experimental and operational values.

Contemporary emphasis on solar-thermal and solar-photovoltaic systems produced identification of crucial system considerations, relating technological and economic parameters. A typical example of this effort is a comparison of solar energy conversion systems at 100 MW(e) (day time) level without energy storage, using a composite of 1973/75 estimates, normalized to 1975 U.S. dollars (Table 1). In this sample case, the data are adjusted to location with solar energy (insolation) of about 2,000 $kWh/m^2 \cdot a$ (average 5.47 $kWh/m^2 \cdot d$). In the absence of energy storage capacity, such systems are envisioned as complementary facilities for heat and/or electricity producing plants (for information on hybrid concepts, see section four). The economic estimates in Table 1 are based on 10 percent interest rates and 20-year amortization periods. The energy cost estimates are given in mills (1 mill = $ 0.001) of 1975 U.S. dollars. Application of lower interest rates and longer pay-back time scales would yield lower energy cost. The table identifies overall efficiencies from 7 percent (flat plate collector)[1] to 22 percent (heliostats and central receiver),

[1]Low efficiencies for production of electricity; for production of low grade heat, the efficiency may reach 60 percent.

Table 1. Comparison of solar energy conversion systems ~ 100 MW(e)[a] without energy storage.

Composite of estimates, 1975 U.S.$
(direct capital cost)

Parameters \ Collectors	Flat Plate (Non-Tracking)	2-D Trough	Paraboloidal Dish	Heliostats & Central Receiver	Photovoltaic Arrays (Non-Tracking)
Collector ~ \$/kW(e)	1,525	920	650	600	1,100
Receiver ~ \$/kW(e)	-	280	50	170	-
Energy Transport ~ \$/kW(e)	180	250	150	50	80
Power Conversion ~ \$/kW(e)	260	200	200	160	100
Other ~ \$/kW(e)	100	100	100	100	150
Estimated Total ~ \$/kW(e)	2,065	1,750	1,150	1,080	1,430
Plant Load Factor ~	0.20	0.25	0.28	0.28	0.33
Overall Efficiency ~	0.07	0.15	0.20	0.22	0.10
Availability ~	1,977	1,980	1,980	1,980	1,985
Energy Cost, mills/kWh ~ (incl. operations & maintenance est. and 2,000 hrs/yr) ~2,000 kWh/m^2•a location	137	93	55	51	58

[a]Daytime only.

which for the given insolation levels would result in power output averages from 0.38 $kWh/m^2 \cdot d$ to 1.20 $kWh/m^2 \cdot d$. The Austrian case study (in section six) offers a nomograph illustrating the many interrelated parameters and their influence on economic evaluations.

The technology assessment reviews at IIASA are yielding representative data on siting, embedding and institutional constraints. These will be processed and reduced to support the development of a solar energy utilization methodology program to be used eventually as a decision-making tool.

SYSTEMS ASPECTS AND OPTIONS

The systems aspects studies provided first an approximation of solar energy conversion criteria in general. Austrian case study data, developed subsequently (~1,000 to 1,200 $kWh/m^2 \cdot a$), and the conversion criteria were then contrasted with economic scenarios, defined by interest rates from 2 to 12 percent, and by oil prices from \$2/bbl to \$15/bbl. Payback time periods up to 30 years were considered (see Figure 3).

Initially, hybrid systems were considered, using heliostats with central receiver tower concept. These are envisioned in connection with conventional power plants, without energy storage capacity. Such systems would use steam produced by the solar energy conversion during the sunny days, thus saving significant amounts of fuel. Studies are in progress for specific (siting) locations.

The next step is a comparative evaluation of the major solar options, with energy inputs subject to insolation variations and different siting conditions. An example of the four principal options and their approximations is shown in Table 2. Depending upon the requirements, these options may operate parallel to conventional facilities (saving fuels), without energy storage requirements. Integration of energy storage capacities for facilitating energy supply during time periods without sunshine necessitates corresponding increases in collector areas. This may range from a few hours storage time (to overcome effects of clouds) to a full 24-hour cycle and beyond. The system aspects are also influenced by reliability estimates, operations and maintenance (O&M) estimates, and numerous other criteria. Most up-to-date data use favorable insolation locations (~2,000 to 2,300 $kWh/m^2 \cdot a$) and some energy storage capabilities, as shown in Figure 1.

Table 2. Major solar options--typical applications.

Solar Options	Overall Conversion Efficiencies (System)	Temperatures (Conversion Phase)	Collector Areas[a)] Moderate Insolation Region: $m^2/kWh(e) \cdot d$ ($3kWh/m^2 \cdot d$ Solar Input)	High Insolation Region: $m^2/kWh(e) \cdot d$ ($6kWh/m^2 \cdot d$ Solar Input)
Low-Grade Heat (Heating)	0.40-0.60	Below 100°C	Residential and communal heating versions	Heating, air conditioning and industrial process heat versions
Solar-Thermal-Electric	0.15-0.22	Near 500°C +	~ 1.8	~ 0.9
Solar-Thermal-Fuel (H_2 via Electrolysis)	0.20-0.30	Near 2,000°C+	~ 1.4	~ 0.7
Photovoltaic and/or Fuel (H_2)	0.08-0.12	Near ambient	~ 3.4	~ 1.7

a) Sunny days operation; eight hours/day average; note collector concepts in Table 1.

The energy storage concepts will be evaluated during the 1976/77 time period, with emphasis on data validation. Typical estimated values (Table 3) provide some visibility of the state-of-the-art. Actual energy storage cost estimates will be based on the "$/kW + (storage time t required) x $/kWh" expression. Data validation will be conducted during 1976/77 time period, before such estimates can be used in econometric projections.

Recognizing the importance of siting selection for large-scale solar energy conversion facilities, we are developing a siting methodology. The siting categories are currently envisioned in three groups:

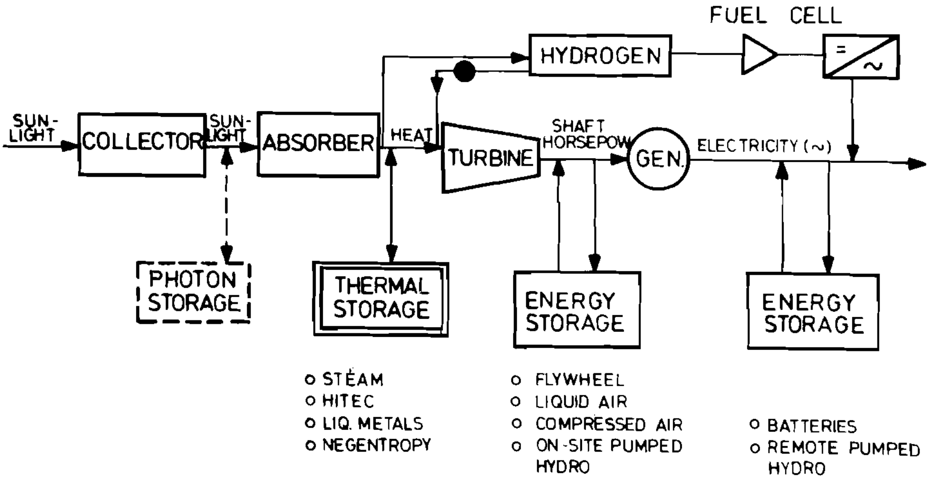

Figure 1. Solar thermal electric conversion–some storage options.

Table 3. Efficiency and cost estimates of energy storage systems.

Energy Storage Concept	Efficiency ~	~ Capital Cost (1975) $/kW + (t)[a] $/kWh	
Pumped Water	0.70	75	9
H_2 Electrolysis	0.60	225	6
Flywheels (composite materials)	0.90	40	58
Compressed Air	0.75	95	12
Batteries, Lead Acid	0.75	90	30

[a] t = energy storage time required.

1) Locations suitable for development of residential and communal heating systems, without energy storage capabilities, using existing technology (relatively low insolation levels, but above 700 kWh/m^2·a);

2) Locations for large-scale hybrid facilities (conventional power plant with auxiliary solar system), without energy storage, using some new technology, but without requirements for major advances (moderate insolation levels, near or above 1,000 kWh/m^2·a); and

3) Locations for large-scale solar energy conversion facilities, with energy storage capabilities, using advanced technology for major subsystems (high insolation levels, near or above 2,000 kWh/m^2·a).

The large-scale facilities in areas of high insolation can also be used for hydrogen production, if the "hydrogen economy" concept gains acceptance. The diagram for siting methodology offers an overview of the parameters used for the siting methodology model (Figure 2).

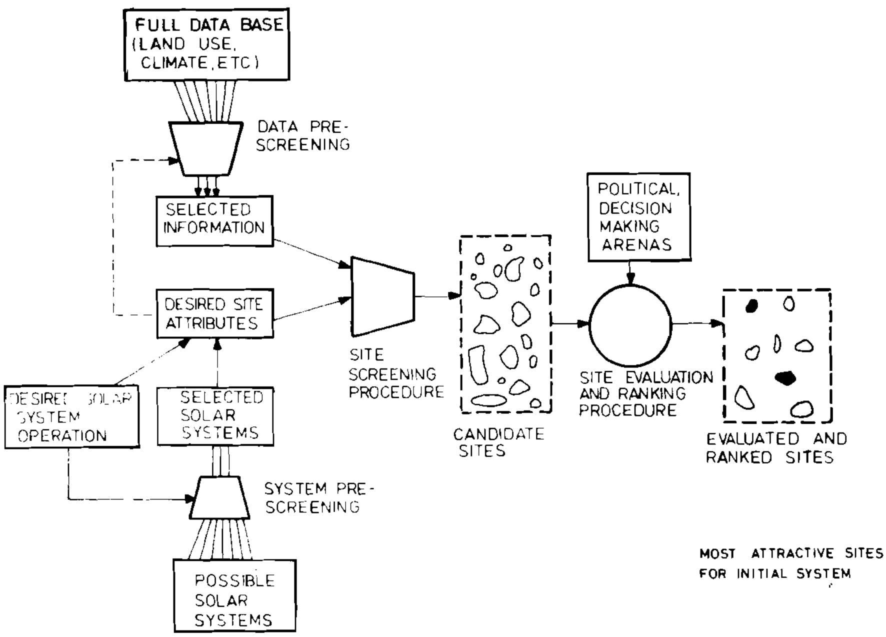

Figure 2. Solar energy conversion facility, siting methodology.

Among the essential considerations for siting are the suitability for energy storage system, where required, and a favorable incline of the collectors' field area to minimize both shadowing effects and subsequent energy collection losses during the early and late hours of solar exposure (use of topographic features of the site). This incline also helps to minimize excessive spacing of the collectors, otherwise often needed to decrease the effects of shadowing.

SOLAR ENERGY EMBEDDING

Development of constructive strategies for gradual introduction of solar options into the economic and industrial mainstream is an essential part of the methodology studies at IIASA. At present, five categories of tasks are studied to provide logical structure for the strategies under the all-encompassing term of "solar energy embedding":

1) Benefit-cost analysis, including supply and demand models and potential impact areas;

2) Multiobjective planning methods and trade-off analysis scenarios;

3) Reliability derivations for system's hardware and for insolation predictability (correlation of supply and demand and projection of trends);

4) Facility siting model integrating environmental, societal and economic trends; and

5) Integration model with existing utilities and relatable networks.

Extensive data acquisition for these tasks is in progress, and a suitable data bank is under consideration. The subject of "Energy Systems Embedding" has been discussed by J. Gros in this Report.

AUSTRIAN CASE STUDY

A comprehensive report "Austria-Economy of Solar Energy Utilization: A Case Study Example for Hybrid Power Plants" was completed[2]. The nomograph constructed for this work (Figure 3) provides an illustrative composite of insolation (solar energy input, $kWh/m^2 \cdot a$), heliostats and central receiver cost ($\$/m^2$), cost of oil (\$2/bbl to \$15/bbl), and interest rates, so that a rapid, preliminary assessment of key parameters can be made.

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[2]This is discussed in detail by N. Weyss in this Report.

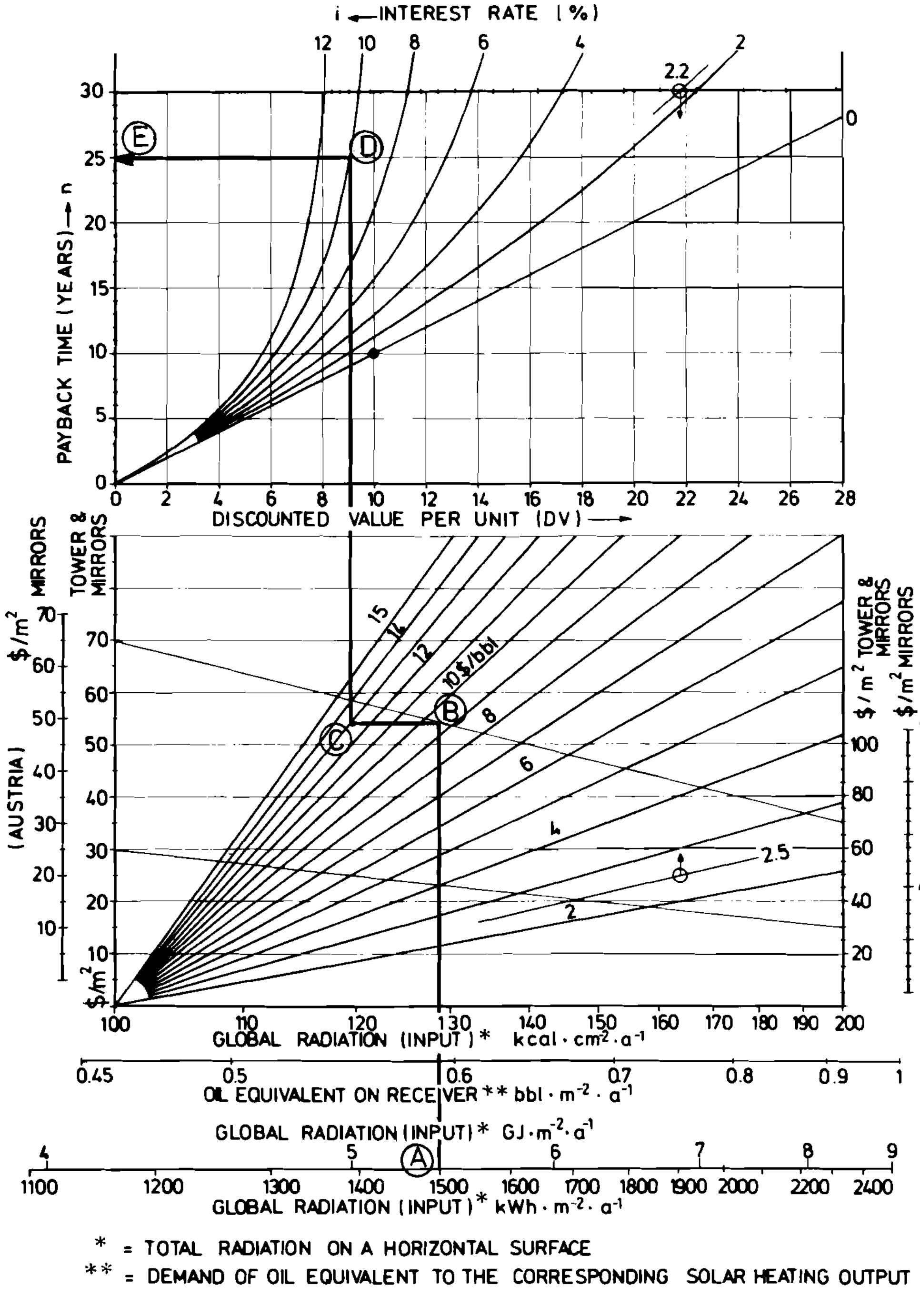

Figure 3. Economic evaluation of solar power plants in hybrid configuration: heliostats (mirrors) with central tower receiver.

The use of the nomograph reaches over the entire practical spectrum of solar energy inputs (from 1,100 kWh/$m^2 \cdot a$ to 2,500 kWh/$m^2 \cdot a$), given also in GJ/$m^{-2} \cdot {}^{-1}$ (GJ/m^2 per year), and kcal/$cm^{-2} \cdot a^{-1}$ (kcal/cm^2 per year) scales, as well as in the equivalent amount of oil in bbl/$m^{-2} \cdot {}^{-1}$ (barrels of oil/m^2 per year). For example, favorable feasibility potential is obtained from a hybrid plant with heliostats and a central receiver tower in a location with a measured solar energy input of 1,500 kWh/$m^2 \cdot a$ (near 128 kcal/cm^2 per year) and an estimated cost of \$70/m^2 (the maximum cost we have found in current literature) for the solar energy conversion system (a vertical line from A to B in Figure 3), a scenario tested with \$13/bbl oil prices (B-C in Figure 3) and 10 percent interest rate (C-D in Figure 3). The payback time estimate indicated in Figure 3 (D-E) shows 25 years for this example. Obviously, the same nomograph can be used to evaluate the impact of each of the parameters used.

Currently, efforts are continuing to broaden the application of such nomographs for evaluating other solar options, and for integrating all parameters involved in advanced methodology for applied systems analysis in the solar energy application projections.

SOLAR ENERGY AND DEVELOPING COUNTRIES

It is apparent that numerous developing countries will have favorable conditions for using solar energy. Current trends in the industrialized countries indicate that a variety of suitable hardware may be developed and standardized within a decade, which would facilitate an effective introduction of large-scale solar energy systems in the developing countries. Current plans of the solar energy project at IIASA include broadening solar option studies for global applications. This will require an intensified acquisition and development process of solar insolation data, as well as a continuing up-date and validation of solar technology information. The 1976/77 time period is viewed as a potentially decisive phase for realistic projection of solar energy options within the overall efforts to secure continuing energy supply for the future.

4.2 Some Aspects of the Solar Case Study Austria Illustrated by the Example of Hybrid Power Plants

Norbert Weyss

At present, there is no suitable cursory methodology for rapid determination of economy for solar energy plants that would be convenient for practical evaluation of decision processes in Central European planning. Assuming a hybrid power plant operated by fossil fuel (when solar energy is not available) or by solar energy (when solar insolation is adequate), it is possible, with emphasis on relatively few key parameters, to construct a simplified methodology that permits economic feasibility evaluation of solar energy augmented power plants.

The two most recognized methods for converting solar energy into electrical energy are: (1) direct solar energy conversion by photovoltaic cells; and (2) indirect solar energy conversion in thermal power plants by steam produced by solar heat (or by pre-heating water by solar heat).

Direct conversion utilizing solar (photovoltaic) cells was advanced by aerospace technology; it is used to provide space vehicles with electrical energy. For the terrestrial conversion, possibly with higher performance levels, such technology is not cost effective at this time. However, there are numerous developments in progress to substantially reduce the cost of the photovoltaic arrays.

At present, the indirect conversion of solar energy is applicable to large-scale production of electricity in thermal power plants. On a sufficiently large area of land, the solar insolation (energy input) can be arranged through suitably positioned mirrors (heliostats). Each mirror must be tracted to follow the sun's position; as a result the mirror concentrates solar energy to an absorbing receiver, located on top of a central tower (Figure 1). Working fluid--for example steam with an adequate temperature of say, 540^{o}C and a pressure of 180 bar--can be produced in this receiver, which is equipped with a single- or double-loop system to produce steam for a conventional turbo-generator facility.

The following discussion deals with a hybrid thermal power plant which can alternately utilize fossil fuels (during the time periods when solar energy is not available), or solar energy for heating the working fluid (production of steam) to yield favorable cost effectiveness of the power plant operation. The hybrid operation for meeting the base-load requirements has the advantage that the frequently posed

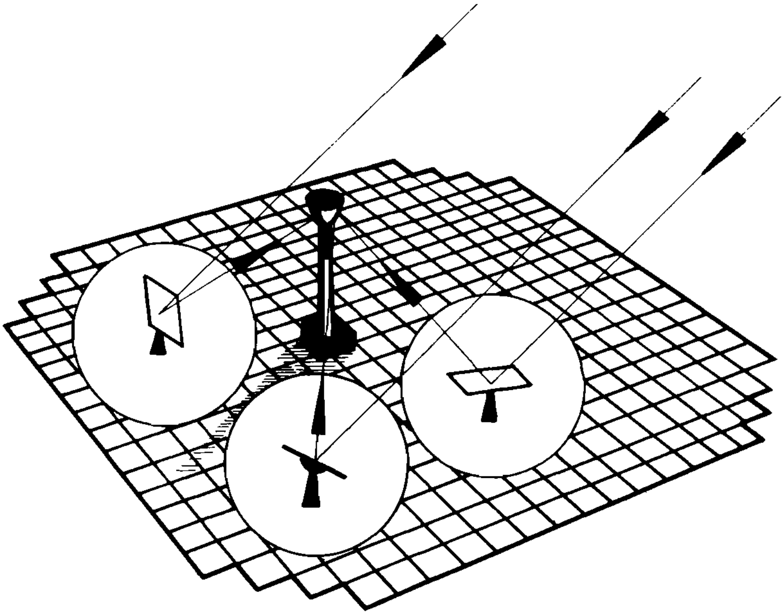

Figure 1. Solar energy conversion power plant – heliostats with central receiver tower (schematic only – not to scale).

questions of energy storage need not be considered. In Austria, for example, a solar energy utilizing hybrid plant producing about 8,000 hours per year with a nominal performance rating of 50 MW(e) (and substantial energy storage facility such as pumped-up water), would require a surface area of about 5.2 km^2 [1]. A power plant utilizing only the available solar insolation (sunny periods with about 2,000 hours per year) with an intermittent 50 MW(e) performance during periods of sunshine (and moderate internal energy storage) would require only 1.3 km^2. Proposals and plans for the central tower solar energy conversion facilities are available, for example, in the U.S.A. and in France; in France a 25 MW(e) size is available [2].

Of special interest is the utilization of hybrid (solar energy with conventional) power plants in the Central European environment. In the climatic environment of Austria, a multitude of major and minor problems have to be resolved before this concept can be applied on a large scale. For example, there is a difference between the supply of electricity obtained by conversion of solar energy, and that supplied by conventional power plants, to adequately meet the short- and long-term electricity demand predictions.

Another important consideration is the integration of solar energy utilizing power plants in the existing electricity network. The energy of one or of several such solar plants can be received by existing networks without special additional facilities, and can be distributed further to the users provided the solar energy contribution is within the spectrum of the current, identifiable demand fluctuations. Within this spectrum, which in Austria is about 500 MW(e), the electricity produced by solar energy may be considered a "negative consumption" in the network. Increased solar energy contributions would be acceptable either in appropriately larger interconnected networks or, where available, in annual energy storage facilities utilizing solar energy powered-pumping for balancing electricity supply and demand. The available and the projected annual energy storage facilities would facilitate considerably the storage of solar energy for cloudy weather time periods. Higher contributions of solar energy are envisioned as a result of higher energy storage capacities, as for example, from elevated altitude valleys that are functional in normal precipitation run-off, and from underground natural storage spaces that may be developed for implementating hydrogen economy [3].

Another decisive factor is the size of future solar power plant units. While their optimum performance levels are below the maximum of nuclear power plants, they do permit more accurate fitting to a variable growth rate of energy expansion demands. Several small-scale solar power plants in various climatic areas would offer the known advantage of conventional hydro-electric plants, namely a higher system reliability as compared to power-plants concentrated in only one geographical area. In addition, the construction of such facilities in the vicinity of users is permissible, thus minimizing the electricity transmission losses. It is obvious that a broad evaluation of a number of parameters has to be considered, the most important being the capital investment for the solar power conversion system. This encompasses the cost for the given structure, the projected inflation rates during the construction time period, and the influence of future mass production of components, e.g., mirrors (heliostats). The seasonal distribution of solar insolation values at the site under consideration for a pilot plant in an area with optimum insolation in summer is certainly of a different profile than that for an operating facility with optimum capability in winter time. A method that permits determination of an effective value of such solar power plants in a given network can be based on the "cost/benefit" comparison of the provision of the energy system by purely solar means, and the best alternative energy option. A significant computation effort is required that would consider a large amount of parametric data and accommodate a multitude of interdependent elements with changing parameters. An additional consideration is the number of unknowns involved in the decision process (e.g., the method of network structuring, the selection of site, availability of materials, impact of public opinion, labor market).

Economic aspects can be considered only after a solar energy conversion facility is integrated within a conventional power plant as a hybrid-base-load operation concept. The base-load requirement means a constant supply of electricity during operating periods, which exceeds significantly the annual availability of solar insolation. Hybrid power plant system means that as long as there is adequate solar insolation (that is, sunshine) the steam is produced by converting solar energy (or the water is merely pre-heated in cases where sufficiently high temperatures cannot be produced); when this conversion is not adequate, the fossil fuel is used to provide the necessary heat. Thus a secure operating performance is assured without an added energy storage requirement, and there is no special requirement of flexibility of the receiving network. As a result, there are significant savings of fossil fuels.

Figure 2 illustrates a possible arrangement of a hybrid thermal power plant, showing the principal sub-systems and general arrangements of this facility with a nominal performance of about 50 MW(e). Figure 3 provides an overview of the operating cycles of a hybrid thermal power plant with both solar and fossil fuel operation cycles.

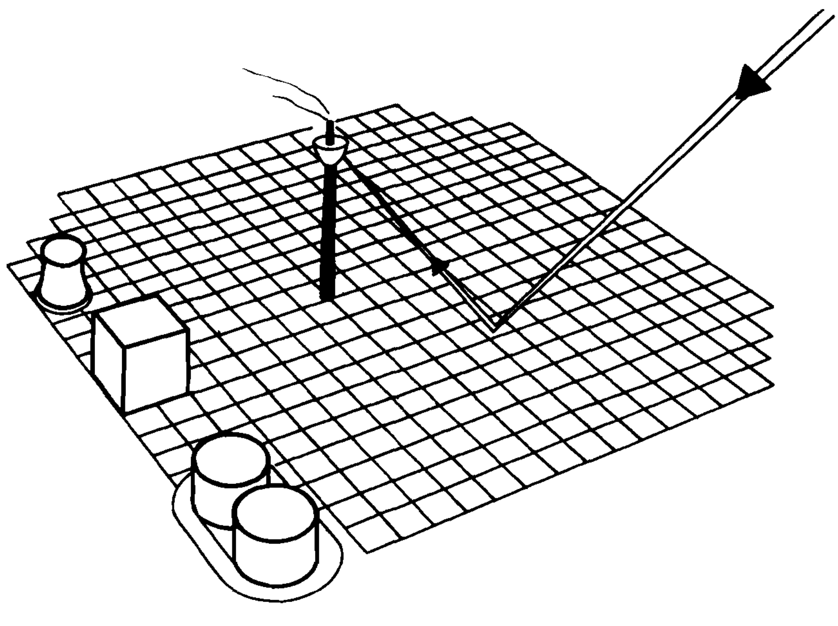

Figure 2. Hybrid power plant facility combining fossil fueled plant with solar plant (schematic only – not to scale).

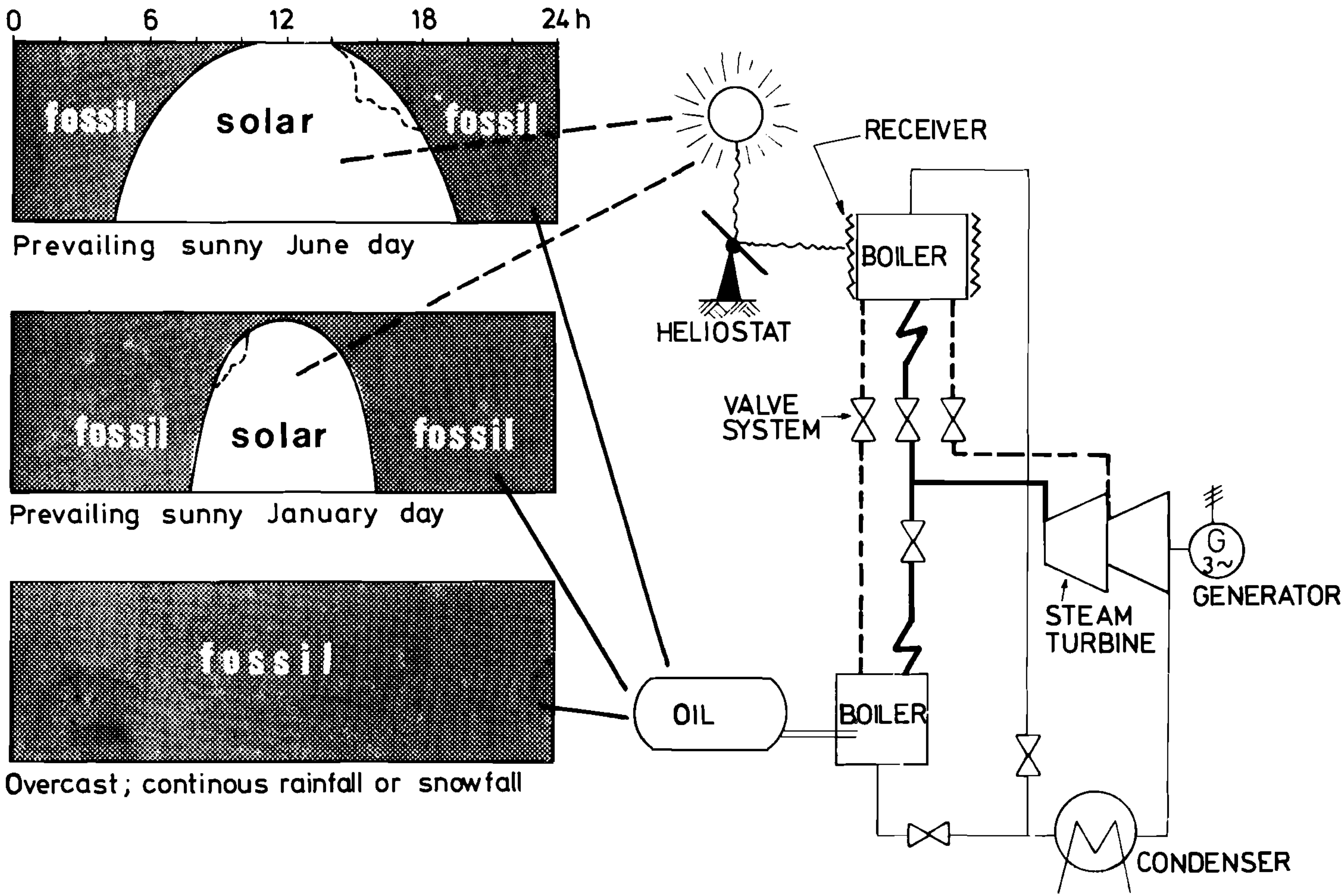

Figure 3. Operation of a hybrid power plant.

When the production of electrical energy (by the conversion of solar energy) offers an economic incentive, it must be determined to what degree the application of the solar-specific plant components decrease the total investment for the hybrid thermal power plant vis-a-vis a pure fossil power station.

Depending upon the repayment modes for the investment (capitalization) for the solar conversion facility, various repayment time periods (n-years) for the various modes are required. If the repayment period for the solar conversion part of the investment is, for example, 30 years and reflects an annuity with a specific interest base (i) in relation to the saved amount of fossil fuels in the 30-year period, then the generating cost per kilowatt hour of the solar facility is the same as that for the fossil fuel operated plant. However, the repayment period may be shorter, for example 10 years, and may have a sufficiently low interest rate, with the annuities equaling the annual cost of the saved fuel up to 10 years; in the remaining 20 years the comparable amount of oil (or equivalent) can be saved. Thus the solar energy conversion part of the power plant that operates without costs for fuel and for kilowatt hour during this 20-year period would be significantly lower. For the national economy, it is important that a significant amount of fuel be saved in all the (hybrid) operating years.

These calculations contain some speculative variables. Of primary importance are the price of oil, and the cost of the heliostats (tract mirrors) together with the cost of supporting structures and system components, the solar insolation values (that is, the solar energy inputs) and the interest rates. The cost estimates for a central tower with the heat absorbing receiver can be derived from similar related structures (television transmitter towers, sight-seeing towers, etc.). In a hybrid facility, a tower of this kind can act also as a smoke stack for the conventional part of the plant. In view of the multi-purpose utilization of the tower, it appears that for the first approximation the added cost estimates for the receiver on top of the tower can be neglected in the average (mirror) collector area cost estimates. The input data are treated as variables; the data give future projections and can be set at levels reflecting the chosen scenarios.

These relationships are shown in the nomograph in Figure 4 where the number of equally large annuities for the repayment with interest of the solar part of the power plant are equivalent to the resulting savings of fuel oil (or other fossil fuels of equal cost per heating unit). The mathematical relationships were shown in a study dealing with the potential role of solar energy conversion for producing electricity in Austria [5]. The nomograph consists of two interrelated graphs. The solar insolation values and their oil equivalents (increasing from left to right) are shown on the horizontal scale of the lower graph. Vertical scales on both sides of the lower graph express the cost of the solar energy conversion components of

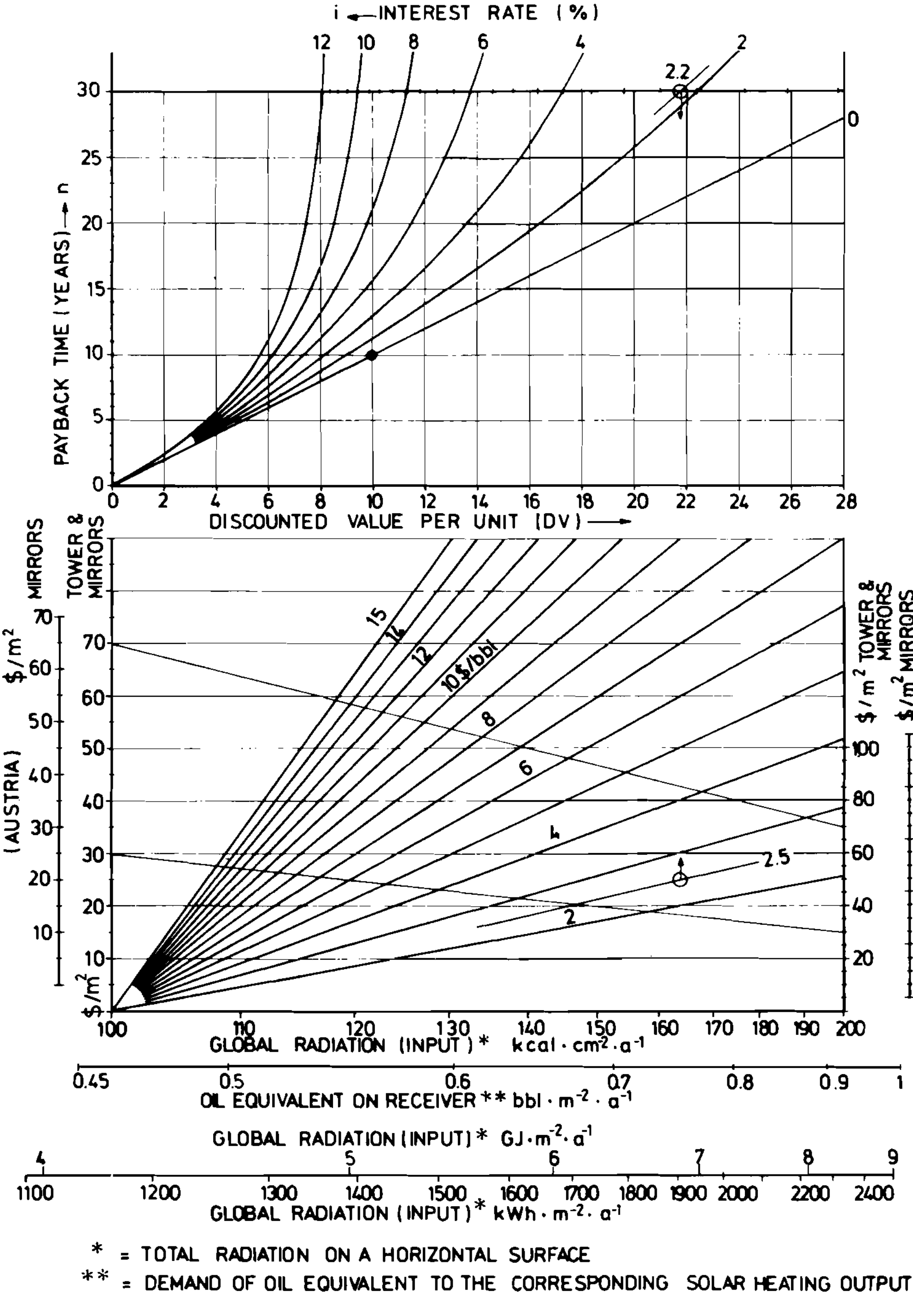

Figure 4. Solar energy conversion economy (parametric relationships).

the plant combined in terms of mirror (heliostat) area cost. The orientation of these scales, ranging from left to right, corresponds to the geographic location of plant sitings, relatable to their annual cumulative solar insolation values (horizontal scale). That is, in this graph the scale values on the left represent solar insolation values (energy input data) for siting in Austria, for example in Burgenland (the area of which is equivalent to the area of Boston, Massachusetts), while the right end of the horizontal scale shows the near optimum solar insolation values (energy input) for the desert locations in the Southwest U.S.A. (e.g. Inyokern, California). There are two vertical scales for each of the sitings. One represents specifically the cost of heliostats in terms of the mirror area, derived from the estimates of U.S. programs [6] for complete heliostats (including support structure, drive and mirror) with an average cost estimate of $\$45/m^2$ (1974 dollars); on the adjacent parallel vertical scale, this corresponds to $\$50/m^2$ which is also based on the mirror surface incremental cost of the entire system, including the central tower. This second scale represents the composite cost of all the solar-specific power plant components--that is, the complete heliostat system with the structures, sun tracking system, and the central tower or towers with the energy absorber and conversion system (but not the conventional power station facility). The distributed cost increment for the tower estimated for Austria, as well as for the U.S.A., is $\$5/m^2$ heliostat (mirror surface) for the given approximations, and is viewed independent of the magnitude of solar insolation.

The lower graph shows the solar power plant system together with the oil market trends, expressed in a cluster of lines as the cost of oil per barrel ($2/bbl to $15/bbl). If we draw a line along the cost estimate of $\$45/m^2$ ($\$50/m^2$ respectively) on the left pair of scales of the nomograph toward the right, moving up to the cross-section with the $10 per barrel oil line, we note that the vertical line points to between $10 and $12 on the horizontal scale (accurately 10.9) of discounted unit value. In the upper graph, the finance market is illustrated by a family of curves representing the interest rates (i). Also, if we observe the vertical line through the 10.9, reading up to the cross-section with a given interest line, for example 6 percent, we note that a payback time of 18 years (during which the annuity is equal to the cost of saved fuel oil) can be evaluated. This indicates (in the case of the usual power plant life of 30 years) that another 12 operational years could be realized after payment has been made for the solar part of the facility, thus yielding a significant period of operating time without the use of fuel oil. Similar evaluations can be obtained for power plants utilizing fossil fuels other than oil as long as their heating unit cost is equivalent to that of oil for a given time period.

The construction of the nomograph is such that the horizontal scale between the two graphs, identified as discounted value per unit, is applicable for both figures. These values reflect, for instance, the debt as related to annuities at various levels of interest for different payback times, and relate to the cash value of the realizable annuities.

On the basis of Figure 4, an evaluation can be made of the influence of each of the five principal parameters. For example, it is possible to evaluate the economic feasibility of added solar energy conversion facility based on the repayment time period, with the objective of estimating the acceptable heliostat (mirror) and solar system cost. It is also possible to evaluate the influence of oil costs variations (or of other equivalent fuels) on the power plant economy attainable with the utilization of solar energy conversion.

Before giving further examples of the use of the nomograph, I should like to show how a selection of a site for a solar plant affects the obtainable solar energy and the related performance of the selected solar energy power plant. The basis is the actual measured annual solar insolation at the location. On the left of the horizontal scale of the bottom graph (Austria and/or Boston locations), the obtainable average solar insolation is 100 Kcal/cm^2 per year; on the right of the horizontal scale is the chosen favorable location in the U.S.A. (for example Inyokern, California) yielding about 200 Kcal/cm^2 per year. The approximate values in between, for instance 140 Kcal/cm^2, correspond to locations such as Madrid (Spain) or Varna (Bulgaria); these are viewed as applicable for the sample cases. In the bottom graph there are two sloping lines connecting the left vertical scale (for systems in low insolation locations) with the right vertical scale (for systems in high insolation locations). The upper line represents the solar system cost of about \$70/m^2, while the lower represents \$30/m^2; this shows the spectrum of envisioned heliostat (mirror) cost (1974 U.S. dollars), within which all the practically considered sample cases may fit. For example, the cost estimate for mirror-surfaces for the Madrid location would be \$65/m^2 corresponding to the specific solar system cost of \$70/m^2, which is translatable by the connecting line reaching from \$70/m^2 on the left side scale of Figure 4 to \$70/m^2 on the right side with its intersecting vertical line from 140 Kcal/cm^2 (value for Madrid). This is accomplished by moving horizontally along the line connecting 50 on the left vertical scale to 100 on the right vertical scale, to the \$10/bbl) oil cost line. From this intersection we can make a vertical projection to the horizontal scale of the upper graph, showing the same value of 10.9 as a discounted unit value and the same payback time estimate for the six percent interest rate as in the previous sample case[1]. Other regionally applicable cost estimates for the specific solar systems can be evaluated by determining the probable values on the left vertical scale of the bottom graph and their equivalent on the right vertical scale--for example $40/m^2 on the left scale connected with $40/m^2 on the right scale. From the cross-section of the sloped line (not shown), with the vertical projection of the regional solar insolation value, a horizontal line is drawn to that line expressing the cost of oil (or of fuel of equivalent cost per same heating unit); this determines the point from which the vertical projection to the upper graph is made.

The equivalents of solar insolation for any location (siting) are expressed in various terms of solar energy input values below the horizontal scale of the bottom graph. For example, it can be shown that annual input of 172 Kcal/cm$^2 \cdot$a equals 7.2GJ per square meter per year (7.2 GJ/m$^2 \cdot$a); this is equal to 2,000 kilowatt-hours per square meter per year (2,000 kWh/m$^2 \cdot$a). In terms of oil, this approximates the energy of about 0.8 barrels of oil per square meter (mirror) per year (0.8 bbl/m$^2 \cdot$a), when the usual values of enthalpy and density of oil are used; likewise, it can be used to determine the solar/thermal conversion efficiency in relation to the solar insolation values. The range of the nomograph is from 0.46/bbl/m$^2 \cdot$a (Austria) to 0.92 bbl/m$^2 \cdot$a (Inyokern, California). This range can be easily broadened if necessary. The results are essentially related to the ratio of:

$$\frac{\text{the cost of the specific solar power plant system}}{\text{the cost of oil.}}$$

This means that the long-term projections of increasing oil prices and other inflationary influences cannot substantially affect the graphical readouts, if we consider that an increase in the cost of oil over a short or long period causes cost increases of constructing materials (steel, concrete, etc.) and of other fuels.

The effects of the oil situation on the economy of solar energy conversion can be shown with the use of the nomograph. Figure 5 illustrates that with the prevailing oil price of $2.50 a barrel (prior to 1973), even the most suitable locations for siting of solar plants in the U.S.A. would not have been economically rewarding. With an average mirror (heliostat) cost of $45/m^2, an interest rate of 2.2 percent would have to be obtained to achieve an acceptable financing potential within a desired system-life of 30 years. However, with the cost

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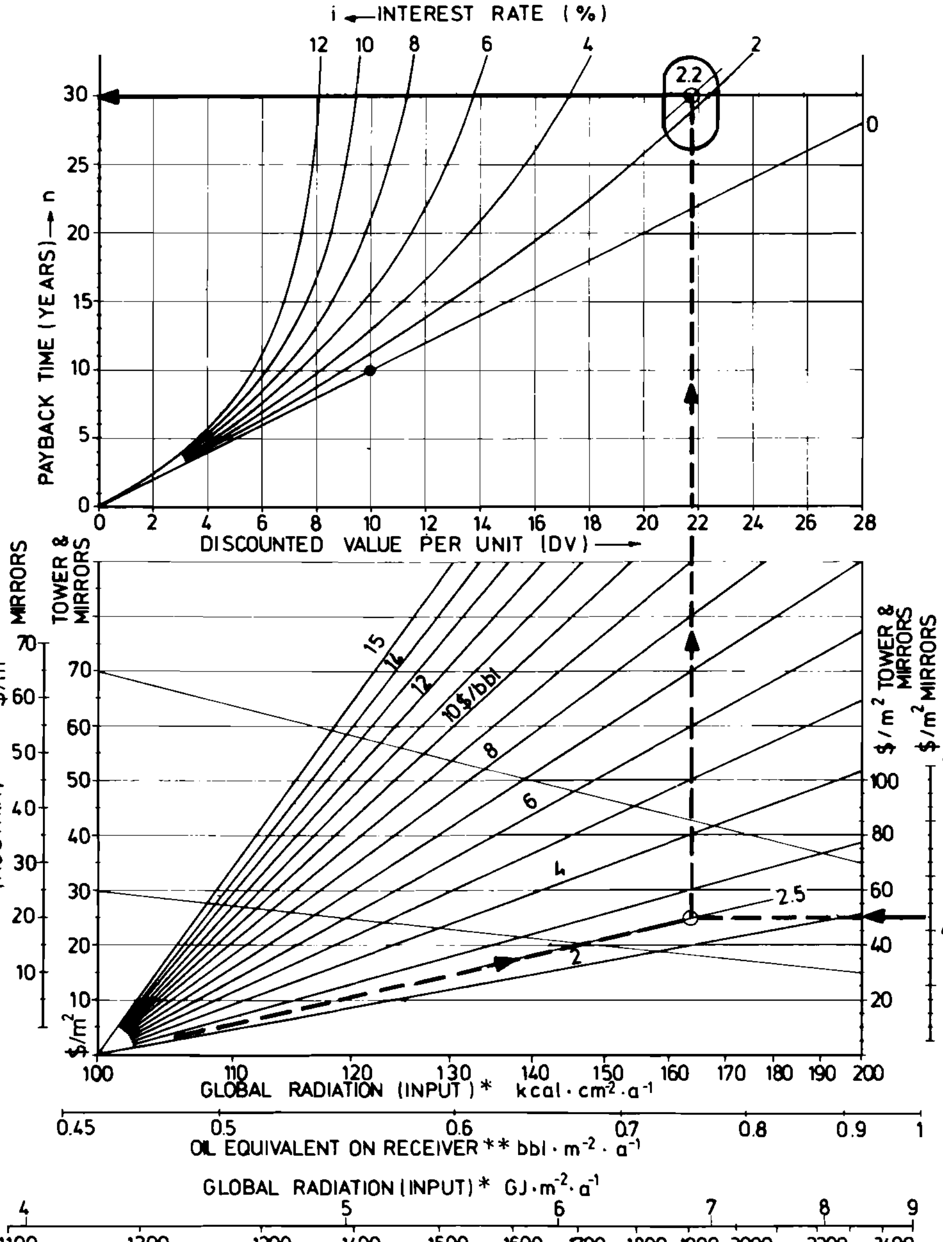
[1]In the sunny regions of Madrid and Varna, the acceptable heliostat (mirror) cost may reach $65/m^2, or up to $20 or more per square meter whereas in Austria or Boston, only up to $45/m^2 cost would be acceptable to meet the same economic requirements.



* = TOTAL RADIATION ON A HORIZONTAL SURFACE

** = DEMAND OF OIL EQUIVALENT TO THE CORRESPONDING SOLAR HEATING OUTPUT

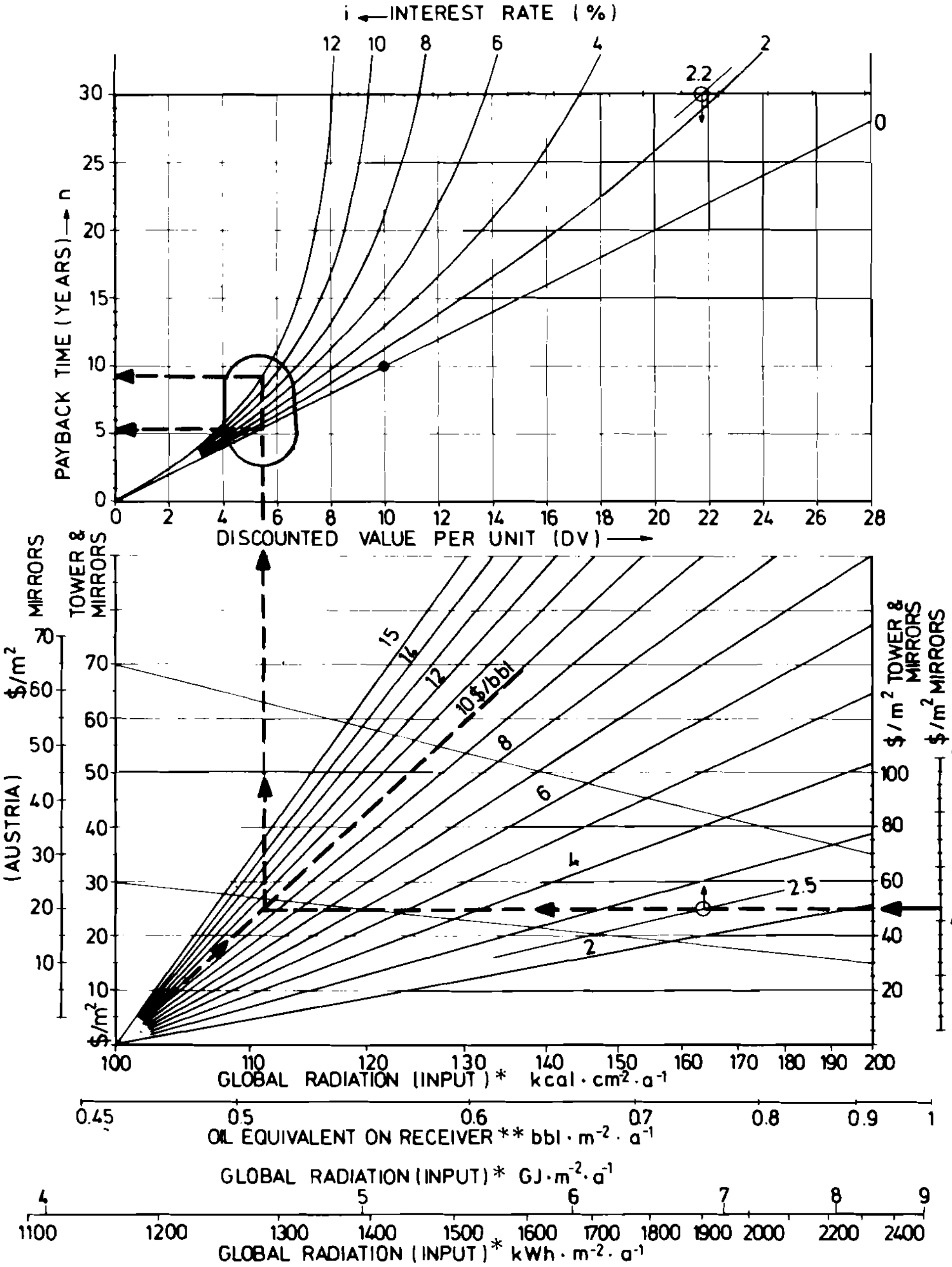
Figure 5. Scenario prior to oil crisis. $2.50/bbl and $45/m^2 heliostats (tracking heliostats [mirrors] with central receiver tower in hybrid configuration with conventional [electricity] power plant). High insolation locations.

of oil at $10 per barrel, the solar plant hybrid concept for equivalent locations yields an economic advantage. Figure 6 shows such parametric relationships. The addition of a solar energy conversion system to a fuel oil burning plant in an area such as Inyokern would no longer require an unreasonably low interest rate. Even with a 12 percent interest rate, only nine years of payback time are needed because of the significant savings of oil in a hybrid power plant. This could be followed by 21 years of further increased savings as a result of integrating solar energy conversion capability.

The changed basis of oil cost has similar positive effects on areas receiving lower solar insolation, as for example Austria where only about one-half of the optimum terrestrial solar insolation is realized. Figures 7 and 8 show how this level of solar insolation can support the economic feasibility of solar energy conversion installations. For example, for a pilot plant and/or a solar energy demonstration plant, a higher cost of the mirrors ($50/m^2) can be assumed (Figure 7). With a 7.4 percent interest rate a cost balance for a steam thermal power plant with an operating life of 30 years appears feasible. As soon as the cost of the heliostats (mirrors) can be decreased by mass production to $30/m^2 (Figure 8), a customary interest rate of 8.5 percent would suffice for reaching a payback time of 13 years. The remaining 17 years of operating without fuel cost during sunny days would show the economical features of the integration of solar energy conversion capability.

We hope that the nomograph described here will provide the user with a practical economic evaluation of the solar energy conversion options. This presentation, based on the choice of a hybrid power plant, is only a partial contribution to the broad discussions that would have to precede the decision processes for implementing large-scale utilization of solar energy conversion plants. The technical and solar energy details need not be derived within this methodology. The problems of internal and external energy storage, as well as of determining reliability and load factors, are minimized with the flexible characteristics of hybrid power plant operation. The assessment of non-technical and peripheral impacts of solar energy utilization need not be considered here. However, it is not the objective of this multi-parametric study to identify the hybrid power plant system as the optimum of all possible concepts for the use of solar energy. More important during the familiarization time period is the clarification in relatively simple terms, of the financial and economic interrelationships connected with the potential use of solar energy power plants.

The nomograph can also be used to provide visibility of the pure solar-steam power plant's economy, including concepts using internal energy storage where the heliostats and the central tower system's cost represent between 30 percent [6(S)] and 78 percent [6(H)] of the entire facility cost. The



* = TOTAL RADIATION ON A HORIZONTAL SURFACE

** = DEMAND OF OIL EQUIVALENT TO THE CORRESPONDING SOLAR HEATING OUTPUT

Figure 6. Scenario after oil crisis. \$10/bbl and \$45/m^2 heliostats (tracking heliostats [mirrors] with central receiver tower in hybrid configuration with conventional [electricity] power plant). High insolation locations.

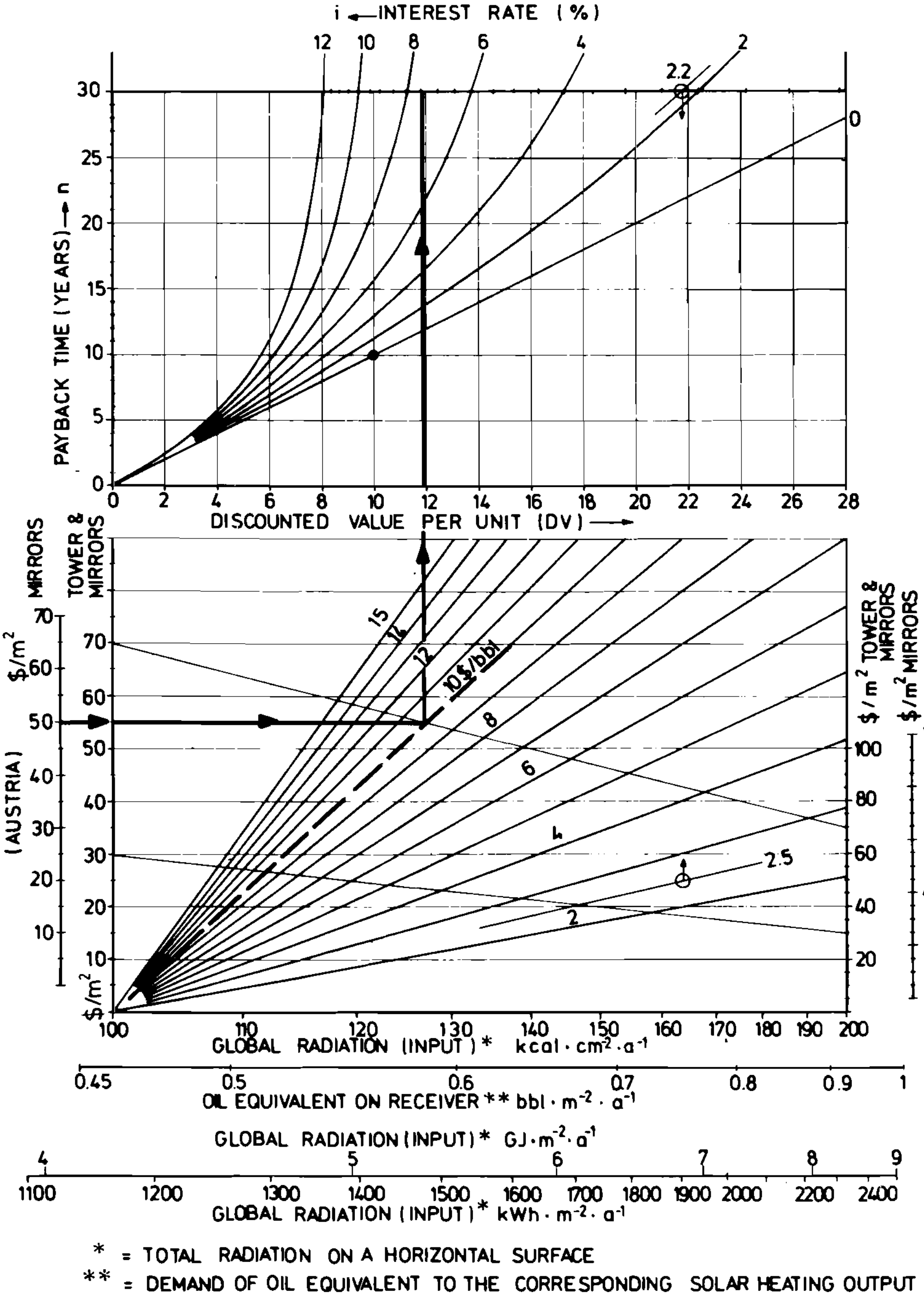
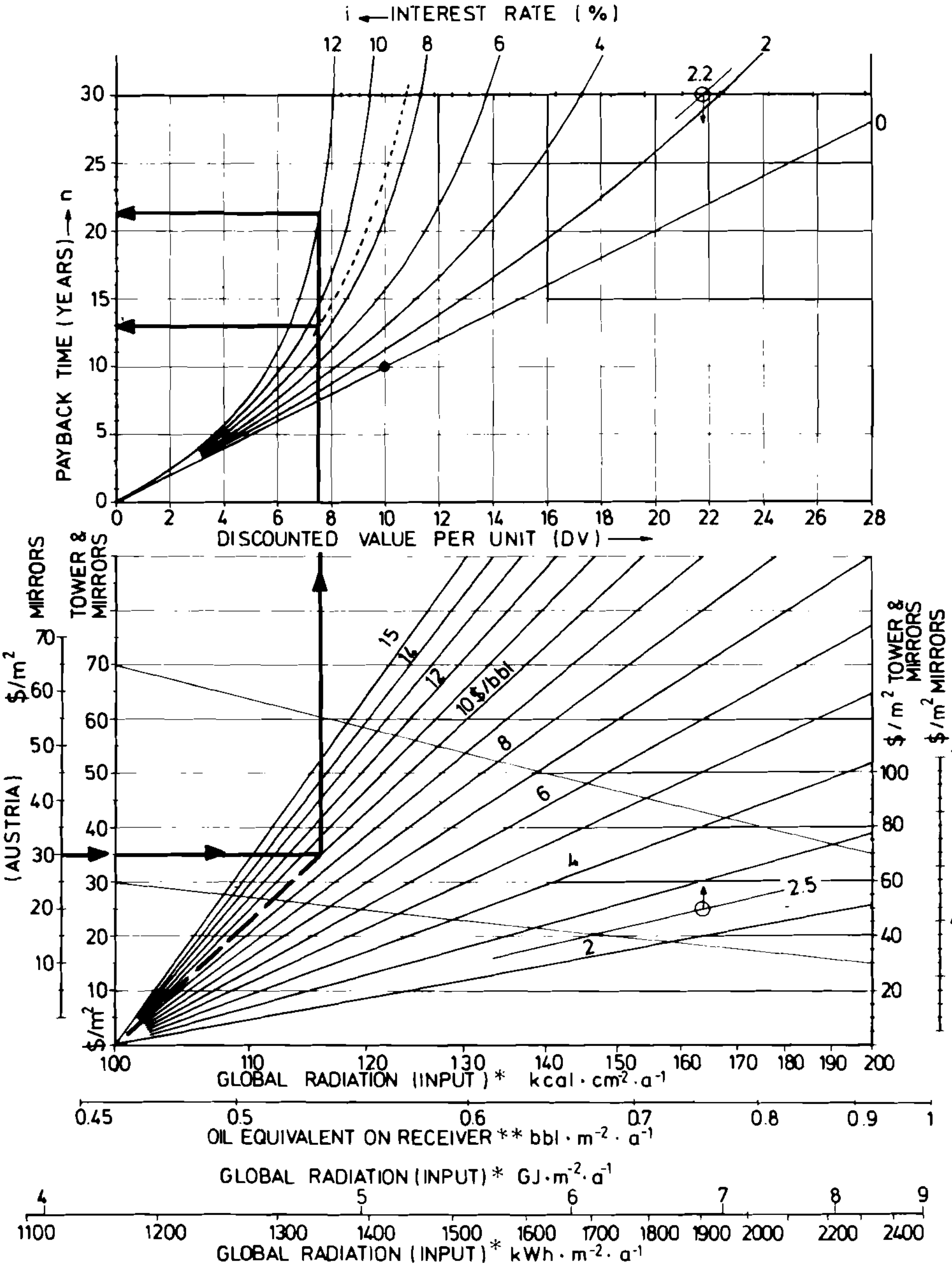


Figure 7. Experimental facility in Austria. \$10/bbl and \$50/m^2 heliostats (tracking heliostats [mirrors] with central receiver tower in hybrid configuration with conventional [electricity] power plant). Moderate insolation locations.



* = TOTAL RADIATION ON A HORIZONTAL SURFACE

** = DEMAND OF OIL EQUIVALENT TO THE CORRESPONDING SOLAR HEATING OUTPUT

Figure 8. Production solar facility in Austria. \$10/bbl and \$30/m^2 heliostats (tracking heliostats [mirrors] with central receiver tower in hybrid configuration with conventional [electricity] power plant). Moderate insolation location.

remaining investment is for the conventional power plant equipment (steam turbines, generators, etc.), prices of which are generally known.

Finally, pilot power plants with their valuable power output have to prove to which extent the electricity sector in the future can use advantageously the important energy source--the sun.

Acknowledgment

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4.3 Energy System Embedding

Jacques G. Gros

With the IIASA Energy Systems Group's long-range perspective it is important not to lose sight of certain short-range effects which can have significant impacts on long-term decisions. In particular, the siting of large energy conversion facilities, their operation, and the reliability of energy systems are of decisive importance, and we have therefore focused attention on solving specific problems in these areas. In siting, we are interested in the usefulness of Paretian analysis, as well as in the comparison of multiobjective planning techniques, and their application to the siting of solar power plants. For the evaluation of operational and maintenance issues, we are investigating what new information is needed, and how it should be used, to determine how an electric system would operate with large solar power plants. Finally, we are analyzing whether electric utility systems with solar power plants are inherently less reliable than those without such plants.

APPLICATION OF PARETIAN ANALYSIS TO FACILITY SITING

Finding an acceptable location for a large energy conversion facility is a complicated process. The site must have certain characteristics. A large variety of environmental and socio-economic impacts can result from the decision. The decision process is in part political, and the decision-maker may be faced with the following:

a) A number of interest groups;

b) Multiple objectives of these interest groups;

c) Limited information on how different decisions affect the group; and

d) Uncertainties as to the decision process and its impacts.

Thus a suitable methodology is needed that considers all these issues.

That is not to imply that there are no analytic techniques for studying political decision-making. Recently, there has been much interest in models of political conflict, as for example the use of such techniques as metagame theory and vote trading; they emphasize one or two aspects of the problem, while generally ignoring others that the decision-maker is faced with. There are remarkably few economic techniques for modeling the political decision-making process. One technique that has been used to gain insights into the trade-offs in siting large facilities is Paretian analysis (Gros [1]); work has been carried out on exploring the usefulness of this technique (Gros et al. [2]; Gros [3]).

A decision is "Pareto-admissible" if it is technically feasible and if no other decision exists that is preferred by an interest group(s) and is not (relatively) detrimental to another group. A change from a Pareto-admissible decision that makes one interest group better off would (by definition) make another group worse off. This is an acceptable foundation upon which a multi-interest group methodology can be based. A "Paretian model" is used to generate the set of Pareto-admissible outcomes; political, economic, environmental, and technological constraints limit the set of feasible alternatives.

Each of the interest groups has normally several objectives, and these objectives may conflict. In addition, siting decisions are made in a world of uncertainties. This suggests choosing an objective function that can handle these two issues conveniently. For our analyses, we have used utility functions. One property of a utility function is that its expected value is a guide for decision-making; in addition, utility functions correspond to people's subjective preferences, so that a function could be assessed for each interest group. Since assessment techniques have been described in detail elsewhere (Schlaifer [4]), we will concentrate on their application.

The Paretian model can be described algebraically as follows: let X be a vector that describes all the impacts and technological alternatives of the siting decision, and let it include all the environmental, economic, and social impacts of concern to the interest groups. The environmental impacts and the technological alternatives are related: pollution levels depend on which pollution abatement devices are used. Let a set of equations $T(X) = 0$ describe the technological relations. There can also be a set of constraints, such as environmental control standards, which limits the set of feasible alternatives. Let us summarize all these technological, economic, legal, and political constraints and relations by $\Phi(X) \leq 0$, where $\Phi(X)$ is a vector of the relevant transformations.

As mentioned the vector X includes all the environmental, economic, and social impacts of concern to the set of interest groups. Each group may, in fact, be concerned only with a limited number of these impacts. For convenience, let $U_i(X)$ be the utility function for the i^{th} interest group, with the understanding that it can be a function of a few of the impacts. Let these functions be scaled so that $U_i(Y_1) > U_i(Y_2)$, if Y_1 is preferred over Y_2. Suppose that Y_1 and Y_2 are two feasible decisions, that $U_i(Y_1) \geq U_i(Y_2)$ for all interest groups, and $U_i(Y_1) > U_i(Y_2)$ for at least one group; in this case Y_2 should not be chosen, since another decision exists that is preferred by some interest group and is not detrimental to the interest of another interest group. The decision Y_2 is said to be inadmissible. On the other hand, decision Y_1 is Pareto-admissible if it is feasible and if there does not exist any alternative feasible decision Y_2 for which $U_i(Y_2) \geq U_i(Y_1)$ for all interest groups, with strict inequality holding for at least one of them.

To find the Pareto-admissible decision, the following mathematical problem must be solved. Choose a set of positive numbers w_i, one for each interest group, and form the objective function $W = \sum_i w_i U_i(X)$. Find the feasible decision that maximizes W. (A feasible decision satisfies $\Phi(X) \leq 0$.) Decision X is one of the Pareto-admissible decisions. The numbers w_i are often called political weights since they reflect the marginal weightings of preferences for the interest groups in the Pareto-admissible decision. The steps are repeated with different values of the political weights to obtain other Pareto-admissible decisions.

To apply Paretian analysis, interest groups must be identified and their utility functions assessed. This involves finding the set of impacts of concern to the interest group, and determining a method for obtaining the group's preferences while interviewing only a few members. At the actual assessment, questions are asked to determine whether a simple functional form for the utility function is appropriate which will then facilitate the assessment. This often occurs in practice. An application of the Paretian approach to nuclear power plant siting in New England is found in [1] and [3]. In the New England study a limited number of impacts were of interest, namely, number of units at a site, cost, surrounding population weighted by number units, and end-of-pipe temperature. The interest groups were the electric utility companies, regulatory agencies, environmentalists, and local interests. A variety of Pareto-admissible alternatives were found, one of which will supposedly be chosen by the political decision-maker. Equity among the groups should be one of their considerations; Paretian analysis makes explicit what the trade-offs are.

COMPARISON OF MULTIOBJECTIVE PLANNING TECHNIQUES AS USED IN LARGE FACILITY SITING

In a previous section, I described a methodological tool for deciding which model agrees with observed data and for weighting them into a composite model. Now we face a similar, but different, problem of choice. There are many multi-objective methodologies for facility siting decisions, each with special characteristics and different underlying assumptions. These methodologies have been applied to different siting studies, often with little thought as to how one method or another biases the results. Thus there is a need for comparing the methodologies. The comparison is, in itself, multiobjective, unlike the simple comparison of the Bayes' theorem mentioned in this Report[1]. To make the comparison, we have to use a multiobjective tool.

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[1]See J. Gros, "A Bayesian Approach to Discrimination Among Models for Exploring Geological Bodies."

The first step in the siting process is to see whether a site is feasible for the facility in question. For a site to be feasible, its characteristics and the predicted impacts of placing the facility there must be within bounds chosen a priori. These include: excessive cost; excessive environmental degradation; excessive negative impact on regional planning; excessive land purchasing problems; and the closing of too many future options. To be feasible, all these bounds must be satisfied. The process used is often called screening, and results in a reduced number of sites for evaluation in depth.

There are three broad methodologies for analyzing the trade-offs of siting decisions: matrix methods; benefit-cost analysis; and preference theories. They differ in how they describe desirability, whether they aggregate impacts, which scale they use, and so forth.

Matrix methods present the characteristics of sites or the impacts of the decision in the form of a matrix or table. Table 1 shows part of the matrix presenting site characteristics for the decision of where, in Austria, to locate the prototype solar-thermal tower electric generating plant. The column on the left lists characteristics important to this decision; the other columns present the corresponding values for different sites. A matrix of this type clearly shows the different values, thus allowing the decision-maker to analyze the trade-offs involved in choosing a site. Many variations of matrix techniques are available. Perhaps the best way to show the variations, assumptions, experience, and usefulness of this and other methodologies, is to use a matrix listing these comparisons. This is presented in Table 2.

Table 1. Two candidate sites for first solar power plant in Austria.

Characteristics	Burgenland Site A	Burgenland Site B
Insolation[a]	2000 hrs	2009 hrs
Area (km^2)	2.0	1.6
Topography	Flat	Flat
Present Use	None (Nonproduct)	Rented - Beets
Transportation Access	1 km to Highway, Good Dirt Road	Highway
Electric Transmission	3 km (220 kV)	4 km (220 kV)
Cooling Water	None	Small Lake

[a]Solar energy input approximately 1,100 kWh/m^2 per year.

Table 2. Comparison of multiobjective methodologies.

Methodology	Examples	Aggregation of Impacts Into Scaler Index	Assumptions on Desirability	Assessment	Experience
Matrix Methods	Planning Balance Sheet Goals Achievement Matrix Environmental Impact Matrix Factor Profile	Usually Not	Assumes Non-Compatibility	No Desir-ability Assessment	Some - in Vogue Now
Benefit-Cost Analysis	Benefit-Cost Analysis	Almost Everything	Uses Monetary Units; Compares Impact in This Unit	Uses Eco-nomic Data	Consider-able in U.S.A.
Preference Theories	Indifference Surfaces Value Functions Utility Functions	Everything	Relationships Explicit and Rigorously Defined	Assessment	Limited

The variations of the matrix method are designed to emphasize different aspects of the decision. The Environmental Impact Matrix (Leopold et al. [5]) presents the environmental and monetary impacts of having the facility at different sites in matrix form. It was designed to satisfy the requirements of the U.S. Environmental Policy Act of 1969. As a variation on this approach, the authors suggest that the impacts be scaled, with two numerical ratings: the magnitude of the impact; and the importance of the impact. Using the Planning Balance Sheet (Lichfield [6]), the impacts are separated according to the interest group they affect. Those that affect more than one group are listed with each group. An advantage of this variation is that it highlights the distribution of impacts. In the Goal's-Achievement Matrix Technique (Hill [7]), goals are determined for each impact and each interest group; achievement toward each goal is listed in the matrix. It should be pointed out that in all these variations, impacts can be expressed in monetary or numerical units, or even verbally.

The aggregation of impacts into a scalar index refers to the process where one number is used to represent the desirability of several impacts. Most matrix method variations assume that impacts are non-comparable, so there is little aggregation into a scalar index. Sometimes aggregation is suggested, but the results are often erroneous because ordinal rankings are combined. Even where cardinal rankings of individual impacts are weighted and summed, the results can be misleading because the desirability of one impact often depends on the value of another. There has been experience with matrix methods because of the need to list and analyze all the impacts of decisions which affect the environment, as mandated by the National Environmental Policy Act of 1969.

In benefit-cost analysis, monetary values are assigned to all impacts and site characteristics; these effects are then divided into two categories--benefits and costs. Values in each of the categories are summed, and a criterion is applied--namely to maximize the difference between total benefits and costs, $\Sigma B_i - \Sigma C_i$, or to maximize their ratio $\Sigma B_i / \Sigma C_i$. Everything that can be expressed in monetary terms is aggregated into the scalar index. This method has been criticized because of the need to express everything in monetary terms, (and to make the necessary assumptions), and because certain impacts defy monetary values. Where more than one impact is expressed in monetary terms and included in an analysis, certain unrealistic assumptions about desirability result. Desirability is often a linear function of impact level for each impact handled separately, and the marginal rate of substitution is constant no matter what values the impacts have. This is inconsistent with real preferences. One concern often left out of benefit-cost analysis is the distribution of the benefits and costs among the different interest groups; this can have a great impact on the political acceptability of a project. Often, great ingenuity is needed to express certain impacts in monetary terms. There has been much experience in the U.S.A. with this methodology since the Flood Control Act of 1936 mandated its use.

There are a set of methodologies designed to handle rigorously the desirabilities of multiple impacts and their dependencies. Three such methodologies, which we group under the heading preference theories, in order of their information content, are: indifference surfaces, value functions, and utility functions.

The use of indifference surfaces involves ordinal comparisons. Each indifference surface represents that set of impacts for which the decision-maker would be indifferent to the choice among these impacts. Different surfaces represent different preference levels. To identify the surfaces, a direct assessment of preferences has to be made. To date, there has been limited experience in this area, and much of it has been used to justify decisions which were made using other techniques. Indifference surfaces normally span only two or three impacts.

It is also possible to assess functions that correspond to people's preferences. For problems with no uncertainty, special functions called value functions are used that contain more information than indifference surfaces in that differences in their values have some meaning while distances between the surfaces have none. The analyst can exploit this difference to reduce the work of assessing and using these functions. For problems with uncertainties, utility functions are used. Not only do differences in values of the utility functions have meanings, but their values in wagers or lotteries are also meaningful. In fact, they are generally scaled so that the expected value of the utility function is the guide for decision-making. Since questions involving lotteries are valid, assessing utility functions is often easier than assessing value functions or indifference surfaces. For all methodologies of preference theories, all impacts can in theory be aggregated into a scalar index. The relationships of desirability are explicit and rigorously defined, with the logic provided by the assessment. As such, they correspond to people's subjective preferences. Of the methods discussed, only utility function theory provides a rigorous method for handling uncertainties. Unfortunately, experience with preference theories techniques has been limited, although several efforts are underway to identify the efficiency of these methodologies.

Applications of the multiobjective planning techniques to solar power plant siting will be discussed in a forthcoming IIASA report. For more detailed comparison of these methodologies, see Baecher, Gros, and McCusker [8].

OPERATION OF INTEGRATED ELECTRIC SYSTEMS WITH SOLAR GENERATED ELECTRICITY

Investment and operating decisions for electric utility systems are made from a system's viewpoint; each decision's impact on the existing and planned system is studied in detail. To understand how the system would operate with solar power, or to determine the value of solar generated electricity, the analyst also should use a system's viewpoint. Many models for conventional systems exist[2], but solar power has certain characteristics that are not shared by existing generating devices. For instance, the demand for electricity is in part related to insolation and hence to solar power plant output. Figure 1 shows the total electricity generated in Austria on 18 June 1969; Figure 2 shows the global radiation for three towns in Austria for the same date. The more correlated the electric power demand and the solar plant's output, the higher the value; lag correlations are also important since energy can be stored. To determine the value of solar power, these correlations must be included in the models used for system investment and operation. We are studying ways of doing this.

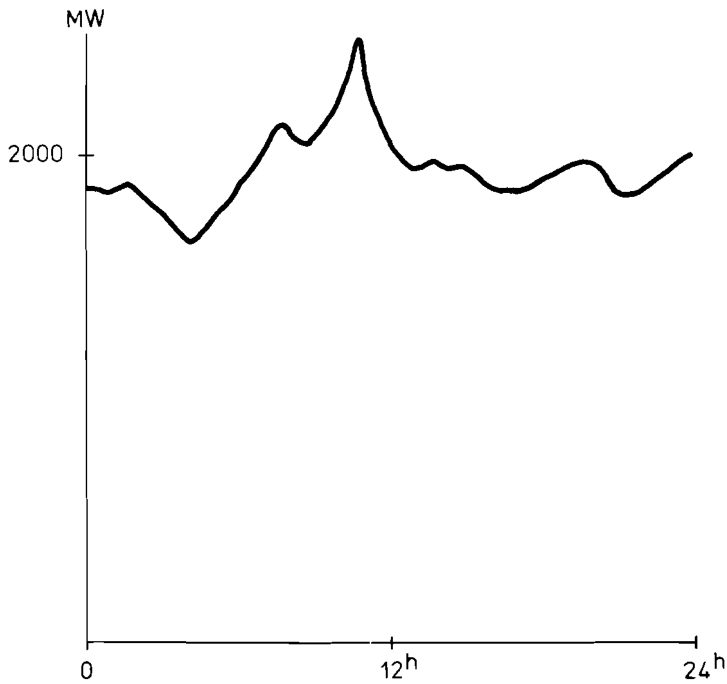

Figure 1. Total electricity generated in Austria, 18 June 1969.

There are other types of correlation which affect the value of solar generated electricity. Consider the case where there is more than one solar power plant. If the output of each plant is not affected by the same weather condition, then the value of the output is higher. Consider Figure 2. Rust and Podersdorf

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[2]Anderson [9] has compared models for conventional systems.

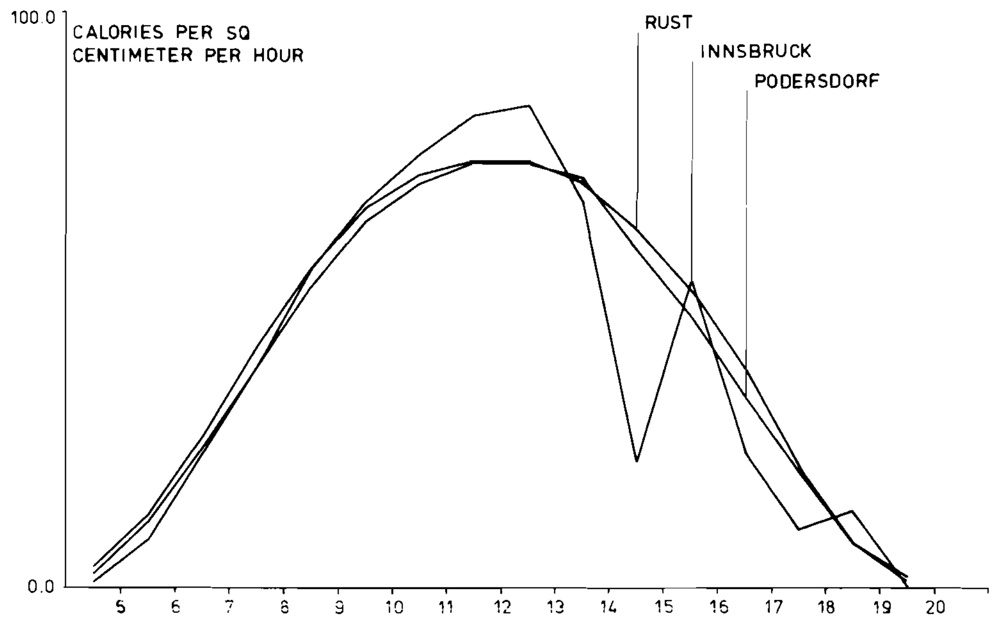

Figure 2. Global radiation in three Austrian cities by hour of day, 18 June 1969.

are two Austrian towns located close together (14 kilometers) and the patterns of solar radiation are similar; Innsbruck is about 400 kilometers away and has a very different pattern. This would be reflected in a correlation analysis; Figure 3 shows the results of an analysis based on time of day for Innsbruck and Rust. When we do a similar analysis for Rust and Podersdorf, we find a much higher correlation. This dependency of the spatial pattern of sunlight is of great importance in siting and operating decisions. Another issue relates to how predictable is the output of a solar power plant. The more predictable it is, the better the system will operate.

We will have to modify existing models to incorporate these special characteristics of solar generated electricity. With such models, we could study the trade-offs involved, such as the trade-off between energy, storage and generation capacity, and the trade-off between economies of scale of a single large plant and the extra transmission costs and lower correlations of a dispersed system. The scheduling of planned maintenance in a system that includes solar power is also an issue which deserves consideration. And it is only with such models that the true worth of solar generated power can be obtained; the true marginal benefit is the difference in total systems cost between the system with solar power and a system with the best alternative generating plant.

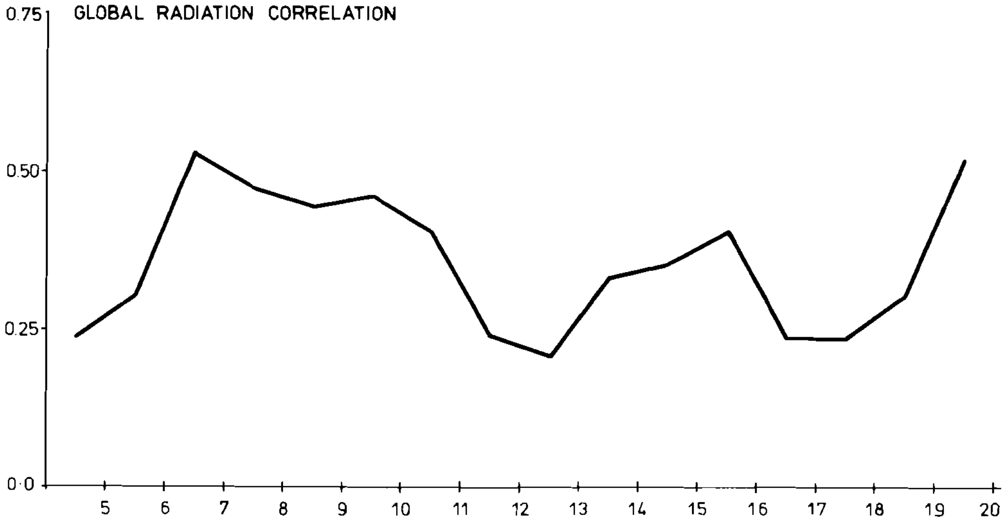

Figure 3. Correlation of global radiation in Innsbruck and Rust by hour of day, June 1969.

ELECTRIC SYSTEMS RELIABILITY AND SOLAR POWER

One objection to the use of solar generated electricity is that it is not always available. The energy source for solar power is different from that of conventional plants. Clouds can block sunlight; sometimes it is cloudy for days. There is a fear that this would inherently lower system reliability. (Or, as the French would say, the system would not meet its "guarantee conditions.") But will it really? To answer this question, we must consider the conventional criteria for systems reliability, consider what is or is not included, and then find a methodology for determining the reliability of an electric system that includes solar power plants.

The conventional index of system reliability used by most utility companies in the U.S.A. is "one day in ten years the load will exceed installed generating capacity" (TVA [10]). The condition shown on Figure 4, with the total demand exceeding total supply, should happen on the average no more than once in a ten-year period. To determine whether a system meets this criterion, demand must be predicted and a probabilistic analysis carried out to find out how many plants are available, that is operational. The analyses generally do not consider security of fuel supply or the probability that a new generating plant will come on line later than planned. For some utility systems, system reliability has been degraded recently for these two reasons. The analyses also assume that the availability of one plant is probabilistically independent of the availability of other plants. (In other words, the probability that one plant is available does not depend on whether other plants are available; in reality, natural disasters, such as earthquakes, can make plants non-functioning so that this independence is not valid.)

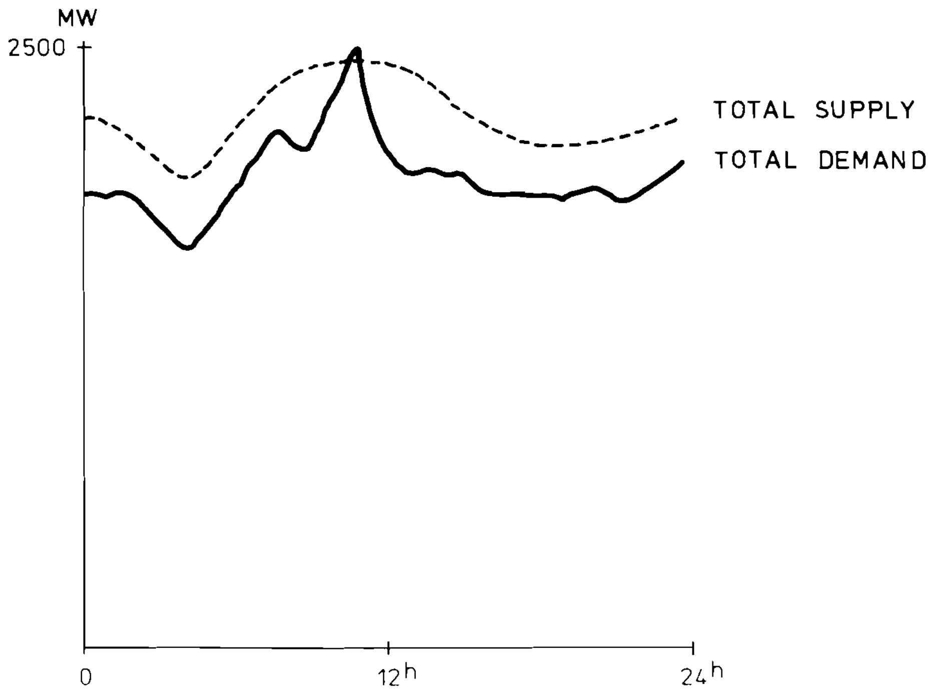

Figure 4. Electricity demand and supply for 24–hour period.

To include solar generated electricity in the calculations of system reliability, a new technique must be used. The output of one plant is not independent of the output of another (because of spatial dependencies of insolation); demand depends in part on insolation. The mathematical technique used should reflect these facts. In addition, because of the nature of solar power and the associated need for energy storage, the reliability criterion may change. It could in part be based on the energy demand not supplied, or on the frequency, duration, and amount of power demand not satisfied. Or the criterion could specify under which insolation conditions the demand must be met. For example the criterion might be that the system meet the reliability index for the worst three-year period expected in 100 years. Other criteria could be chosen. What we are saying is that careful analysis should be given to determine the appropriate index of system reliability.

A need exists for a methodology for determining system reliability for an electric system with solar power plants. Since the computational steps will be described in a forthcoming IIASA report, we will illustrate the technique by presenting results of each of the important computational steps. It is sufficient to say that the technique was designed so that the minimum number of computational steps is required. The technique was also designed that if a plant is to be added or retired from the existing system, only a small number and not all the steps have to be repeated.

We have a set of conventional power plants. Each has a probability of being unavailable when not shut down for planned maintenance. For the illustration, we have 6-1000 Mw plants with .01 probability of not being available, and 6-500 Mw plants with probability .03. By considering all combinations of these plants, we can find the probability that different amounts of generating capacity would not be available. The result is shown on Figure 5.

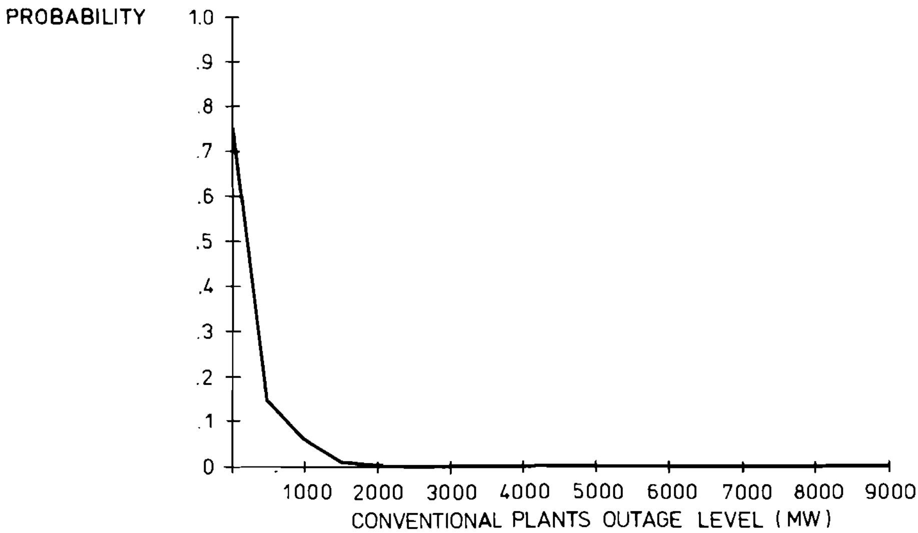

Figure 5. Distribution of different conventional plants outage levels.

Demand depends in part on insolation. Both quantities are uncertain. To include the dependence and the uncertainty, the joint probability density of different demand levels and insolation rates should be found. Corresponding to each insolation value is a solar power plant output; from this, the solar power plant shortfall can be found. (Shortfall equals rated capacity minus actual output; we are treating shortfall as though it was an additional demand that must be met.) The probability density should be updated to include solar plants not operating because of equipment failures. The updated probability density can then be used to find the distribution of the sum of demand and shortfall values. The result of one such analysis is shown on Figure 6 for a solar energy conversion plant of ~1,000 MW(e) size.

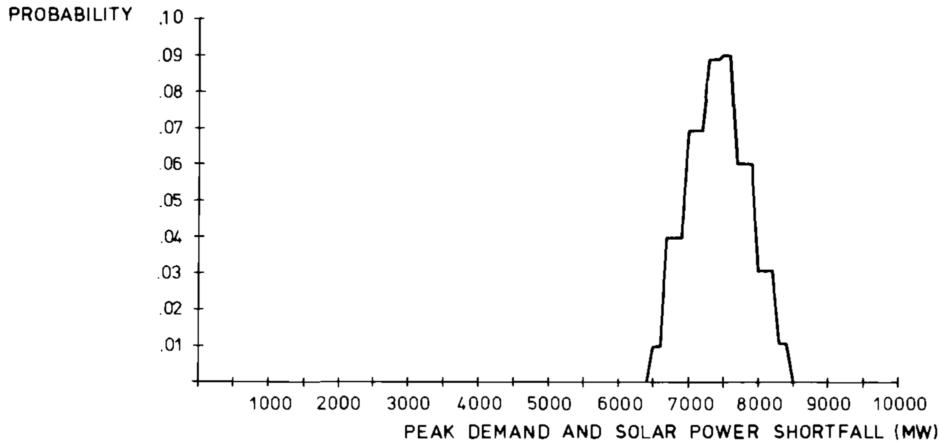

Figure 6. Distribution of sum of peak demand and solar power shortfall.

If the curves on Figures 5 and 6 are convoluted, the distribution of total generating capacity needed to meet demand is found. This is illustrated on Figure 7; the area under this curve to the right of total capacity is the probability of not meeting the demand. For our illustration, with 10,000 Mw of capacity, the probability is 0.0003. That is, for 99.97 percent of the time, the system will be able to meet peak demand.

The method shown is a preliminary one. We will have to repeat the analysis for the Austrian electric system. More details about the interaction of solar and pump storage will have to be included. The work is continuing.

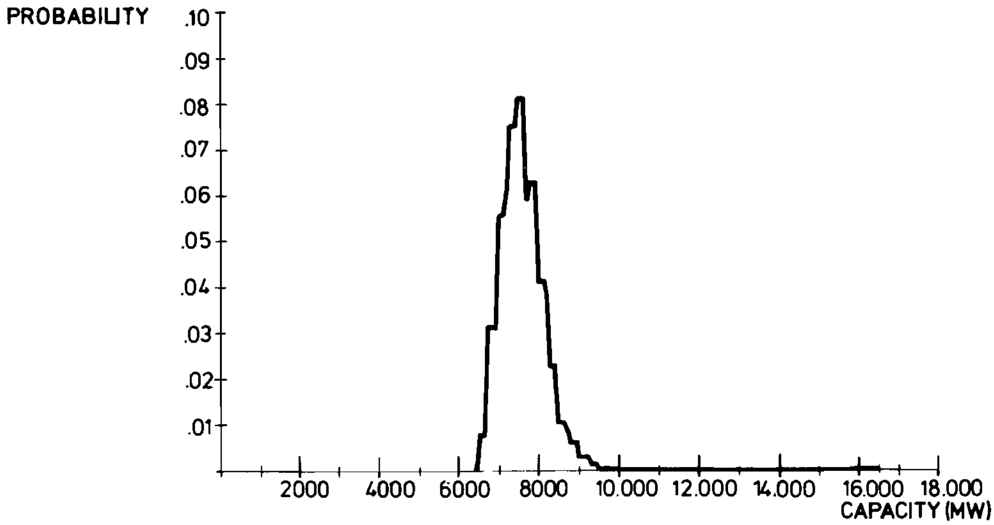

Figure 7. Distribution of capacity needed to meet peak demand.

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Part 5: CONSTRAINTS

5.1 Possible Impacts of Waste Heat on Global Climate Patterns

Wolf Häfele

5.2 Risk Assessment

Harry J. Otway,
Philip D. Pahner,
Friedrich Niehaus

PART 5. CONSTRAINTS

5.1 Possible Impacts of Waste Heat on Global Climate Patterns

Wolf Häfele

The IIASA Energy Project is making an attempt to identify and understand constraints for the large-scale production and handling of energy. The observation was made several times that the impacts of waste heat on global climate patterns might possibly establish one such constraint (see, e.g., [1]). A. Weinberg and R.P. Hammond of the Oak Ridge National Laboratory (ORNL) in Tennessee were the first to take initiative in this matter. In 1970 they worked out a waste heat release scenario and made it available to W. Washington of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado [2]. Then it became possible to operate large global circulation models (GCM). We are, of course, aware of the limitations of GCM's--among them computer time, input data, and perhaps most of all the failure to consider a coupling with the dynamics of oceans--but one should nevertheless try out what tools are available. Figure 1 shows the result of these early calculations by W. Washington [3]. The assumption was made in that scenario that with today's population distribution, a total of 75Q/year was released to the atmosphere. Above northern Africa there is a temperature increase of $+6^{\circ}/C$, above Scandinavia a cooling of $-8^{\circ}/C$ and so on. The pattern of Figure 1 depicts the difference between cases with and without waste heat releases. It was taken for January, after a period of 40 to 60 days of simulated waste heat release. The values are averages over a period of about 10 days. The pattern looks like a change of weather patterns. To extrapolate from such weather averages to the climate remained an open problem. Nevertheless, the differences appeared to be large. W. Washington then repeated the calculation for negative waste heat releases; the evolving pattern of weather changes appears to be qualitatively the same (see Figure 2). In addition, when a random error of between $-2^{\circ}/C$ and $+2^{\circ}/C$ (surface temperature) instead of a waste heat release was introduced, a similar pattern again evolved (see Figure 3). This reveals the problem of the signal-to-noise ratio: all three experiments in part seem to involve noise, and the calculability of weather over a longer time period becomes the central problem.

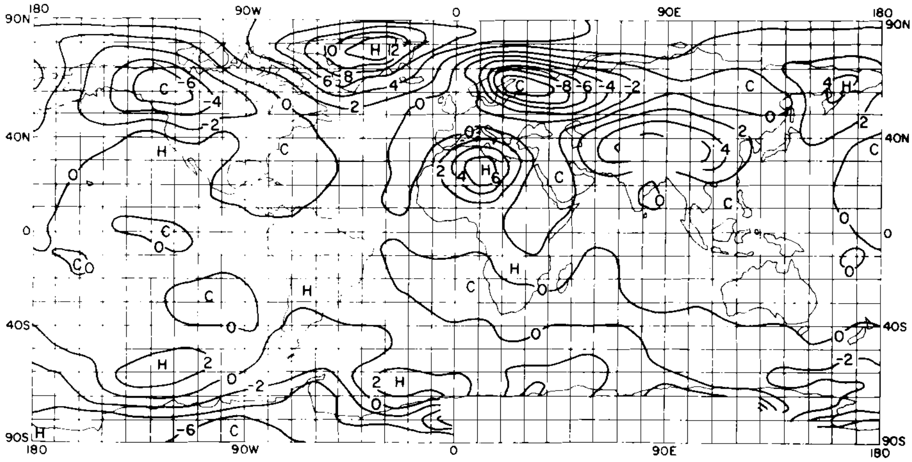


Figure 1. Positive thermal pollution
(Source: W. Washington, NCAR).

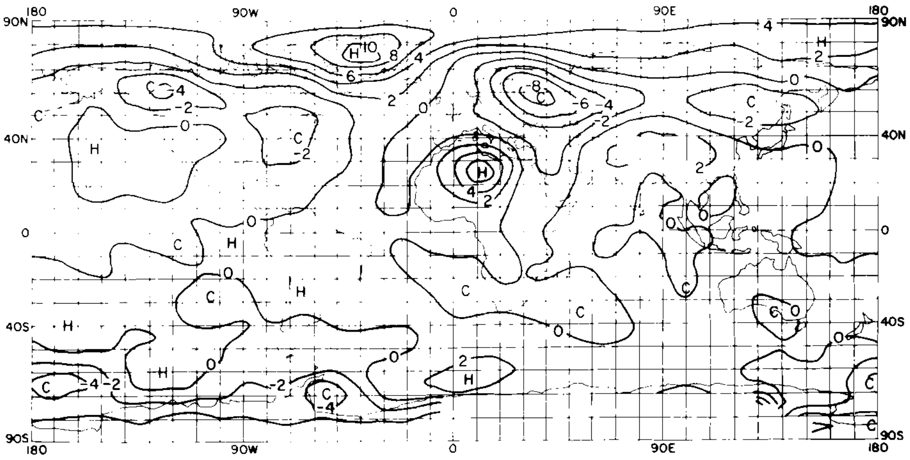


Figure 2. Negative thermal pollution
(Source: W. Washington, NCAR).

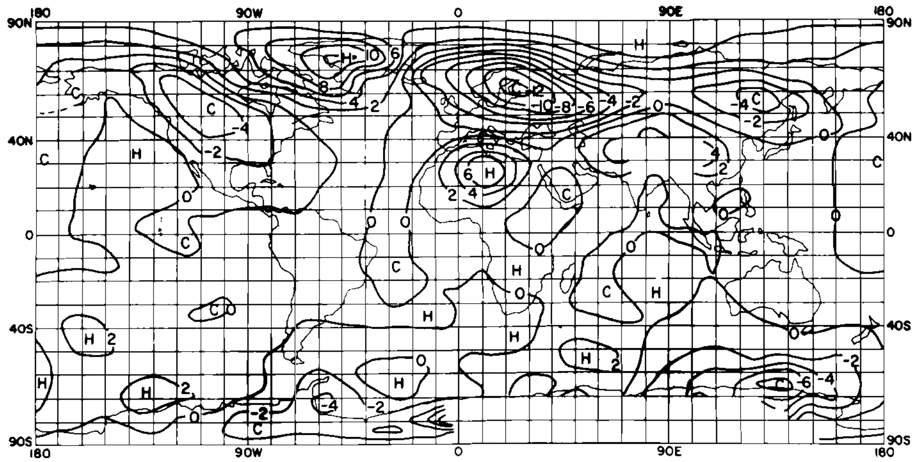


Figure 3. Random error experiment
(Source: W. Washington, NCAR).

The IIASA Energy Project wanted to understand these phenomena better because of the importance of waste heat releases as a possible constraint to energy strategies. Besides NCAR, the British Meteorological Office (BMO) at Bracknell, Herts., U.K., also conducted such numerical experiments using its own GCM [4]; it was therefore natural for IIASA to establish contacts with the BMO as well as NCAR. Figure 4 shows the weather differences for the northern hemisphere in the case of a sea-surface anomaly east of Newfoundland. Here an area of 10^6/km^2 releases heat in the order of some 10^{14} watts. The BMO also conducted random-error experiments, and again the problem of the signal-to-noise ratio appeared. The BMO was kind enough to make its GCM available to the IIASA Energy Project. Together with some routines for evaluations, it was made operational at the Kernforschungszentrum Karlsruhe. At IIASA we then proposed the following waste heat release scenario. Waste heat was released at only two places in the northern hemisphere (the underlying idea is the concept of large energy parks). The amount of waste heat in each case was chosen to be $1.5 \cdot 10^{14}$ watts. This is in line with the heat releases of the BMO experiment and is a high but not inconceivable upper limit for mankind's energy production ($2 \cdot 5$Q/year). The hope was to see an impact of waste heat

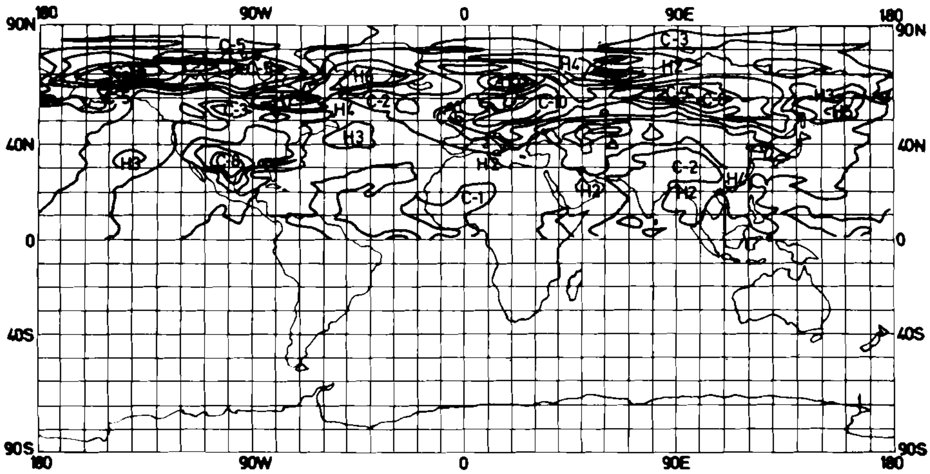


Figure 4. Positive thermal anomaly in Newfoundland (Source: BMO).

above a signal-to-noise ratio of one. Figure 5 shows the location that was chosen for the IIASA-1 experiment.

A second scenario was conceived (IIASA-2), in which the "energy park" east of Japan was retained while the one west of England was moved to equatorial regions west of Africa (see Figure 6). The amount of waste heat remained the same. In both areas the waste heat was released to the atmosphere and not to the waters. This is unrealistic, but the intention was to study an extreme and hypothetical case to find a discernible signal above noise level. In Figure 7 the grid-point configuration is given. For numerical reasons it was not possible to concentrate the entire release in one point. Instead, four points were chosen, representing power densities as indicated in the figure. Figure 8 thus shows the temperature distribution for the control random error experiment and experiments IIASA-1 and IIASA-2. Similar maps were drawn for pressure and wind velocities. Of particular interest are impacts on the precipitation pattern. We assume that this is a specially sensitive quantity and additionally of the utmost importance to any civilization. The precipitation results are thus given in Figure 9. Experiments IIASA-1 and IIASA-2 were conducted by A. Murphy of NCAR and C.H. Young, Bedford, Md., during their stay at IIASA.

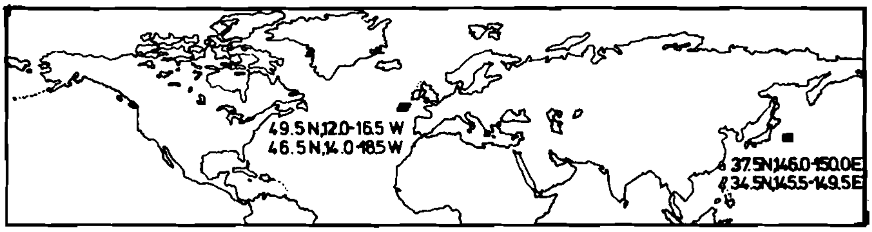


Figure 5. Locations of nuclear parks in Experiment IIASA–1.

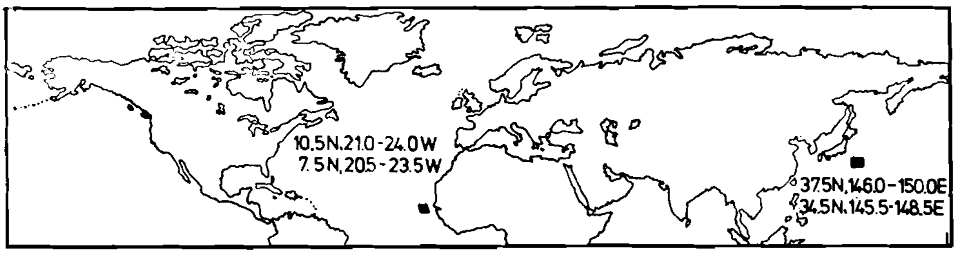


Figure 6. Locations of nuclear parks in Experiment IIASA–2.

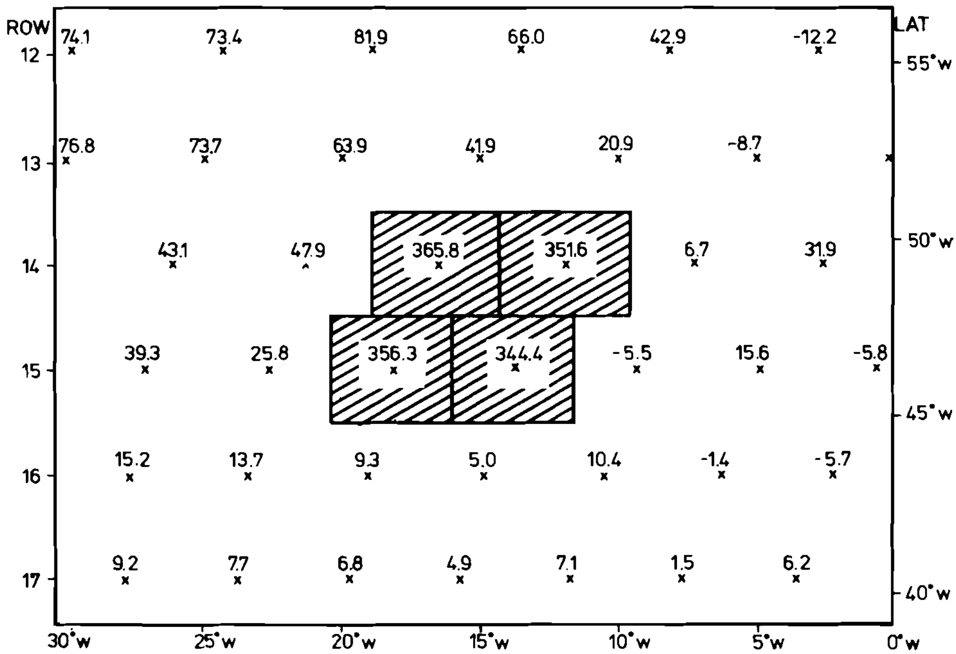
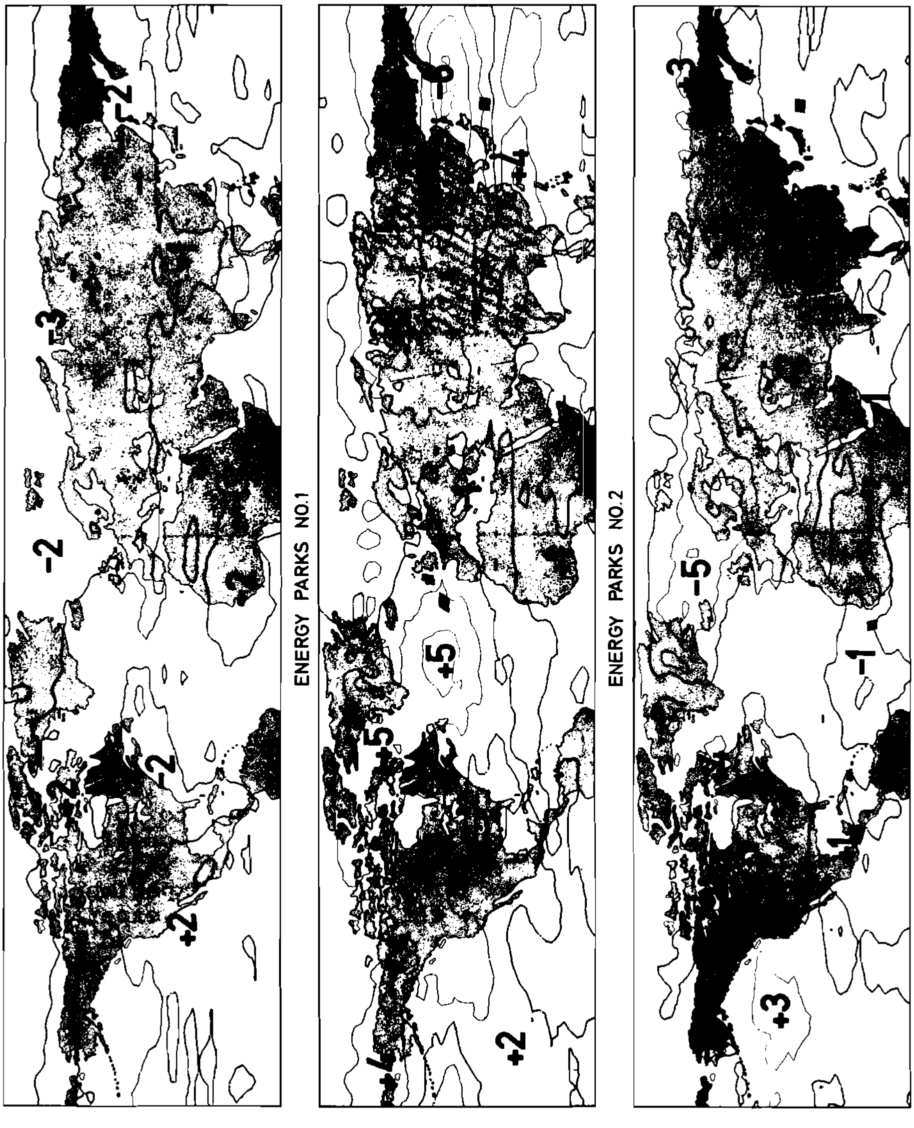


Figure 7. Atlantic Park – sensible heat values (watts · meter^{-2}).

With these results in hand we convened a small workshop of experts in April 1975. Our first impression from Figures 8 and 9 was confirmed: it is hard to see an effect that could be statistically significant and above noise level. At this workshop A. Murphy and A. Gilchrist decided to go a step further, relating the impact patterns not only to one reference case but to three cases by extracting the best σ^2 value from the latter. An average value for σ^2 from three experiments provides more information about the noise than one experiment. Figure 10 shows the precipitation results thus obtained for IIASA-1: this definitely seems to establish a clear signal above noise. There is a sharp decrease in precipitation over the Atlantic in the area of the park and Spain while the precipitation of Scandinavia is significantly enhanced. Figure 11 shows the related results for pressure changes.

The results of the IIASA-2 experiment with respect to pressure are shown in Figure 12. To facilitate comparison with the IIASA-1 case, we again give the IIASA-1 results for pressure in Figure 13 using the format of IIASA-2 results. It is interesting to note the seemingly smaller impact of this case. While we are fully aware of the complexities of these nonlinear mechanisms and hence the difficulties in drawing conclusions from such results, they should nevertheless be noted. IIASA will continue to explore these matters.



DIFFERENCES IN TEMPERATURE AT σ = 0.5 (T_5) WITH RESPECT TO CONTROL EXPERIMENT
(AVERAGE : DAYS 41-80, UNIT : °C, LIGHT/HEAVY ISOTHERMS : 2°C/10°C)

Figure 8.

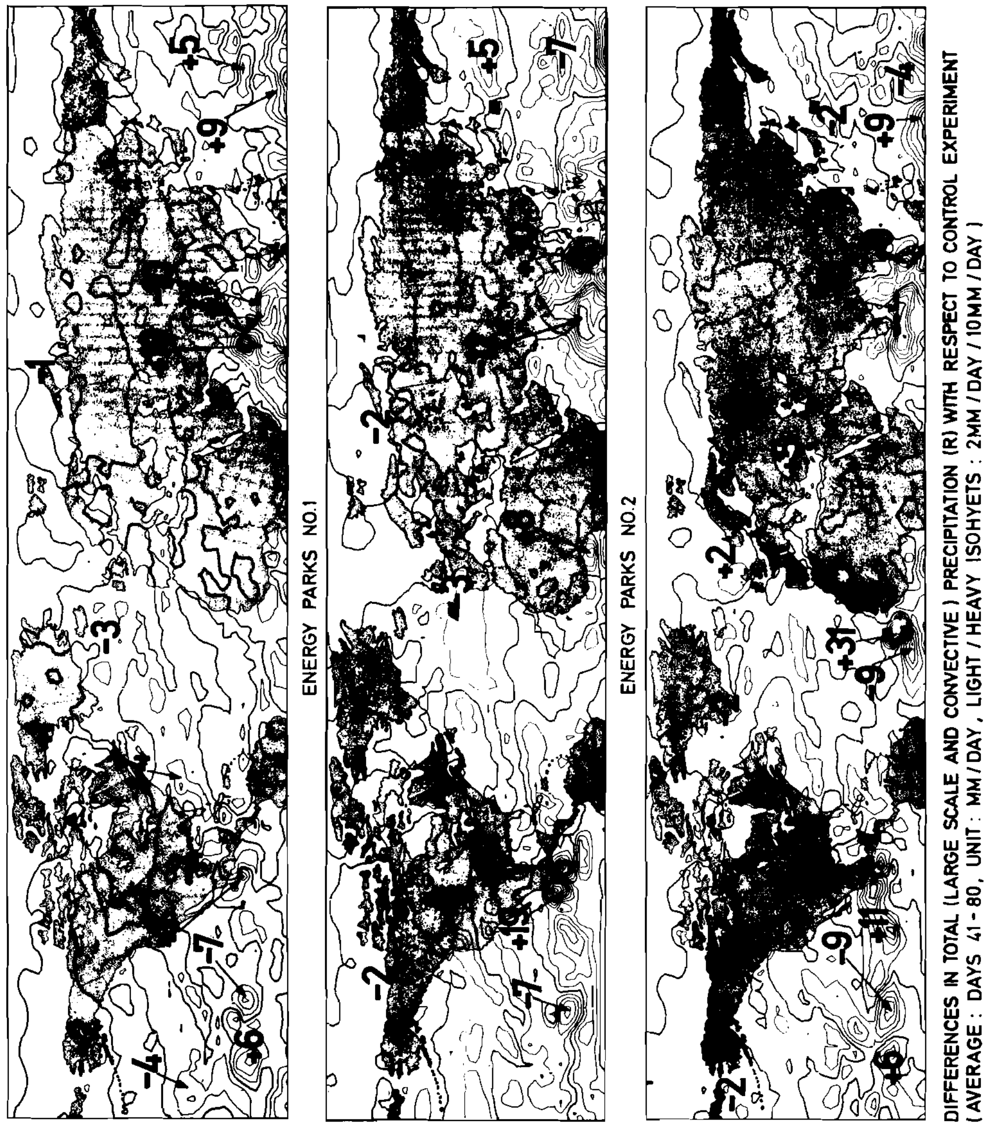

RANDOM
ENERGY PARKS NO.1
ENERGY PARKS NO.2
DIFFERENCES IN TOTAL (LARGE SCALE AND CONVECTIVE) PRECIPITATION (R) WITH RESPECT TO CONTROL EXPERIMENT
(AVERAGE : DAYS 41-80, UNIT : MM/DAY, LIGHT / HEAVY ISOHYETS : 2MM / DAY / 10MM / DAY)

Figure 9.

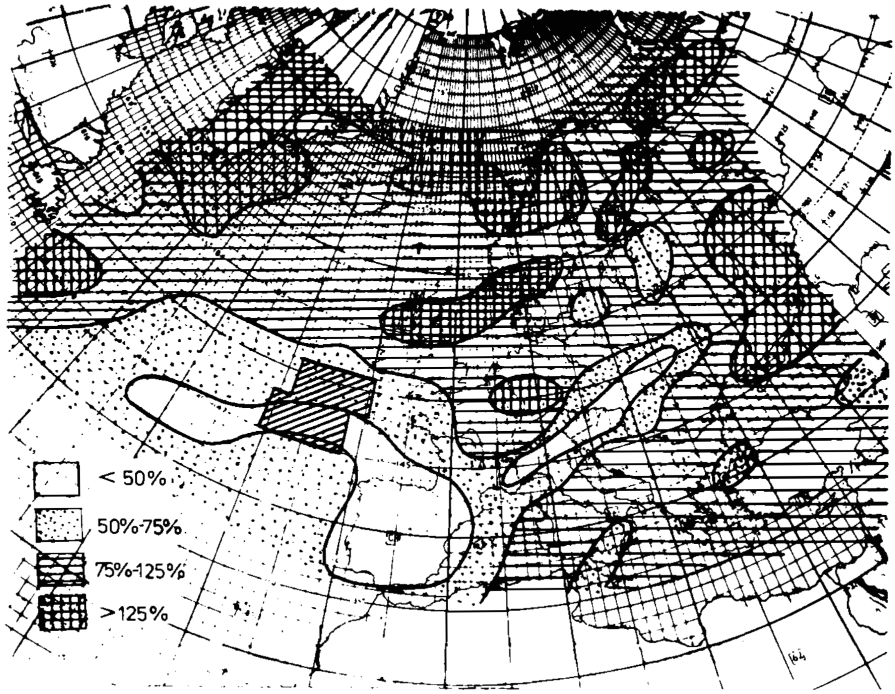


Figure 10. Ratio of rainfall with Atlantic Park and mean rainfall for three control integrations (day 41–80).

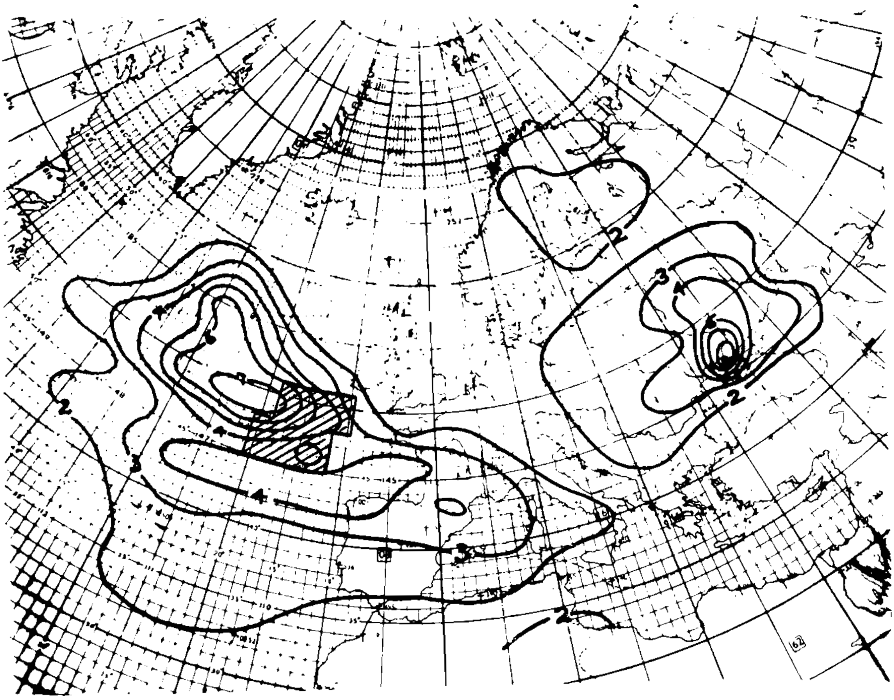


Figure 11. Ratio of surface pressure difference to range of surface pressure in controls.

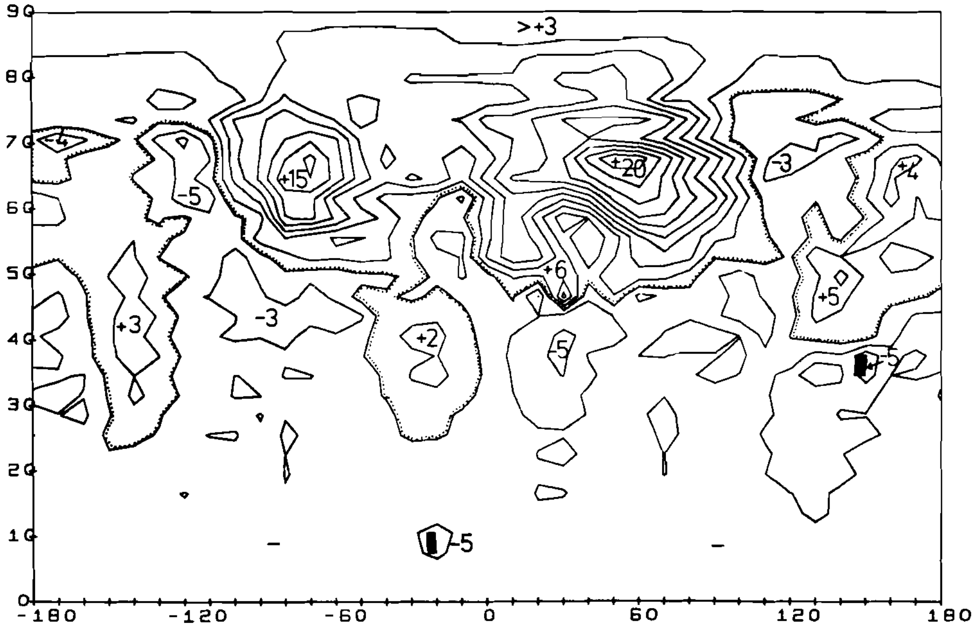


Figure 12. Differences in surface pressure with respect to average of controls–2 (average: days 41–80, unit: mb, isobars: 2mb).

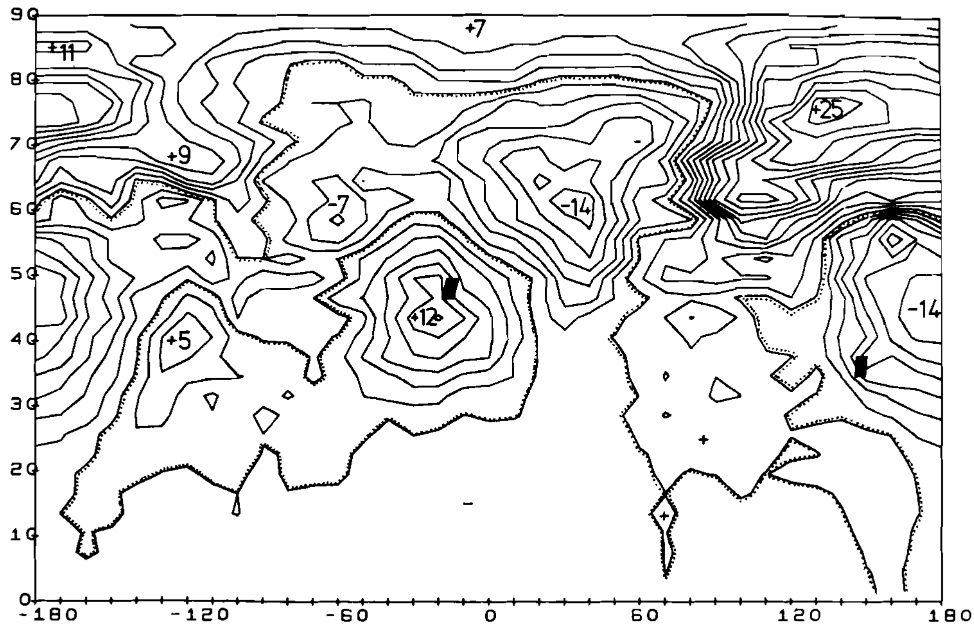


Figure 13. Differences in surface pressure with respect to average of controls–1. (average: days 41–80, unit: mb, isobars: 2mb).

It is now even more important to say a word about the truth value of these results. We rate it low because of the limitations inherent in the present GCM's. Rather, we interpret the results as a way of articulating the issue more clearly with the intention of thereby stimulating a larger long-range action of the meteorological community. In view of the importance of the underlying question, this seems to be necessary.

The IIASA Energy Group has received a contract from UNEP to carry these investigations further.

Waste heat releases pose a problem that is common to all sorts of primary energy production, conversion and use. Energy from fossil sources has a specific problem: the release of CO_2. Even if all other by-products, i.e. SO_2 or NO_x, were retained, CO_2 would still be released into the atmosphere. Increases in the CO_2 content of the atmosphere could lead to the so-called greenhouse effect, i.e. an increase in average global temperature to overcome the CO_2 infrared absorption barrier of the atmosphere. This has been estimated to be perhaps as high as 1 to 2°C for a doubling of the CO_2 content in the atmosphere, which would be enough to induce major climatic changes. Through these conceivable climatic changes, large-scale releases of CO_2 would create a risk. This risk, generated by fossil fuel waste disposal, may be considered in much the same sense as the risk from nuclear fuel waste disposal. Both should be evaluated by the same yardstick.

The problem of assessing the climatological consequences of the greenhouse effect are one side of the coin. More work is required as there are many other effects of a similar order of magnitude that compensate for each other [5].

The other side of the coin is a scenario for the release of CO_2 along with certain energy strategies. What are the orders of magnitude involved? W.D. Nordhaus extended his energy allocation model while he was at IIASA [6], allocating fossil and non-fossil fuel reserves to various markets of the world according to certain demands. Using the data of Machta [7], W.D. Nordhaus considers the CO_2 content and flow in the various layers of the atmosphere and the ocean; see Figure 14, where the CO_2 inputs the troposphere are also identified. In 1970 $2.8 \cdot 10^9$t/year of carbon was emitted, while the carbon content of the troposphere was at $51 \cdot 10^9$t. W. Sassin and W. Häfele considered a scenario [8] for a growing world population of ultimately $12 \cdot 10^9$ people, where an average of 5kW/capita is provided for each inhabitant using fossil energy. This implies a CO_2 disposal to the troposphere of $29 \cdot 10^9$t/year in the year 2020. Without further calculation, simply by looking at orders of magnitude as given in Figure 14, one realizes that there will be a problem of some sort. W.D. Nordhaus therefore considers a situation for standard maximum levels in the CO_2 content of the troposphere. This would finally lead to a limitation in the use of fossil fuels.

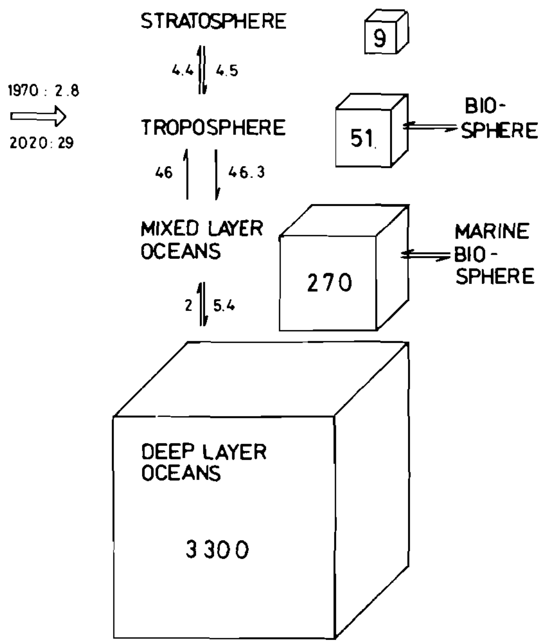


Figure 14. CO_2 reservoirs and CO_2 flow - C contents in 10^9 t, C flow rates in 10^9 t per year (1970 values) (Data: Ref. [7]).

The troposphere could fill up like a balloon, after which fossil power would have to be sharply reduced to values consistent with the rates of transfer from the troposphere to the upper layer of the ocean, and with those from the upper ocean layer to the deep seas. The latter rates are low and therefore so is the permissible fossil power in the scenario considered. Figure 15 gives W.D. Nordhaus' results for standards of CO_2 increases of 50 percent, 100 percent and 200 percent. Figure 16 then indicates the usable integrated amount of fossil fuel. Within the limits of the scenario considered, it appears that only a fraction of fossil resources could thus be used. This would necessitate the building up of non-fossil power as illustrated in Figure 17.

During 1975 R. Avenhaus together with G. Hartmann of the Kernforschungszentrum of Karlsruhe [9] also investigated the CO_2 problem. They considered the asymptotic equilibrium across the atmosphere and the ocean after a major input of man-made CO_2. There exists one condition for all contents and transfer coefficients involved, which can be used as a check for the consistency of measured data. All measured data but one can be used as input into this relation. If the transfer coefficient from the upper ocean layer to the deep sea were to be chosen as this one datum, for instance, one could compare the value

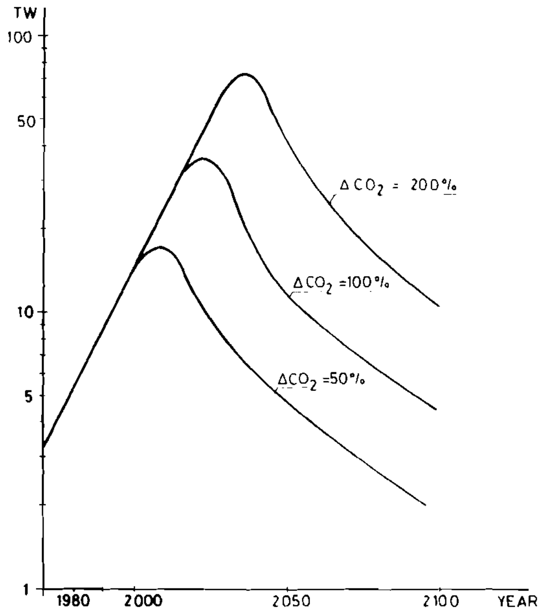


Figure 15. Necessary control of fossil energy consumption, if supplied in the form of coal, to stay below certain CO_2 levels in the troposphere (After: W.D. Nordhaus, IIASA).

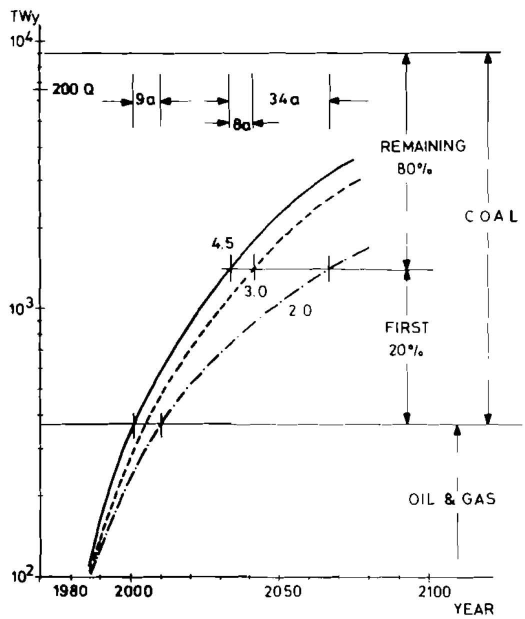


Figure 16. Fossil energy reserves and cumulated energy consumption.

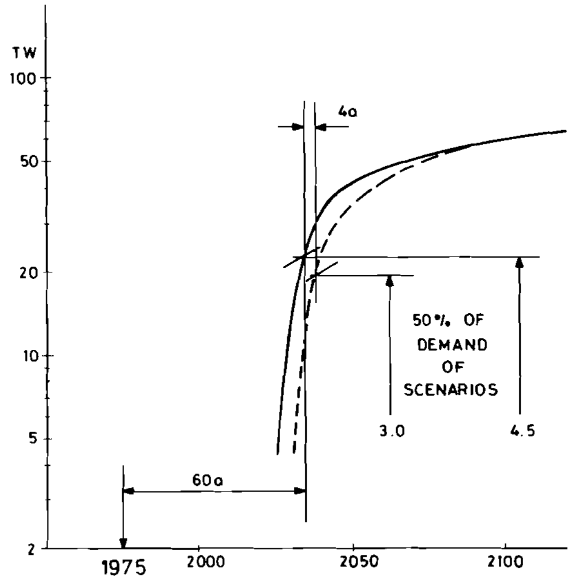


Figure 17. Required non–fossil power production: time for action.

required by the relation with the measured value. It appears that there are significant uncertainties. As this transfer coefficient is the smallest of all, thus dictating the time scale of adjustment to a new equilibrium, it is an important quantity and the uncertainty is relevant.

The interplay of scenario writing and evaluation with discipline-oriented groups is important. It provides brackets for the impacts that must be considered. In the case of the CO_2 problem, the brackets for the CO_2 increase to be tolerated are wide, one may say between 100 percent and 1,000 percent. It is therefore sufficient for the energy problem that the discipline-oriented groups study the greenhouse effect in such crude terms.

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5.2 Risk Assessment[∞]

Harry J. Otway*, Philip D. Pahner[†] and Friedrich Niehaus*

INTRODUCTION

Risk has emerged as a major constraint in the consideration of energy systems, or virtually any technological system. Man has always been exposed to environmental hazards; however, until recently, the nature of these hazards did not change appreciably. Their effects were limited to relatively small geographical areas and discrete time intervals; thus, exposure to these hazards could, to some extent, be influenced by the actions or skills of the individual.

The interest in risk assessment is due to concerns about the dangers man has created for himself. In recent decades technological systems of unprecedented size have been developed and the side effects of these large-scale systems are correspondingly larger, sometimes of world-wide significance for extended time periods. A new category of risks, which accompany the benefits provided by man's technology, has emerged; here the actions and skills of the individual are essentially ineffective.

The occurrence probabilities of many of these side effects are not accurately known because there has not been enough experience with these technologies to obtain statistical measures of risk. Further, there are often uncertainties in the consequences (should a specific side effect occur) because of an incomplete knowledge of the relevant natural laws necessary for prediction. Häfele [1] has referred to an age of "hypotheticality" where theoretical estimates of risk must substitute for experience.

The resulting societal response to these risks has been observed in the emergence of attitudes which tend to regard much that is new as being potentially harmful; the fundamental value of science to society is also being questioned. A variety of

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[∞]Also presented at Commissariat à l'Energie Atomique, Fontenay-aux-Roses, France, 24 November 1975, and at the World Health Organization, Geneva, Switzerland, 27 November 1975.

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individual and group demands have been put forward for a closer examination of the benefits and risks of technological innovations and, indeed, many such advances are encountering difficulties in gaining acceptance by the public.

The nuclear energy field presents an excellent study in risk assessment[1] because the public response to these risks is, in many cases, providing a very real limitation to the development of nuclear power programs. Further, the nuclear field provides many risk situations that are of research interest, such as: examples of cost-effective standard setting where operational risks may be reduced by control equipment expenditures; the possibility of large-consequence, but infrequent, accidents; accident occurrence probabilities which can only be estimated, thus are highly uncertain; the non-random distribution of risks and benefits to different groups of people; concerns about possible future (genetic) risks where benefits are realized at the present time.

The work of the Joint IAEA/IIASA Research Project is directed toward gaining an improved understanding of how societies judge the acceptability of new technologies and how objective information on risks, and the anticipated responses to them, may be considered in decision-making. Examples of energy-related decisions where such information could be useful are: policy-level decisions on the selection and deployment of alternative systems, the setting of regulatory standards, the design of control and safety systems and the development of operating procedures.

The following sections describe the various levels, or types, of risks which must be considered, outline the general structure of risk assessment and discuss the process of risk assessment as applied to technological systems, such as energy systems. The research program of the Joint Project is reported and some preliminary results are presented. More information on Joint Project staffing and organization is presented in the Appendix.

LEVELS OF RISK

The most obvious risks, and those most extensively researched, are those directly affecting man's health and environment; that is, the risks most easily observed and measured. However, one may think of risk situations as being characterized by several levels of risks which must be considered:

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[1] Pahner [2, 3] has suggested that nuclear energy represents a general, and perhaps even symbolic, example of societal concerns about technological development.

1) Physical, biological risks to man and the environment;

2) Perception of these risks by individuals;

3) Potential risk to the psychological well-being of individuals based upon these perceptions; and

4) Risks to social structures and cultures (the structure and values of a society are largely determined by the psychological state of its individual members).

The second level concerns the perception of these risks by the individual. It is known that a number of psychological factors, conscious and unconscious, influence how people perceive situations. There are differences in the way in which individuals perceive situations and, further, their perceptions may be at variance with the "actual" situation.

The third level is the risk to the psychological well-being of the individual due to the anxiety generated by perceiving a situation as potentially threatening. It should be noted that the anxiety generated by a situation inaccurately perceived is no less real than if an actual risk existed.

The final level are risks to social structures and cultures due to the cumulative effects of these psychological risks. If there are a number of individuals in a society who are anxious about a particular situation which they perceive as threatening they seek some form of expression for their concerns. One mode of expression is through identifying and interacting with others sharing these concerns. This may result in the formation of interest groups which may take an active role in trying to influence policies affecting technological development. These interest groups themselves represent new social structures with their own value systems. Thus they have an impact upon the existing social and cultural values; this potential conflict of values may pose a risk to existing social and cultural systems.

Examples of these levels of risk may be seen in the controversy surrounding nuclear energy. A great deal of effort has been made to estimate the physical and biological risks to man from accidents in one type of nuclear power plant [4]. These estimates were then compared to other risks existing in society, implying that the nuclear risks should be "acceptable." However, this controversy is nevertheless characterized, in many countries, by the aggregation of concerned individuals into interest groups whose perceptions of the risks differ from these formal estimates. Their actions create the potential for changes in social and cultural systems which constitute another level of risk. In some countries, policies toward nuclear energy have become an important political issue.

THE GENERAL STRUCTURE OF RISK ASSESSMENT

Risk assessment has been suggested as a general term for the incorporation of risk concepts into the decision-making process [5] and has been defined as occurring in two stages [6], risk estimation and risk evaluation, which will be discussed in detail in this section. A general structure of risk assessment is shown schematically in Figure 1.

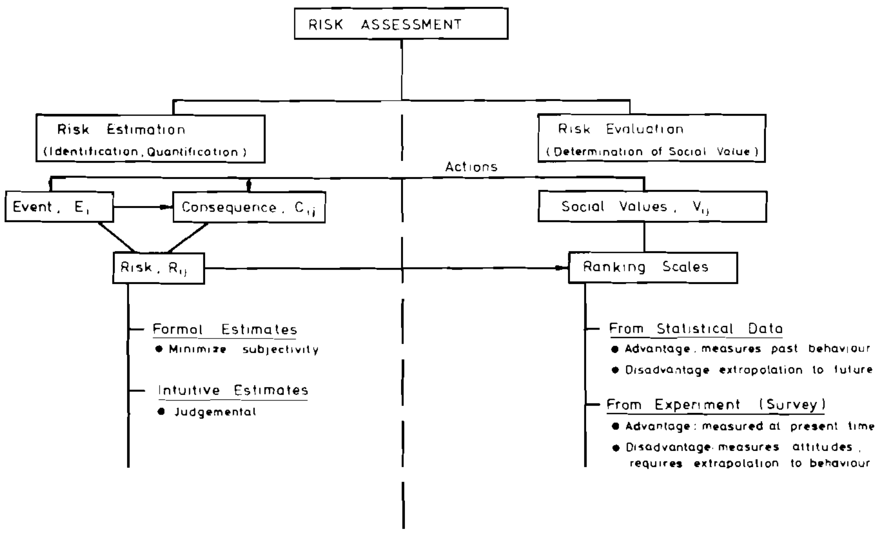

Figure 1. General structure of risk assessment.

Risk Estimation

Risk estimation is the identification of the side effects of a decision and the subsequent estimation of their probabilities and the magnitude of the associated consequences. Some of the earliest formal risk assessments were made in the nuclear energy field, the most recent and comprehensive estimates being those of the U.S. Reactor Safety Study [4] which treated risks from accidents in light-water-cooled nuclear power plants.

In everyday usage risk is usually thought of as the probability of an undesired occurrence, e.g., the risk of having an automobile accident. In this paper risk is thought of as a functional combination of event probability, the uncertainty of the probability, the probability of a specific consequence given the fact that the event has occurred and the uncertainty of this probability. This is shown in Figure 1 by the combination of event, E_i, and its consequence, C_{ij}, to form risk, R_{ij}.

Probability is an important variable in speaking of risk. The measurement of probability has a long history of academic debate (see, for example, [7]). Definitions range from the classical notion that probability is the ratio of favorable occurrences to the total number of equally likely cases (e.g., the roll of a die or toss of a coin) to the subjective or judgmental view, which holds that probability measures one's degree of belief as measured by behavior. Risk estimates might be considered as ranging from objective to subjective; however, the technological risks which are of interest to us can never be estimated in a completely objective manner because the necessary data base does not exist. As pointed out by Fishburn [8], "all measurements of probability rely upon human judgment to some extent." What we would like to think of as objective estimates of risk because they are the product of careful calculational procedures are only attempts to minimize subjective aspects through a more formal approach. The estimate of the layman that a risk is too high is the result of an intuitive approach to the same problem. The point is that these two extremes differ only in the degree of subjectivity involved and, therefore, have been identified in Figure 1 as formal and intuitive methods rather than objective and subjective.

Risk Evaluation

Risk evaluation is the complex process of determining the meaning, or value, of the estimated risks to those affected, i.e., individual, group and society. This has been referred to by Häfele [9] as the embedding of risks into the sociosphere. Evaluation may be thought of as a process of ranking, or ordering, of risks so that their total effects, both objective and subjective, may be compared. This process essentially defines the "acceptability" of risk. The embedding process is shown schematically in Figure 1 as a mapping of risk into ranking scales reflecting societal values toward risk situations. By using the definition of risk proposed earlier we take into account the fact that man is not indifferent to the nature of the event which results in a particular consequence.

A feedback loop is shown through which actions reflecting social values may be taken in order to affect events or consequences. An example of this may be seen in the design of safety systems intended to prevent accidents or to limit the effects should they occur.

Two basic methods of obtaining ranking scales are outlined in Figure 1. The first is based upon the analysis of statistical data to determine the preferences that society has shown in the past toward existing risks. The second is that of experiments (e.g., psychometric surveys) to measure attitudes toward risks.

The former yields information on past behavior, the latter on present attitudes.

The most elementary approach to obtaining rankings is to simply compile a table of accident statistics. A new risk is placed in perspective by comparing a formal estimate of risk with statistical data on existing, and therefore accepted, risks. A limitation of this method is that risk acceptance is situation dependent; many variables determine risk acceptance and they cannot be reflected in such comparisons.

Rankings determined by the analysis of statistical data have the advantage of being based upon actual behavior. However, they are limited by the assumption that past is prologue, that preferences revealed in the past will be valid in the future. This would not be expected to hold for technological risks because social values are changing with time - primarily due to changes introduced by technology. Further, behavior with respect to risk acceptance is multiply determined, i.e., many factors influence the response to risks and all of these determinants are not even known, let alone clearly identified in the data base. Risk perception is important since the response to risk depends upon how situations are perceived, but statistical data report things as they were, e.g., accident rates, demographic variables, public expenditure by categories. Some limitations of rankings based upon these revealed preferences are summarized in [10]. At this point we may observe that evaluations of nuclear power risks made by this method have indicated that nuclear power should be acceptable. However, experience has shown that this is not always the case. This indicates that revealed preferences could be useful in helping decide the risk levels that might be acceptable from an ethical point of view, but may tell us little about what the public find acceptable.

A distinction must be made between attitudes and behavior. The former represent what one says, or thinks, his views toward a given situation. Behavior reflects his actions when actually encountering this situation. Rankings based upon psychometric surveys provide information on attitudes rather than behavior, but the attitudes are measured at the present time.

In summary, we have two methods for risk evaluation available to us: revealed preferences and controlled experiments. The former measures past behavior; it is difficult though to anticipate future behavior based upon observations of past behavior. The latter provides information on attitudes at the present moment; the problem here is one of anticipating behavior based upon attitude measurements.

The Determinants of Risk Perception

The location of a specific risk in a ranking scale is multiply determined; many factors, conscious and unconscious, are involved. We have already mentioned voluntary versus involuntary exposure to risk and that virtually all technological risks, in which we are interested, are essentially involuntary.

People react to a threat based upon what they perceive it to be, not necessarily upon what it actually is. Intuitively derived probability estimates, and therefore risk estimates, may be inaccurate due to the effect of psychologically determined factors [11] [12] which influence perception. There has been little research in the behavioral sciences on attitudes and beliefs with respect to the perception and acceptance of technological risks. As a result there is no body of behavioral theory from which to seek guidance. Therefore, identification of the factors determining risk perception and the knowledge of their relative importance is an important research topic.

THE PROCESS OF RISK ASSESSMENT: TECHNOLOGICAL SYSTEMS

Figure 2 introduces social dynamics into the structure of risk assessment developed in the last section. This process includes the contributions of three social groups: the sponsor who proposes a technological development, the public for whom the benefit is intended, and the regulator who has the responsibility of balancing the needs of both groups[2]. In the following discussion the numbers in parentheses refer to the respective boxes in Figure 2.

The Sponsor

The process starts with a societal need which may be satisfied by some proposed application of technology; for example, energy needs met by the construction of a power plant. The sponsor may perceive the proposal (Box 1) as a design problem (Box 12). In his design he must ensure that the required benefit is provided and that any potential side effects meet regulatory standards. These side effects are characterized by events, E, (such as accidents) and their consequences, C, which must be considered in the design.

Figure 2 also introduces the concept of an unknown set, $\emptyset$, of potential events or consequences which could actually occur but cannot be included in design considerations because their existence has not yet been discovered. An additional "inverse," unknown set, $\emptyset'$, has also been postulated to represent those events and consequences which have been imagined by the designer but could, in fact, be proved impossible if natural laws were perfectly known. Regulatory agencies may require situations to be considered in design

[2]Figure 2 closely parallels the structural hypothesis of mental mechanisms proposed in reference [13].

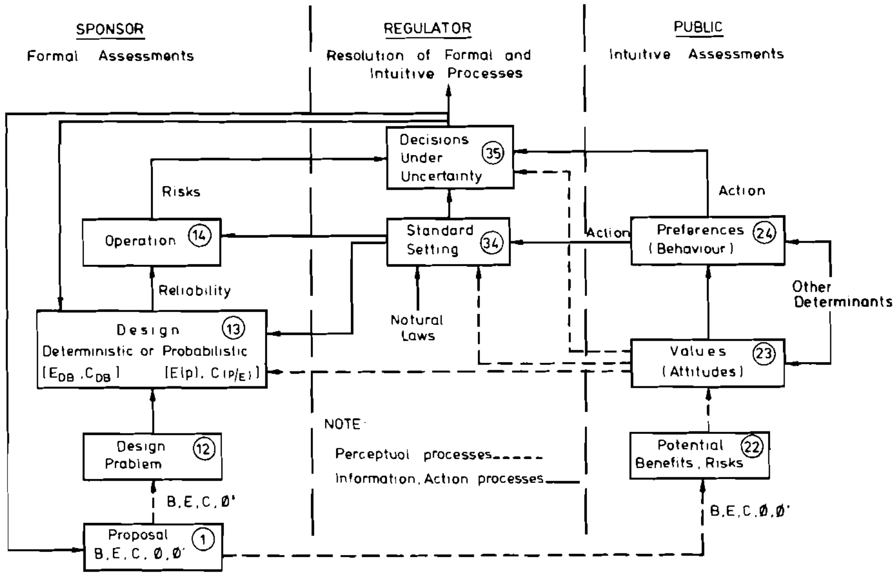

Figure 2. Process of risk assessment: technological systems.

which are unrealistic; this is done in order to provide safety margins. These also form part of the inverse unknown set.

The design of the sponsor (Box 13) may proceed in the traditional, deterministic manner in which design base limits are assumed for E and C. Safety systems are engineered which will allow adherence to regulatory standards should the design basis situation occur. An alternative design method is the probabilistic approach which does not employ artificial design limits. There are no limits to the events and consequences considered; however, they are weighted by their probabilities and risks are kept to acceptable levels through reliability design. Whichever design method is chosen the reliability of systems is fixed, either directly or indirectly. Reliability combined with operational philosophy (Box 14) determines the risks to which the public is exposed. The designer's perceptions of the relevant social values are also considered in the design process.

The Public

The public perceive the proposal (Box 1) as a potential source of societal benefit and risk (Box 22). Their intuitive estimations of risk can include allowances for the unknown set, Ø, of things possible but not considered in design. These allowances are not based upon superior technical knowledge but may be expressed simply as a lack of confidence in the designers, operators or regulatory authorities. An inverse unknown set, Ø', of things that cannot happen based upon natural laws may also be considered. An example of this is the fear of some that nuclear power plants may explode as atomic bombs. As unrealistic as such concerns might be they still influence the perception of risk. The public and the designer consider different inverse unknown sets; this reflects different conceptual frameworks.

This difference in conceptual framework initiates the process of social controversy, one manifestation of which is the interest group. The interest group may be viewed as a confluence of social systems which includes: the individual and his repertoire of psychological responses; the influence of the scientific community; availability and communication of information; various economic and political considerations; societal and cultural determinants; and the historical moment. The interest group thus represents the focal point of the interaction of these various systems.

On an individual level the response to a fear-provoking stimulus (e.g. new technology) is distributed along a continuum, conceptualized most primitively as "flight or fight." There may be an apathetic physical and emotional withdrawal from the perceived threat. In some cases an attempt to deny the existence of any risk is seen. At the other extreme there may be a readiness to confront, a struggle to understand the nature of the risk, and a willingness to deal with it effectively. In any case these may be understood as expected human responses to anxiety-provoking, external situations. In addition to external threats, internal fears and anxieties may be projected onto a symbolic external object. As these fears are expressed the individual encounters others who think and feel and act similarly.

An interest group reflects, to varying degrees, elements of its members' individual responses, characteristics of its societal-cultural environment, and an indication of the information available. An interest group, however, has its own characteristics. Observations and research on interest groups support the following generalizations:

a) Interest groups tend to form around affect-laden, social and environmental concerns;

b) They tend to be solution-oriented rather than problem-oriented, inclined to a dialectic, adversary position rather than one of collaborative exchange;

c) Constituency and cohesiveness of a group is related to the degree members share similar values and attitudes;

d) Communication patterns are often distorted, especially in groups with a vertical status and power hierarchy;

e) New information may be accepted or rejected contingent upon the support it provides for group values and beliefs; and

f) Behavioral responses of members are influenced by the group so that the strength and integrity of individual values may be weakened or strengthened.

Thus, the interest group tends to be a body of persons emotionally committed to their position and screening information according to the utility it has for their position [14].

It must be realized that such generalizations fail to consider the more adaptive, positive aspects of interest groups. They may serve an important alerting, activating function-drawing attention to possibly threatening social, political or environmental situations. The interest group may break through a tendency to withdraw from or to deny potential risks and thereby promote a deeper understanding of poorly conceptualized technological proposals [15].

Values or attitudes toward risks (Box 23) are multiply determined. The perceived risks are intuitively incorporated into this system of values which can be measured by means of the ranking scales referred to earlier. Preferences related to risk acceptance (Box 24) exist only when revealed by behavior. Thus lines of action are shown in Figure 2 leading from Box 24 into the regulatory sector.

The Regulator

Regulatory functions occur on several levels. One is the agency responsible for setting standards (Box 34) to regulate specific environmental effects which may arise from, for example, radioactive, thermal or chemical releases. Standard-setting takes into account the effects of environmental insults as predicted by natural laws and the perception of the relevant social values (Box 23). If standards are incompatible with social values then societal preferences may be expressed by active demands that standards be changed (the action represented by the line from Box 24 to Box 34).

Another level of the regulatory process is one where a decision must be taken, under conditions of uncertainty, regarding approval of the proposal (Box 35). This decision might require changes in the proposal, design or operation and could be appealed by societal action (Box 24). The final regulatory step which, depending upon the political process might include the judiciary, is the resolution of the formal risk assessment of the sponsor and the intuitive risk assessment of the public. For simplicity, these regulatory functions have been shown as one step in Box 35.

estimations of risk can include allowances for the unknown set, $\emptyset$, of things possible but not considered in design. These allowances are not based upon superior technical knowledge but may be expressed simply as a lack of confidence in the designers, operators or regulatory authorities. An inverse unknown set, $\emptyset'$, of things that cannot happen based upon natural laws may also be considered. An example of this is the fear of some that nuclear power plants may explode as atomic bombs. As unrealistic as such concerns might be they still influence the perception of risk. The public and the designer consider different inverse unknown sets; this reflects different conceptual frameworks.

This difference in conceptual framework initiates the process of social controversy, one manifestation of which is the interest group. The interest group may be viewed as a confluence of social systems which includes: the individual and his repertoire of psychological responses; the influence of the scientific community; availability and communication of information; various economic and political considerations; societal and cultural determinants; and the historical moment. The interest group thus represents the focal point of the interaction of these various systems.

On an individual level the response to a fear-provoking stimulus (e.g. new technology) is distributed along a continuum, conceptualized most primitively as "flight or fight." There may be an apathetic physical and emotional withdrawal from the perceived threat. In some cases an attempt to deny the existence of any risk is seen. At the other extreme there may be a readiness to confront, a struggle to understand the nature of the risk, and a willingness to deal with it effectively. In any case these may be understood as expected human responses to anxiety-provoking, external situations. In addition to external threats, internal fears and anxieties may be projected onto a symbolic external object. As these fears are expressed the individual encounters others who think and feel and act similarly.

An interest group reflects, to varying degrees, elements of its members' individual responses, characteristics of its societal-cultural environment, and an indication of the information available. An interest group, however, has its own characteristics. Observations and research on interest groups support the following generalizations:

a) Interest groups tend to form around affect-laden, social and environmental concerns;

b) They tend to be solution-oriented rather than problem-oriented, inclined to a dialectic, adversary position rather than one of collaborative exchange;

c) Constituency and cohesiveness of a group is related to the degree members share similar values and attitudes;

d) Communication patterns are often distorted, especially in groups with a vertical status and power hierarchy;

e) New information may be accepted or rejected contingent upon the support it provides for group values and beliefs; and

f) Behavioral responses of members are influenced by the group so that the strength and integrity of individual values may be weakened or strengthened.

Thus, the interest group tends to be a body of persons emotionally committed to their position and screening information according to the utility it has for their position [14].

It must be realized that such generalizations fail to consider the more adaptive, positive aspects of interest groups. They may serve an important alerting, activating function-drawing attention to possibly threatening social, political or environmental situations. The interest group may break through a tendency to withdraw from or to deny potential risks and thereby promote a deeper understanding of poorly conceptualized technological proposals [15].

Values or attitudes toward risks (Box 23) are multiply determined. The perceived risks are intuitively incorporated into this system of values which can be measured by means of the ranking scales referred to earlier. Preferences related to risk acceptance (Box 24) exist only when revealed by behavior. Thus lines of action are shown in Figure 2 leading from Box 24 into the regulatory sector.

The Regulator

Regulatory functions occur on several levels. One is the agency responsible for setting standards (Box 34) to regulate specific environmental effects which may arise from, for example, radioactive, thermal or chemical releases. Standard-setting takes into account the effects of environmental insults as predicted by natural laws and the perception of the relevant social values (Box 23). If standards are incompatible with social values then societal preferences may be expressed by active demands that standards be changed (the action represented by the line from Box 24 to Box 34).

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Summary

Reports such as the U.S. Reactor Safety Study [4] serve a valuable function in formalizing the estimation of risks to which the public is exposed. Such work would also allow the determination of the system reliabilities necessary to satisfy standards based upon risk consideration. The emphasis here is upon formal risk estimates which correspond to Boxes 13 and 14.

The work of the Joint Project is directed toward gaining a better understanding of the perceptual processes shown in Figure 2. This would allow information on societal attitudes (Box 23) to be considered in design and standard setting. The uncertainties in the general decision-making process (Box 35) would also be reduced.

RESEARCH PROGRAM AND PRELIMINARY RESULTS

The research activities of the Joint Project may be divided into six sub-tasks, related to the process illustrated in Figure 2 which will be described in this section. Preliminary results will be briefly summarized, readers are referred to the referenced publications for details.

Advanced Methods in Risk Estimation

Due to the relatively small statistical data base it is difficult to make risk estimates for low-frequency, high-consequence accidents such as those that might occur in nuclear power facilities. Mathematical techniques, such as fuzzy set theory, are being applied to making macroscopic risk estimates which may then be compared with estimates based upon microscopic techniques such as accident/fault tree analysis [16]. This work represents a supplement to the methodologies used in the U.S. Reactor Safety Study.

The Application of Risk-Benefit Principles to Standard-Setting

An important factor in standard-setting is that of expressing disparate variables in consistent units so that comparisons may be made between risk reduction and its cost. This is especially difficult in the case of activities which involve risk to human life. The Pareto theoretical approach is being adapted to the evaluation of such risks and the possibility of using Pareto criteria for the treatment of statistically and non-statistically distributed risks is being examined. The effects of further variations are also being considered in this theoretical work, for example, the question of genetic risks that occur in the future where the benefits are short term and are taken by the present generation.

A survey has been made which concentrates upon practice (mainly in France and the U.S.A.) in evaluating public projects involving life saving [17]. Further a review of theoretical models for determining the "value" of mortality risk in decision-making has been completed [18]. These theoretical treatments have been applied to nuclear power plant economics [19] and the problem of quantifying environmental risks [20].

An application was made to the treatment of tritium and krypton-85 in nuclear facilities [21,22]. This work indicates that, based upon the number of publications on the health and safety effects of these two isotopes, more attention has been given to the control of tritium releases. However, the world-wide radiation dose from tritium released in the nuclear industry is not only less than that from krypton, but it is smaller than that from naturally occurring tritium and far smaller than that due to residual tritium from weapons testing. This means that adding controls to further reduce tritium releases from the nuclear industry would hardly change the total tritium dose. Since there is essentially no krypton background level, krypton controls would have a direct effect. An estimate of the cost of reducing tritium releases by fifty percent using current technology, is about $170,000 per manrem of radiation exposure avoided. A comparable cost for reduction in krypton releases might be less than $100 per manrem. The theoretical considerations mentioned earlier would indicate that $200 is a reasonable expenditure for the avoidance of one manrem of whole body irradiation. The conclusion here is that further consideration might be given by the nuclear industry to the relative expenditures for control of these two isotopes.

A further application was made to the cost-effectiveness of remote nuclear power plant siting [23]. Figure 3 shows the basic principle of the cost-effectiveness of risk reduction. The hypothesis is that it will be much easier to reduce a risk from a high level S_0 to a lower level S_1 than to reduce an already low risk, e.g. S_5 to S_6. The marginal costs of risk reduction given by $\Delta R_i/\Delta C_i$, increase rapidly with decreasing risk levels.

In order to apply these principles to the remote siting of nuclear power plants (NPP), a model densely populated area (DPA) was assumed to be located at different distances from a nuclear power station. The population distribution is shown in Figure 4. Population densities and electrical energy needs were derived from a recent study for the Federal Republic of Germany [24]. The city was assumed to be divided into two sectors surrounded by a suburban ring. Outside of this area the population is homogeneously distributed with a density of 248 people/km^2. The energy needs of this model area are assumed to be supplied by a 1,000 MW(e) NPP operating at an average load factor of 0.74.

The NPP was assumed to be a light-water reactor of the type analyzed in WASH-1400 [4] and risk calculations were performed for the reference accident (PWR 2) analyzed in that report (failure of core cooling system, core melting, failure of containment barrier through overpressure). As the

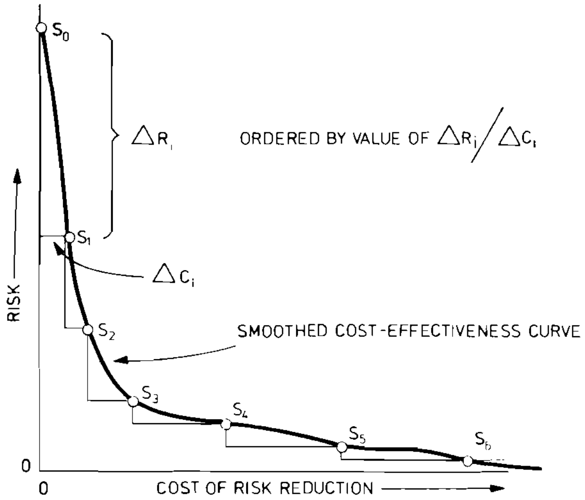

Figure 3. Cost–effectiveness of risk reduction, ordered relationship for discrete actions S_1–S_6.

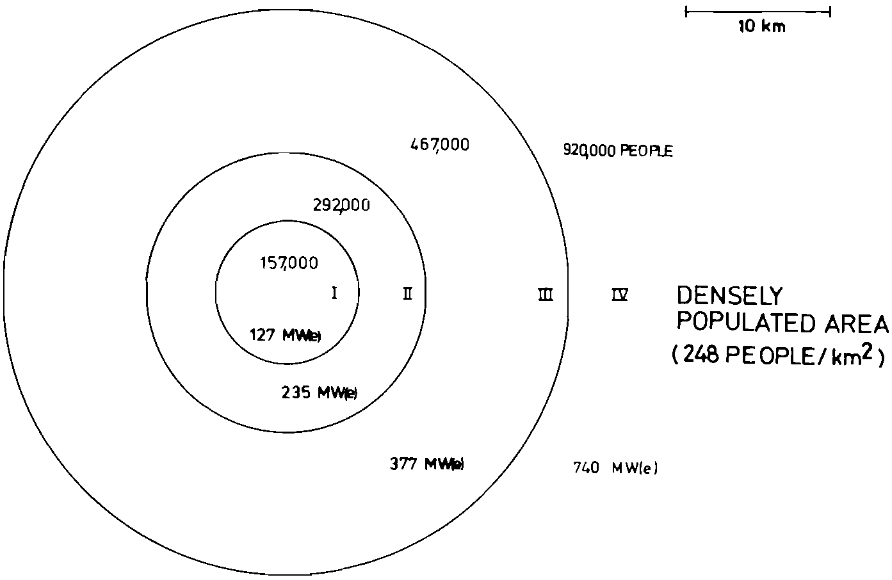

Figure 4. Population and energy use distributions.

consequences of this reference accident were calculated to account for sixty-five percent of the overall risk from pressurized water reactors, the risk from this accident dominates the total risk from reactor accidents. It was therefore assumed that the remainder of the accident risk would be proportional to that from this reference accident. The results of these calculations are given in Figure 5 which shows the incremental population dose as a function of the distance to the NPP. The lower curve was calculated using the average population distribution; therefore, the hatched area under this curve gives the overall population dose due to the reference accident and the average population distribution (base case). This integration was performed, as was done in WASH-1400, up to a distance of 500 miles (800 km), and the population dose found to be 28 x 10^6 manrem. If the DPA were located at distances of 20, 30, 50, 70 or 100 km from the nuclear power station, the variations shown in the other curves of Figure 5 would result. Therefore, the area between the base-case curve and the curves for various DPA distances is a measure of the additional risk due to the presence of the densely populated area at the distances indicated. For example, in the case of the DPA 30 km from the NPP the additional risk is given by the dotted area of Figure 5.

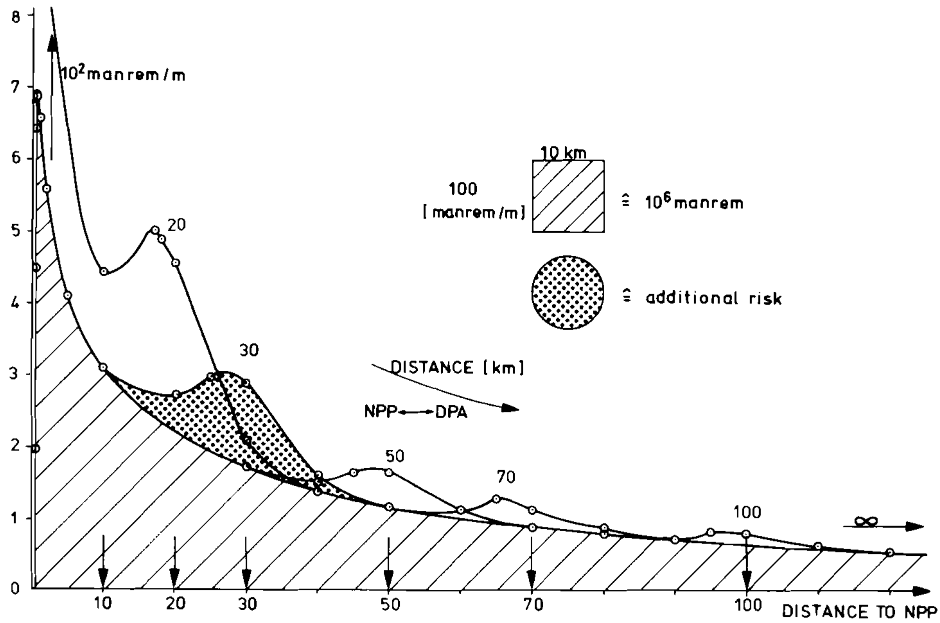

Figure 5. Incremental population dose versus distance.

A smaller distance between NPP and DPA causes a saving in energy transportation costs. Recent calculations for the Federal Republic of Germany lead to an estimate of 1.8 DM/Gcal x 100 km for a two-system 380 V transmission line [24].

Based upon these data the dose-cost relationship given in Figure 6 can be derived. Spending an infinite amount of money for energy transportation would make it theoretically possible to build - in this model area - the NPP at an infinite distance from the DPA. Therefore, the additional risk would be zero. This is expressed by the curve approaching the abscissa. However, if only 2 x 10^6 DM/year is spent for long-distance energy transportation (instead of an infinite amount) there would be an additional risk of about 50 manrem/ year.

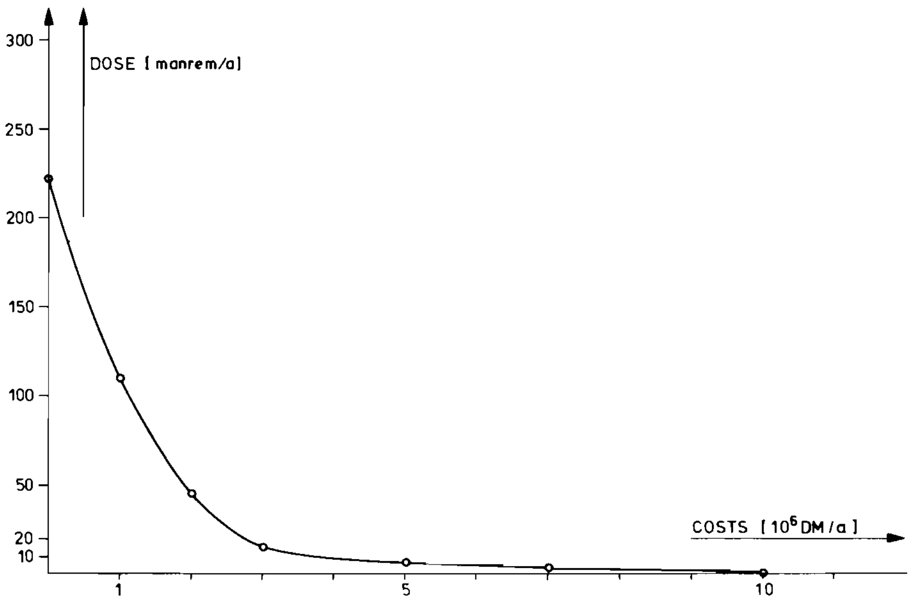

Figure 6. Dose–cost relation of siting.

The derivative of this curve gives the marginal costs of risk reduction due to remote siting (shown by Figure 7). At a distance of 100 km between NPP and DPA the marginal costs are in the range of about 10^6 \$ per manrem reduction. With decreasing distance the cost of preventing one manrem of exposure decreases rapidly. But the value of $1,000 per manrem exposure chosen by the United States Nuclear Regulatory Commission [25] as a conservative estimate of the expenditure justified to avoid one manrem of exposure is not reached. This indicates, based upon the foregoing, that remote siting is not cost effective.

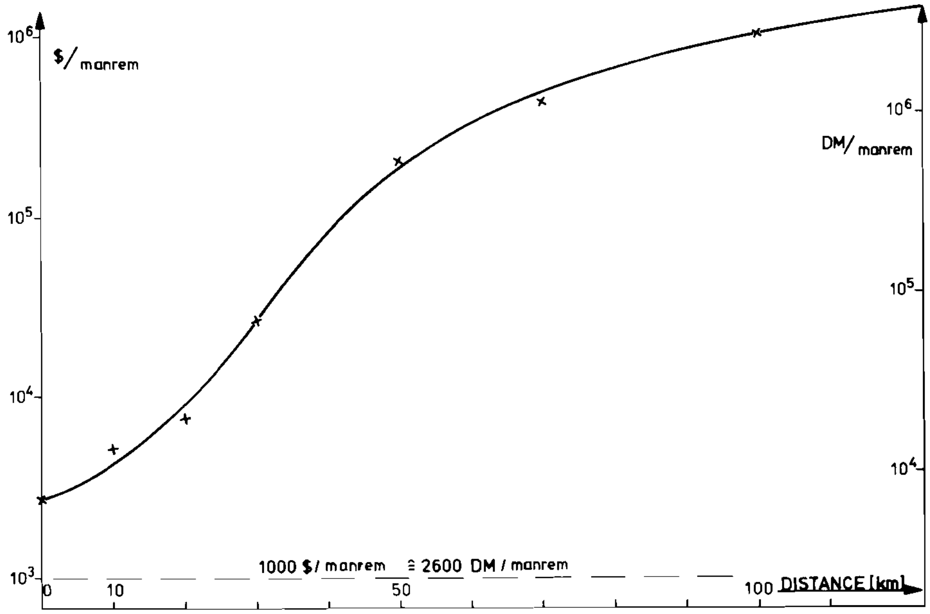

Figure 7. Marginal costs of risk reduction through remote siting.

In order to improve these calculations with regard to the acute deaths in the vicinity of the NPP a disaggregation of the consequences into acute deaths and sub-acute radiation exposures was performed. This allows consideration of the differing biological effects of acute versus sub-acute radiation exposure. Assuming indifference between one acute death and 10^3 manrem to a large population leads to nearly the same results as were shown in Figure 7 except that the curve has a minimum at about 20 km, or 10^4\$ manrem, reduction. If one assumes that one acute death is equivalent to 10^4 manrem, it leads to a minimum at a distance of about 20 km - a little less than 1,000 $/manrem. It is thought that these two relationships bound the range of proper estimates for the biological effects of radiation.

In discussing these results it must be stressed that only energy transportation costs were taken into account. Further advantages of central siting given by the possibility of waste heat utilization or district heating were not considered. These criteria, however, do not consider sociological and psychological factors which may be of critical importance, perhaps providing sufficient justification for remote siting.

These calculations were performed for estimating what costs we are paying today for risk reduction in one specific area, and it is planned to compare them with data from other technical or social systems in order to provide more insights into man's behavior toward risk.

The Perception of Risks

The perception of risks is a crucial factor in determining attitudes; obviously people respond to a threatening situation based upon what they perceive it to be rather than what it might actually be. An effort is therefore being made to develop survey techniques for determining how various types of risk are perceived. A further goal is the identification of the variables which influence risk perception and the determination of their relative importance.

A survey has been done in Austria [26] as a replication of one previously done in Canada [27], to obtain ordinal rankings for various hazard situations. The objectives of the Austrian study were primarily to gain experience in administering this type of survey and to develop computer programs for data analysis. A secondary objective was to make a cross-cultural comparison of risk perception.

The overall cross-cultural rank-size correlation coefficient for the two groups was found to be $r = 0.62$. In the Canadian group the effect of the experience with specific risks was found to be most important in determining response (experienced respondents versus inexperienced, $r = 0.45$). This was not found in the Austrian sample ($r = 0.81$) where the most important determinant of risk perception was found to be the subjects' self-rated ability to imagine themselves in particular risk situations ("good" imaginability versus "poor," $r = 0.59$). This latter result is conjectually interesting in the case of nuclear power plant risks where imagination must substitute for experience and difficulty in imagining a specific hazard situation correlates with the higher ranking of that hazard.

Another survey [28], designed to be less culturally dependent by using pictures of risk situations, confirmed by factor analysis that an important determinant of risk perception is the active-passive dimension. This is a significant result supporting theories that activeness in everyday situations is a crucial psychological dimension (see, for example, [29]). This study also indicated statistically significant differences between men and women in the perception of risk situations: men tend to perceive a given situation as being of lesser risk. This finding raises interesting questions about the conscious and unconscious mental mechanisms involved in perception processes.

A pilot survey, presently being evaluated, explores the effect of fourteen different potential determinants upon the perception of risk situations. These determinants include: experience, skill, flexibility, transparency of the situation, and others.

An interesting survey compared the risk perception of various technological or public facilities: gas works, district heating plant, oil refinery, psychiatric hospital, nuclear reactor, prison, airport. Respondents were asked to rate the risk of living near each facility. Three groups were sampled: those living near the fossil-fueled district heating plant, those living near the nuclear reactor and a control group. One preliminary result indicates that those living in the vicinity of a nuclear reactor felt that they were at lower risk than a group living somewhat further away. This could be interpreted in several ways ranging from the hypothesis of the unconscious mental process of denial of threat to the possibility that the group living nearby is better informed. These data are still being analyzed. The survey work is a collaborative effort with the University of Vienna, Psychological Institute.

The possible unconscious process of denial of the threat of nuclear war and the unconscious displacement of this anxiety to the civilian applications of nuclear energy has been suggested by Guedeney and Mendel [30] and Pahner [3]. Additional consideration is being given to the psycho-analytic aspects of the symbolic and unconscious determinants of risk perception.

Preferences Related to Risk Acceptance

Starr [31] postulated some determinants of risk behavior based upon the analysis of national accident statistics. This work developed a philosophical basis for risk assessment and served to draw attention to the importance of such research. Based upon these analyses Starr suggested three major determinants of risk acceptance and assigned weightings to them. The major points were:

"1) The indications are that the public is willing to accept 'voluntary' risks roughly 1,000 times greater than 'involuntary' risks.

2) The statistical risk of death from disease appears to be a psychological yardstick for establishing the level of acceptability of other risks.

3) The acceptability of risk appears to be crudely proportional to the third power of the benefits (real or imagined)...."

The methodology used was reviewed and an attempt was made to reproduce the Starr results [10]. The results could not be reproduced using this method and it was concluded that, while the Starr hypothesis regarding the identification of these determinants (at least 1 and 3 above) was probably philosophically correct, the results could not be justified on the basis of his analysis. It was further concluded that the mathematical relationships indicating the relative importance of the determinants must be regarded as unlikely.

Further efforts in this direction will concentrate upon the combination of statistical analysis and behavioral theories employing an iterative process of empirical, multi-variable analysis. This work is a collaborative effort with the Study Group for International Analyses, Vienna.

Information Transmission and Group Dynamics

The communication of scientific information also plays a role in the development of societal attitudes, shown in Figure 2. Groups serve a mediating function between the individual and the larger society, because the individual interacts with society through his membership in various groups, e.g., family, professional, fraternal, etc. Therefore, an understanding of group dynamics is important in learning how individual attitudes and preferences are aggregated to form attitudes at the societal level. In the case of nuclear power plants it has been observed that until a project is made known there is often little immediate concern about nuclear hazards among most inhabitants of the area. Once the plans are announced, people soon become acquainted with thinking about the possible threats; they may be forced by circumstances to form relevant opinions. The project then is judged on a number of levels: individual, group, community, national and perhaps even international. As the responses to the proposal gradually emerge it has been noted that various interest groups start to form, develop their sources of information and, in many cases, work actively to promote or oppose the proposed facility.

As a preliminary step in understanding this problem, risk phenomena in traditional, small-scale societies have been analyzed [32] to aid in understanding this process. The observation of several interest group situations has allowed the derivation of a set of typical interest group characteristics [15]. A systems analysis application to nuclear power plant siting has been published [33]. The group dynamics observed in the nuclear power plant debate, as well as the information transmission patterns are being studied in collaboration with the European Centre for Social Welfare Training and Research (Vienna) through an analysis of nuclear power plant siting controversies.

CONCLUDING REMARKS

The intent of this paper was to outline a conceptual framework for risk assessment studies which includes, not only consideration of physical risks to man and environment, but also pays attention to factors influencing how risk situations are perceived and the resulting psychological and sociological levels of risk. The research program of the Joint IAEA/IIASA Research Project is presented and some preliminary results of this work were summarized. Most risk assessment research to date has concentrated upon estimating the risks from technological activities and upon comparison of these estimates with other, but different, risks existing in society. These comparisons, however, cannot take account of the situation dependent factors which determine both how risks are perceived and the response to them.

Preliminary results cited here suggest that nuclear power plant siting practices may be far from being cost effective. In fact, expenditures for nuclear safety appear, in some cases, to be several orders of magnitude higher than would be justified if biological risks alone were a sufficient criterion. The fact that these expenditures are being made and that, even then, many facilities cannot gain broad-based public approval underlines the practical importance of better understanding the sociological and psychological levels of risk. Observations indicate, however, that anxieties generated by concerns about the perceived risks of technological development pose risks to the psychological well-being of individuals. These individual concerns are then aggregated in the form of new social groups which may play an active role in trying to influence policies affecting technological development. These interest groups themselves represent new social structures with their own value systems. Thus they have an impact upon the existing social and cultural values; this potential conflict of values may pose a risk to social and cultural systems.

There has been very little research on these higher order effects of technological risks. It is hoped that the research program which has been presented here will provide new insights into these questions.

APPENDIX

The Joint IAEA/IIASA Research Project was formed in mid-1974. Organizationally the Joint Project comes under the IIASA Energy Systems Project and the IAEA Department of Technical Operations. As of October, 1975 the project consisted of eight professional and three general services staff; IAEA provides the Project Leader and general service staff, and IIASA provides three scientists. IAEA Member States (Federal Republic of Germany, Japan, Sweden, the United Kingdom and the United States of America) have indicated their interest in this work by providing seconded scientists on a cost-free basis. Additional scientific collaboration is obtained through IAEA-sponsored research contracts with the Psychological Institute of the University of Vienna, the Study Group for International Analyses, and the European Centre for Social Welfare Training and Research. The following disciplines are represented in the Joint Project: physics, public health, systems engineering, economics, anthropology, psychiatry/medicine, psychology and sociology.

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Part 6: STRATEGIES

PART 6. STRATEGIES

6.1 Transition Strategies - A Linear Programming Model

Leo Schrattenholzer

INTRODUCTION AND SUMMARY

Five options are being discussed for a long-term energy supply, namely nuclear fission, nuclear fusion, solar, geothermal and coal. The work of the Energy Project focuses on a comparison of these options. The approach is to look into scenarios in which one option dominates and to study the systems implications of each option. An important aspect of a scenario is the transition problem, i.e., the transition from today's situation to the one envisaged for the future. One contribution to solving this problem has been made by Häfele and Manne [1] who constructed a model that determines the minimum-cost transition to an all nuclear energy supply. The basic idea underlying this model can also be used to study other kinds of transition problems.

This paper roughly describes the Häfele-Manne model[1] and mentions the results that can and have been obtained, the modifications that have been made, as well as future uses of the model.

DESCRIPTION OF THE BASIC MODEL

The basic model is a linear programming model that minimizes the sum of discounted costs for supplying the total energy demand of a model society over a given planning horizon. The planning horizon is 75 years divided into 25 time periods.

Demand

Three model societies have been considered; each has the following initial conditions:

a) $250 \cdot 10^6$ people consuming;

b) 10 kW(th)/cap in 1970 (the base year); and

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[1]For details concerning model description, results and conclusions, see [1] to [7].

c) 25 percent of total primary energy is used for electricity generation.

Model society 1 saturates in the year 2015 at:

a) $360 \cdot 10^6$ people consuming;

b) 20 kW(th)/cap; and

c) 50 percent of total primary energy is used for electricity generation.

In model society 2, the demand grows exponentially at annual rates of 3 percent for electricity and 1 percent for non-electric energy (Figure 1). Model society 3 is similar to model society 2, but the demand of model society 3 is assumed to be price responsive and therefore endogenous; the demand of model society 2 is used only as a "reference."

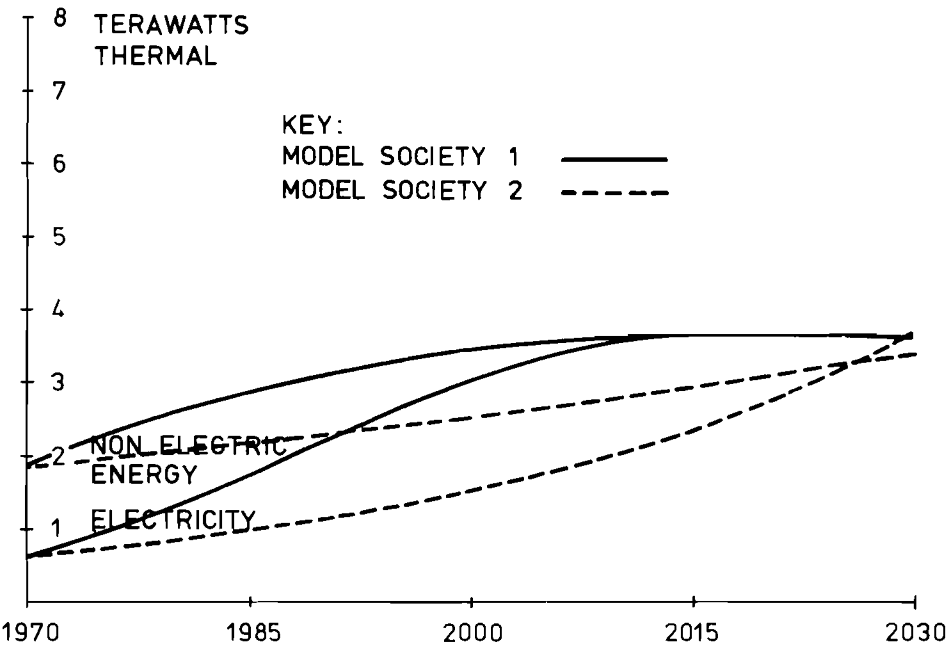

Figure 1. Exogenously–fixed demands.

Thus there is a qualitative difference between model societies 1 and 2, and model society 3. This means that the basic model can be applied for any set of demand data either for the price responsive case or for the fixed cases.

Supply

The following supply alternatives are being considered. For electric energy - coal, light-water reactors (LWR), and fast-breeder reactors (FBR); and for non-electric energy - oil and gas (these are aggregated in the model), synthetic fuel (e.g., hydrogen) produced by the process heat of the high temperature gas-cooled reactor (HTGR) and electrolytic hydrogen. The interconnection between the two demand sectors is twofold. First, the FBR breeds uranium-233 needed as fuel for the HTGR; secondly, intermediate demand for electricity is added endogenously to the projected demand to provide electricity for producing electrolytic hydrogen.

Constraints

In addition to the demand constraints which ensure that the demand is met in each time period, there are the following constraints on the supply side:

a) Natural resource availability.

The amount of oil and gas available to the model society is one of the key parameters of the model; nevertheless much uncertainty is connected with the actual figure. Therefore, the first step of a sensitivity analysis has always been to vary the amount of oil and gas reserves. To distinguish these different cases, a "static" number is employed indicating the ratio between the total reserves that may be used by the model society and the society's consumption during the base year. Therefore, case 1.60 refers to model society 1 and to 60 years of oil/gas availability.

For natural uranium, only the reserves of low cost uranium are constrained, and there is no limit to high cost uranium.

A limit to the coal resources can be set, but since the world's coal reserves are much less critical than those of oil/gas, this possibility has not been used so far.

b) Nuclear material balance.

These constraints ensure that the stockpiles of both plutonium and uranium-233 are non-negative in each time period.

c) Upper bounds for introducing new technology.

These upper bounds reflect one of the most important aspects of the transition problem, namely the limited speed of introducing new technologies.[2]

Input Data

The following input data are needed:

a) The model society or, in other words, the projected demand of each of the sectors specified for each time period;

b) The cost figures (both low and high) for current and capital costs of the primary energy supply as well as for natural uranium;

c) The data for the availability of coal, oil/gas and low cost natural uranium;

d) Reactor performance data;

e) Specification of upper bounds for introducing new technology; and

f) Conversion efficiencies and fuel utilization factors.

Since the demand for non-electric energy is equivalent, in terms of oil/gas, the fuel utilization factors are necessary to compare the amounts of oil/gas and synthetic fuels.

Output

The following information is contained in the computer output:

a) The value of the objective function;

b) The shadow prices of the constraints;

c) The construction rate for power plants in each time period;

d) The actual power production of each plant type in each time period;

e) The amount of natural resources used by the model society; and

f) The ratio between plutonium and uranium-233 in the FBR breeding gain.

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[2] See C. Marchetti "On Strategies and Fate" in this Report.

Figures 2 to 6 are given for illustrating results rather than for showing conclusions. They are mainly taken from Suzuki [6] and therefore are based on the extended model, as discussed under "Extensions and Modifications".

Figure 2a shows the optimal solution for the case 1.60, non-electric energy sector. The oil and gas (PETG) reserves are exhausted by 2025; the increase of HTGR supplied energy, which is the cheapest substitution, is limited by two facts: first, there are upper bounds that limit the speed of introducing HTGR's, and secondly, the breeding gain provided by the FBR's is scarce. Thus, solar hydrogen (SHYD) and electrolytic hydrogen (ELHY) have to be used as auxiliary fuels. The reason why there is no clear preference for one of these two is that solar hydrogen is cheaper only if the power plant is fully utilized; if there is some fraction of capacity underutilized because of obsolescence (which is likely to be the case for auxiliary fuels), the electrolytic hydrogen is preferred because of its lower capital costs.

Figure 2b shows the electrical energy sector. It shows that coal plants will be needed until about 2005 and LWR's until 2030, partly for generating electricity and partly for providing the plutonium requirements of the FBR's. The difference between supply and demand is due to the need for electricity for electrolysis.

Figures 3a and 3b show the results for case 1.80. For cases 1.60 and 1.80 there is no significant difference in the electricity sectors; a significant difference does appear in the non-electric energy sectors since no solar hydrogen is needed because of the additional amount of oil and gas.

Figure 4 illustrates the solution from the market penetration point of view. For the case 1.40 the share of hydrogen in the non-electric energy market is about 60 percent in the year 2000, which could mean that this case is practically unfeasible under the assumptions of the model. Nevertheless, it follows that electrolytic hydrogen could play an important role in the non-electric energy sector. First, it can prepare the market for the HTGR - and solar hydrogen. Secondly, in the event of increased availability of oil and gas it can be an economically attractive auxiliary fuel over a long period (see Figures 2a and 3a).

Figures 5a and 5b show the uranium-233 aspect of the cases 1.60 and 1.80. For case 1.60 there is no stockpile over the entire planning horizon, which means that U-233 is always immediately used; in case 1.80, there is a scarcity of U-233 mainly at the end of the planning horizon. The shadow prices (or dual variables) of the constraints to the U-233 stockpile in terms of current values are shown in Figure 5b. However, these figures should not be taken literally (they are meaningless for the first time periods where there is no HTGR available) because they are very sensitive to the demand mix, the performance of the reactors, etc. The point should be made that there is the possibility of profitable international trade between countries of differently adopted FBR-technology.

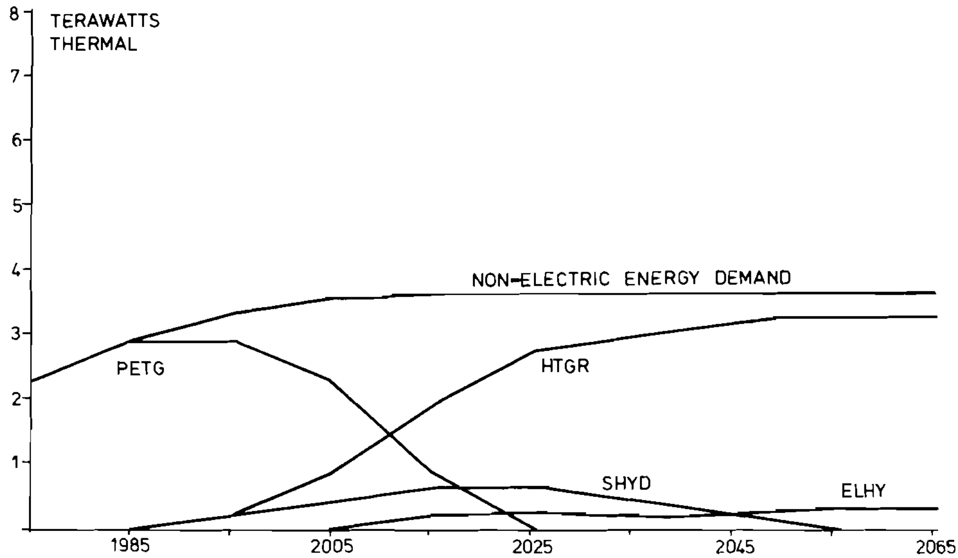

Figure 2(a). Model society 1.60, 60 years of petroleum and gas reserves, non–electric energy demands and supplies.

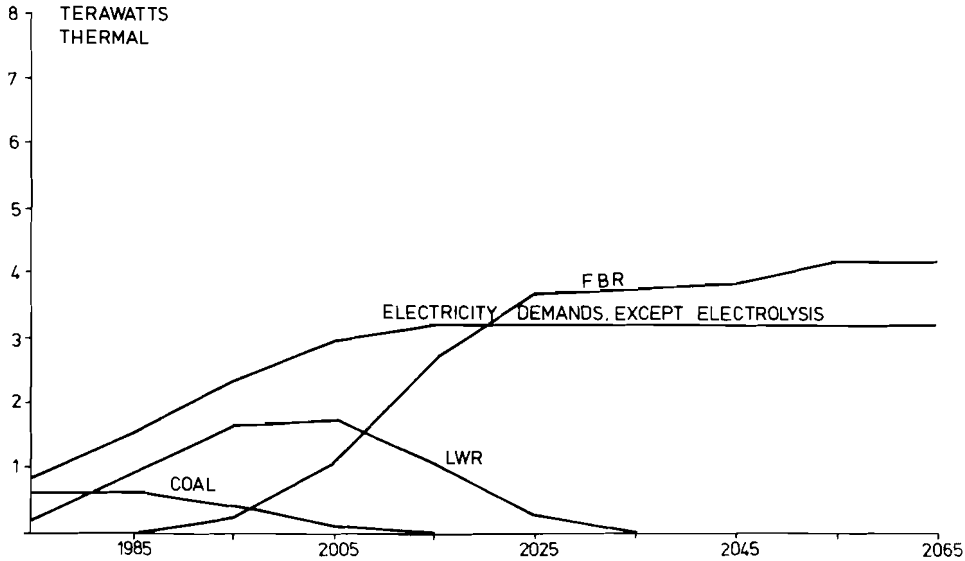

Figure 2(b). Model society 1.60, 60 years of petroleum and gas reserves, electric energy demands and supplies.

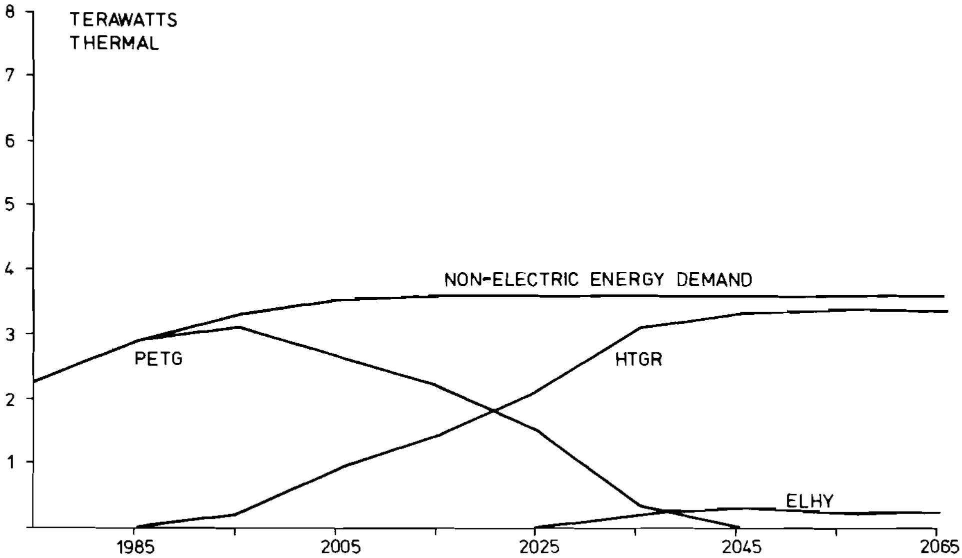

Figure 3(a). Model society 1.80, 80 years of petroleum and gas reserves, non–electric energy demands and supplies.

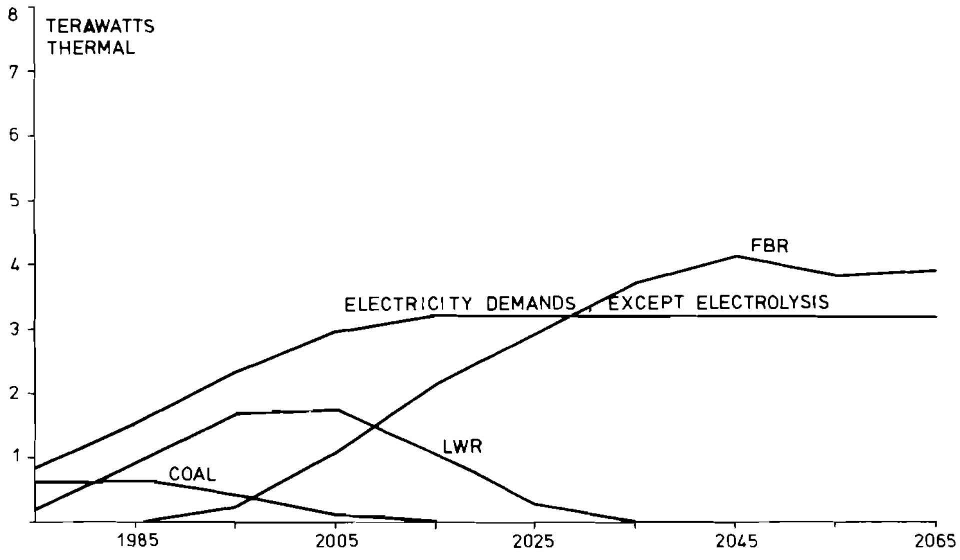

Figure 3(b). Model society 1.80, 80 years of petroleum and gas reserves, electric energy supplies and demand.

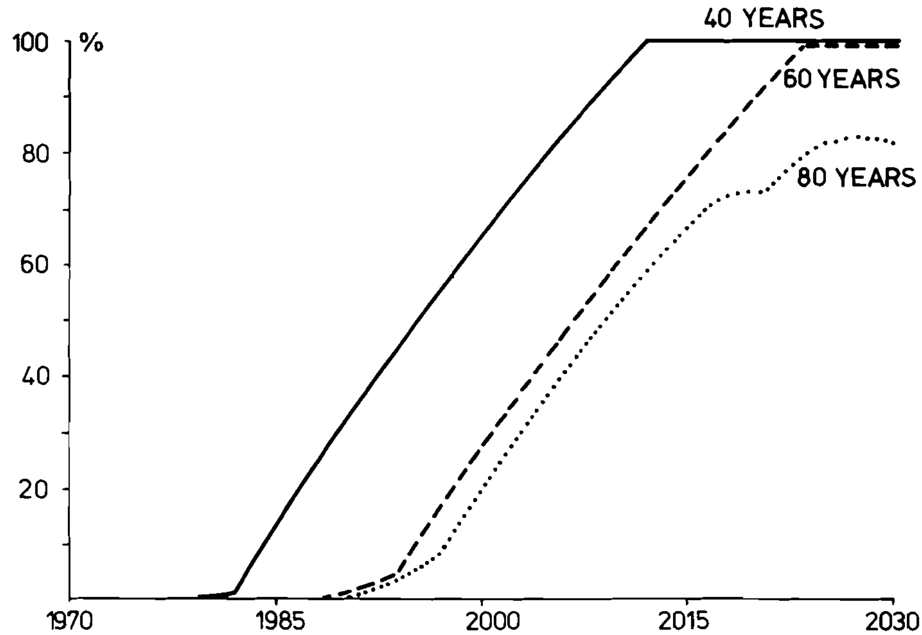

Figure 4. Hydrogen, percent of non–electric energy, model society 1.

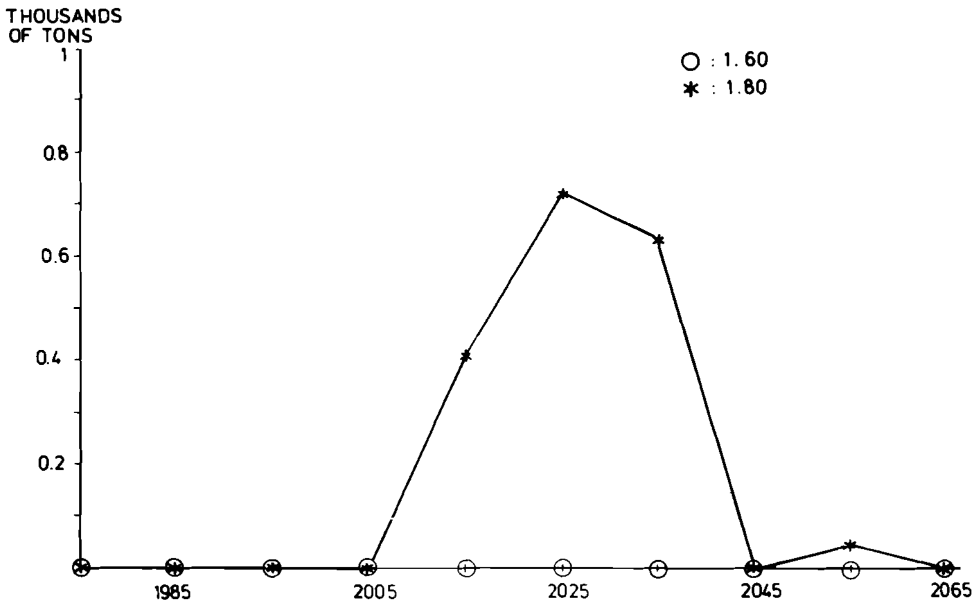

Figure 5(a). U–233 stockpile.

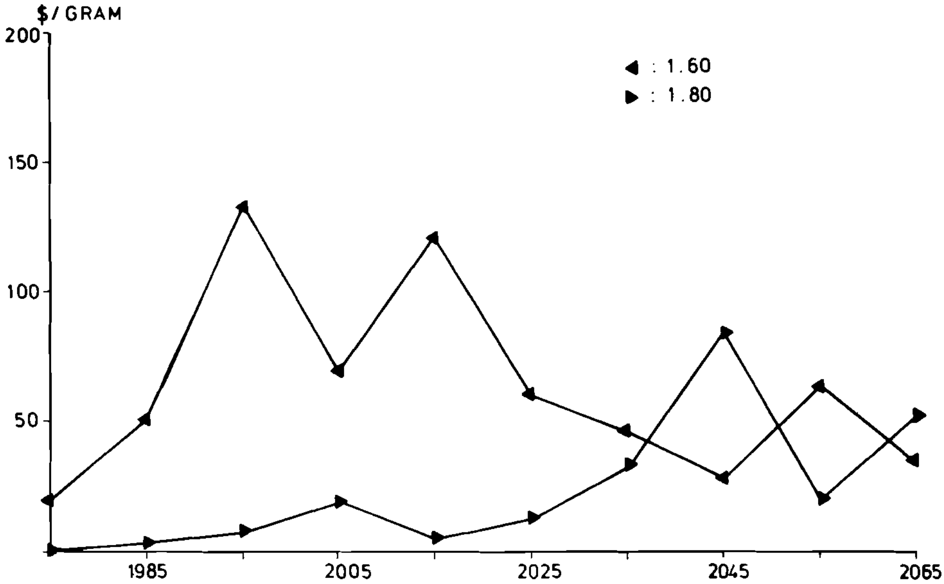

Figure 5(b). Shadow price of U–233 constraint.

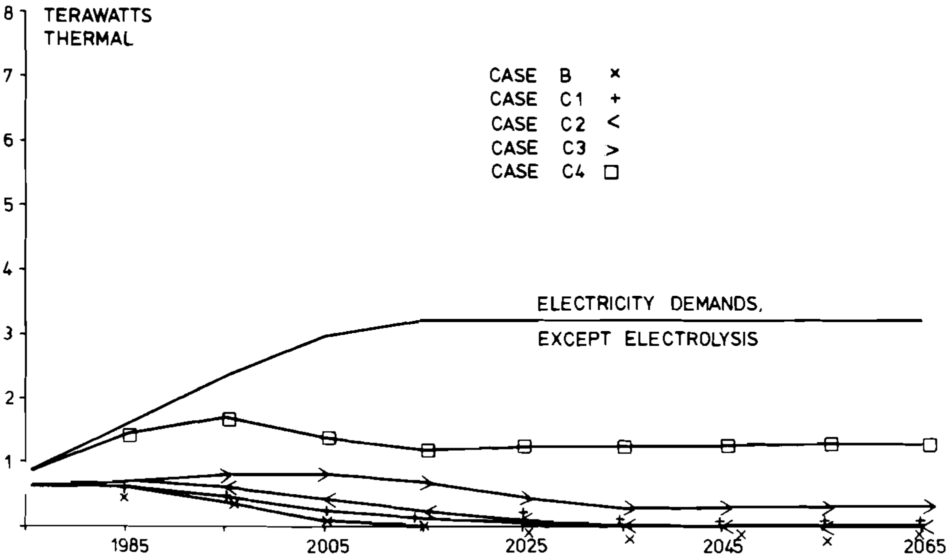

Figure 6. Model society 1.60, coal plant electricity.

Figure 6 shows the result of a sensitivity analysis with respect to coal-fuel costs in the range between 10 and 30 \$/KW(th)·a (this relates to .33 and 1\$/10^6 (BTU)). It also shows a comparison of the static costs for electricity production by LWR and FBR. It can be seen that even in the most favorable case (C4 1.40) there is no more than about two-thirds of the electricity generated by coal plants. The reason for this is that the benefit of the FBR breeding gain is so great that it makes up for the difference between the costs of FBR-generated electricity and the cheaper coal generated electricity.

APPLICATIONS

This section contains an overview of the work carried out using the Häfele/Manne model and that which is planned for the future.

Sensitivity Analysis

Since the model contains many factors which depend on future conditions, it is obvious that uncertainty is related to these factors. One way to take care of these uncertainties is to perform a sensitivity analysis; this has been done in the following fields:

a) Alternative discount rates have been considered 0, 3 and 15 percent, whereas the original model assumes 10 percent [2];

b) Cost and availability of natural resources: in addition to the "standard sensitivity analysis" for the amount of oil/gas available to the model society, the effect of alternative prices for coal [6], oil/gas [2] and natural uranium [2] has been studied;

c) The penetration of a market by some item seems in many cases to follow a logistic curve[3]. Therefore, constraints have been imposed on the penetration of the electric energy by nuclear energy and on the penetration of non-electric energy by hydrogen [2];

d) Consideration has been given to the three alternative values for the hydrogen utilization factor (the amount of BTU of oil/gas replaced per BTU of hydrogen utilized), namely 1.0, 1.2, 2.0 instead of 1.5 in the original model [3];

e) Cost of solar technology: this sensitivity analysis has been made with the extended model, as described below.

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[3]See C. Marchetti "On Strategies and Fate" in this Report.

Extensions and Modifications

The latest major modification to the model was done by Suzuki [6], and comprises the following major points:

a) Inclusion of solar technology for both electricity generation (solar thermal electric conversion) and non-electric energy (solar hydrogen);

b) The two macro-demand sectors have been disaggregated as follows: electricity into residential/commercial and industrial, both of these being subdivided into base load and intermediate peak load; and non-electric energy into three sectors: residential/commercial, industrial and transport.

c) The 75-year time horizon with 3-year steps has been changed to a 100-year time horizon with 10-year time steps.

Another modification has been done by Suzuki and Grenon [4]. In their paper they consider a final energy supply system by molten salt reactors instead of by FBR and HTGR, Rogner [5] modified and applied the original model for the case of the F.R.G.

Present Activities

a) Work is going on to include environmental constraints and trade-offs with the final target of excluding environmental "costs" in the objective function.

b) Additional work is planned in the field of molten salt reactor strategies.

c) Coal gasification will be included as a supply alternative for the non-electric energy sector.

d) The problem of optimal allocation of capital over time is being studied.

e) The energy demand will be determined by the use of the "resilience" concept[4].

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[4] See W. Häfele "Resilience of Energy Systems" in this Report.

[2] Konno, H. and T.N. Srinivasan, "The Häfele-Manne Model of Reactor Strategies: Some Sensitivity Analysis," RM-74-19, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1974.

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[6] Suzuki, A., "An Extension of the Häfele-Manne Model for Assessing Strategies on a Transition from Fossil Fuel to Nuclear and Solar Alternatives," International Institute for Applied Systems Analysis, Laxenburg, Austria (forthcoming).

[7] Suzuki, A. and R. Avenhaus, "A Study on the Demand Aspects of the Häfele-Manne Model - An Application of the Mathematical Technique of the Hoffmann Model," RM-75-4, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

6.2 Resilience of Energy Systems

Wolf Häfele

Optimization programs such as the linear programming model for the transition from fossil to nuclear fuels normally make use of discounted costs as an objective function. While this continues to be important, other objective functions must be considered. Environmental pollution or primary energy input could be considered for that purpose. We are pursuing this. The concept of shadow prices can make such investigations helpful for establishing standards and for other lines of interest.

The Ecology Project under the leadership of C.S. Holling coined the term resilience [1]. Qualitatively, this means a system's capability to absorb impacts from outside without ceasing to exist as a system. Absorbing impacts from outside certainly changes the system's state, possibly drastically, but not the fact that the system exists. Ecological dynamic equilibrium seems to follow along these lines. The Energy Project has taken a deep interest in this new concept, and on several occasions has observed that it is the large-scale deployment of energy systems that introduces problems into the system. For example, in the past the amounts of waste heat have not constituted a problem, although they may well do so in the future. Since large-scale deployments may lead to unexpected impacts, one should therefore strive for resilience. This becomes even more important when considering the long-range nature of systems analysis. While established econometric techniques are probably good for a time-span of about ten years, the considerations of the IIASA Energy Project focus on the time-span of between 15 and 50 years from now.

IIASA's Ecology and Energy Projects are jointly pursuing the problem of resilience indicators that make the concept mathematically operational. The Energy Project has conceived a set of equations for heuristic and therefore experimental purposes. We are not concerned with the validity of these equations.

Let us consider a society where the gross national product $\overline{G}$ is determined mostly by the yearly energy consumption E and by labor, and let us equate labor with population P. Let us assume that a given gross national product induces a certain energy growth rate; let us further assume a relation whereby population P induces a growth rate while personal well-being, expressed as per capita energy consumption e, leads to a decline.

If these were the only considerations, we would have the following equations:

$$\bar{G} = A \cdot E^{\alpha} \cdot P^{\beta}$$

$$E = eP$$

$$\frac{dE}{dt} = \mu\bar{G}$$

$$\frac{dP}{dt} = \sigma P - k \cdot e \quad ,$$

where A, α, β, μ, σ, k are assumed to be constants. Such a crude concept would be clearly in the domain of so-called objective economic features. Let us go one step further and assume that society asks for gradually smaller residual risks as the personal well-being increases:

$$r = r_o \cdot \left(\frac{e_o}{e}\right)^2 \quad .$$

The exponent 2 was chosen arbitrarily. If we now assume that specific costs for energy k are inversely proportional to r we have

$$k = k_o \frac{r_o}{r} \quad .$$

Total energy costs S would then amount to

$$S = kE \quad .$$

By assuming inaccurately that most of these energy costs are due to hypothetical safety and risk considerations, and therefore are not really part of the production process that leads to $\bar{G}$ rather than to "dead" investments, we would then have to substitute G for G, assuming

$$G = \bar{G} - S \quad .$$

This second line of reasoning explicity establishes an interface between traditional economic quantities and certain assumed societal behaviors. Straightforward mathematics then leads to a differential equation of the following kind:

$$\frac{de}{dP} = \frac{f(e,P)}{g(e,P)} \quad .$$

By assuming certain values for the various constants, we are led to the phase portrait of the problem illustrated in Figure 1.

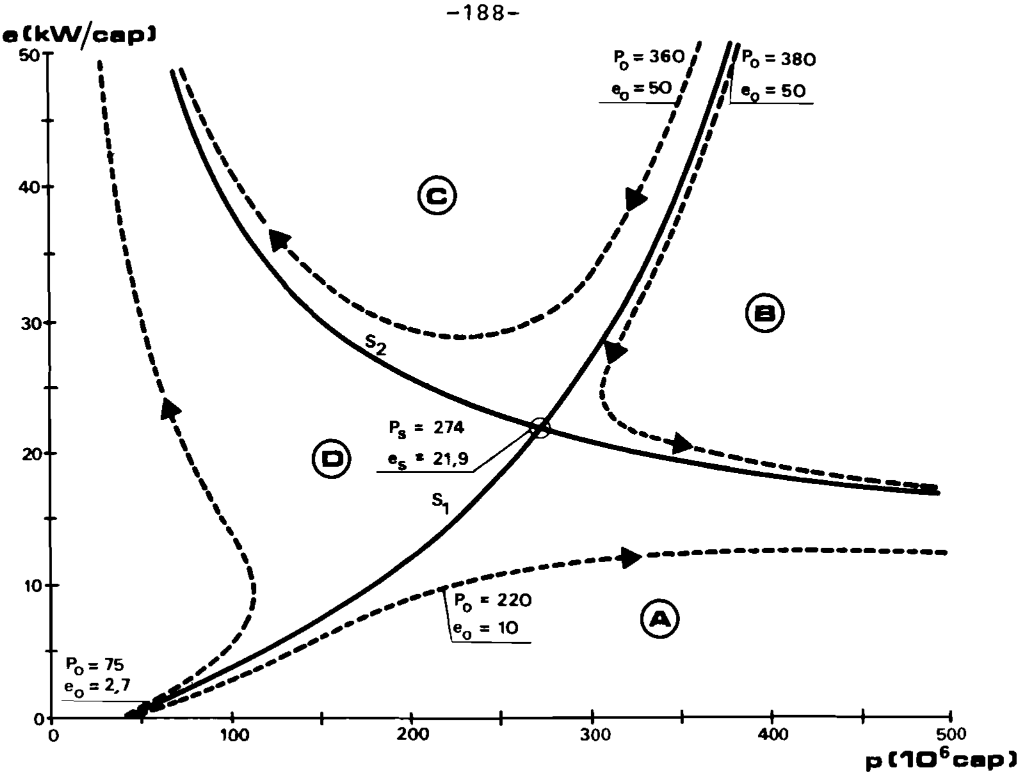

Figure 1. Solutions in the [e,p]–field.

The dominant feature in the figure is the singular point--a saddle point; two trajectories cross each other at this point. These two trajectories divide the phase space into four basins; they are therefore separatrices. Let us now consider an initial condition: P_O=200 million people, e_O=10kW/cap. The identified trajectory evolves into an asymptotic behavior where e becomes constant and P grows exponentially. If a different initial condition were considered, for instance P_O=75 million, e_O=2.7kW/cap, the trajectory in question would be in a different basin of the phase space; its asymptotic behavior leads to $P \to o$ and $e \to \infty$. If, by using procedures external to the model, one wants to opt for one of these evolutions, then one should avoid being drawn across the separatrix by unexpected events not foreseen in the model. Likewise, one should avoid being passed by the separatrix since it may change its position in the phase space because of mechanisms not foreseen in the model. It is therefore desirable to avoid the known separatrix as much as possible. We have consequently proposed that the following quantity be considered a resilience indicator (see Figure 2):

$$R = 1/\int_{s_O}^{s_1} \frac{ds}{\frac{ds}{dt} \cdot a(s)} ,$$

where a is the distance of the line element ds from the separatrix and t is the time. Line elements with a long residence time are weighted more heavily than those with a shorter residence time.

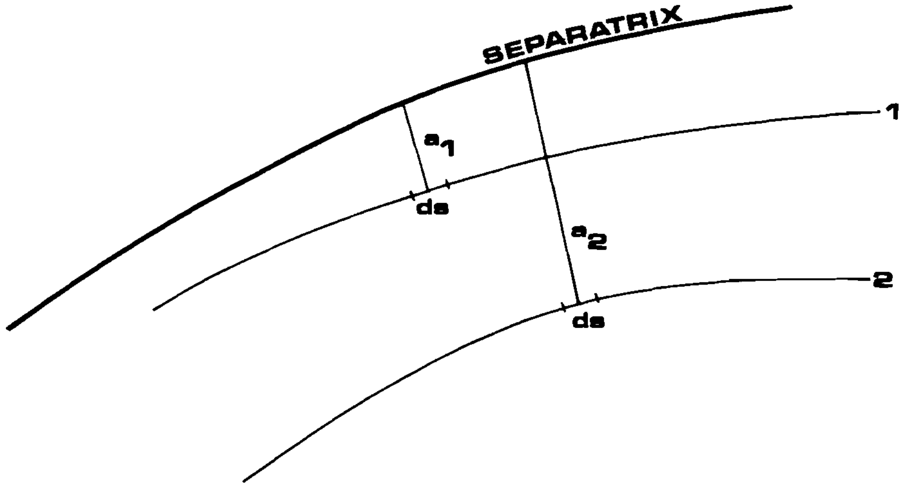

Figure 2. Distance of line segments from the separatrix.

Measuring a distance in a phase space implies a matrix. Basic relations of units of the considered dimensions must be introduced; in one way or another this must come from value judgments.

We are considering here the resilience of a trajectory. Our ecology partners are more interested in a resilience indicator for a basin as a whole.

We are pursuing this line of investigation further. More reasonable three-, four-, and five-dimensional models have been or are being considered. The hope is to arrive at a topological representation of macroeconomic-societal models. Certain policies may be represented there as trajectories. By going beyond the concept of resilience, one may be able to arrive at policy judgments that would be based on mathematical models and not on numbers. One may envisage these models as topological comparisons of strategies or policies.

One additional observation is necessary. Any model of this type has variables and parameters. While parameters are assumed to be constants, in reality they may change slowly. "Slowly" here means in comparison to the rate of change of the model's variables. This suggests a distinction between fast and slow variables, which may have possible connections to Thom's catastrophe theory [2]. We are working along these lines.

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6.3 Strategies and Decisions

Wolfgang Sassin

THE ENERGY PROBLEM

The global energy prospects outlined in the various contributions to this Status Report reveal that many features of our present energy system are of a transient nature. At least in the perspective of the decades following the turn of the century, the basic structure of supply and demand will change, and we might ask how to control this process.

Putting the problem of local and regional differences aside, the global situation is characterized in brief:

- By a scarcity of oil and gas. In terms of the present annual energy consumption rates we would have to go some 50 years with the known and inferred reserves of liquid and gaseous hydrocarbons;

- By a fast growing overall energy demand. Even if we make the certainly unrealistic assumption that from now on the average individual would not increase his consumption level, the overall energy demand would grow as a consequence of the world population growth, thereby drastically reducing the time period within which substitutes for mineral oil and natural gas have to be introduced;

- By the feasibility in principle of new technologies, allowing the tapping of abundant forms of primary energy such as nuclear, solar and geothermal, or at least providing access to coal which exists in far larger quantities than oil and gas;

- Finally, by the fact that any use of any form of primary energy on a world-wide and truly large scale causes serious side effects, thus building up its own specific constraints.

Recognizing a definite time pressure, and at the same time experiencing a general uncertainty whether mankind will be happy just to survive or will resume ambitions goals, we have to ask how to act prudently in the field of energy. It is certainly not sufficient to develop a bundle of new energy supply technologies and provide methods to optimize their utilization in a strictly techno-economic sense. The history of peaceful nuclear power clearly indicates that this is not the proper recipe for success.

THE ROLE OF NEW STRATEGIES

If we want to avoid energy becoming a limiting factor for the general global development, we must add to the development of new technologies the design of new strategies. They must reflect the present uncertainty and therefore should aim to increase the flexibility of a future energy system. By flexibility I mean the possibility to accept a variety of primary energy forms, the capability of readily substituting one form of primary energy by another, and last but not least a certain structural insensibility of the energy system with respect to larger variations of overall demand growth rates.

In designing a strategy with such goals in mind we are not free to choose operational measures. Time as ever is an important factor, and we must look for the right sequence of a large number of minor decisions that would finally move the energy system into the intended direction. Each single decision within the system has to be made in favor of a solution for a given local problem at a given point in time. It is during these decision-making processes that the various constraints apply which finally result from the interaction of the energy system as a whole with other systems such as the general economy or the climate.

So the first step in the process of designing a long-term strategy is to explore the possible evolutionary paths of the present energy system. These pathways can be taken as a consequence of possible open decisions. It is this step of our work on which I will report in more detail now. I will present three decision trees: one that displays alternative ways to achieve an advanced energy system, mainly based on nuclear energy, and two others that will be based on coal.

A DECISION TREE FOR NUCLEAR ENERGY

In order to show how to derive such decision trees I will simply follow the lines along which our own thinking evolved. Investigating the question of what share nuclear energy could possibly gain up to the year 2000, W. Häfele and I together with a number of experts made an extensive survey of the technologies that are being developed now and could use a nuclear input [1]. Besides electricity production, we considered the application of nuclear heat for direct reduction of iron ore, for district heating and for the supply of synthetic gases, among others. In order to assess the potential penetration of these conversion processes it was necessary to look into the future development of the energy market. The most useful representation to display inherent market trends turned out to be in terms of secondary energy.

Figure 1 shows, for the example of the F.R.G., the fractions of different forms of secondary energy that were produced and delivered to final consumers. Within a time period of 25 years solid fuels were substituted by liquid fuels; the remaining fraction of solids comprises mainly the use of coke for blast furnaces. For the time period between 1975 and 1985 the shares of secondary energy were derived from the "Energieprogramm" of the government of the F.R.G.; these are also included in Figure 1. It is interesting to note that, whereas a discontinuity was introduced in the planning of the primary energy data as a consequence of the oil crisis in 1973, no influence on the anticipated behavior of secondary energy consumption can be seen.

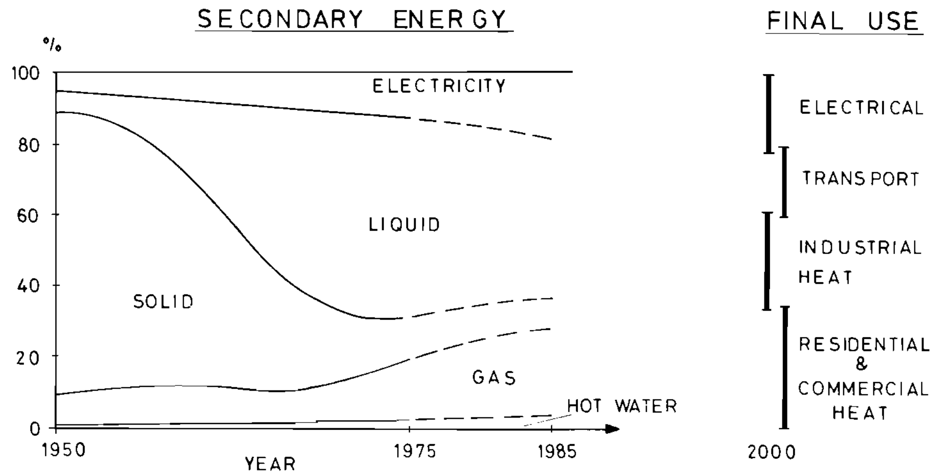

Figure 1. Partitioning and final use of secondary energy (F.R.G.).

For the year 2000 a splitting of the final use of energy is given in Figure 1. We have distinguished among four consumer groups according to their specific energy requirements. The projections are partly the result of detailed sectorial demand forecasts, and were partly taken from econometric model runs. Electricity is expected to cover roughly 20 percent but certainly less than 25 percent of the final energy demand; hot water for district heating limited by its distribution problems may achieve 5 percent or slightly more. No indications could be found of an increase in the share of solid fuels. Thus the main demand will be for liquid and gaseous fuels with a definite tendency favoring gas.

One point needs specific attention: the supply conditions for secondary energy imposed by the consumer. Without going into details, Table 1 illustrates how important it was to include these in the studies on which the demand projections in Figure 1 are based. Some cost components for the transmission and distribution of both electricity and natural gas are compared in Table 1. The first column repeats the well-known fact that it is much cheaper to transmit gas than electricity. It is less well known, however, that the actual distribution costs of electricity and gas are nearly the same. The figures in column 2 apply to suburbs of larger towns with the actual load factors of the grids. Because of the high distribution cost the economic advantage of natural gas for large consumers is largely reduced for domestic applications.

Table 1. Some cost components of secondary energy systems (F.R.G., 1973).

	Transmission (6 GW, 100km, $\frac{8000h}{Year}$)	Distribution (Pop. Density ∿1000/km^2)	Consumers Cost
Electricity	0.16 $\frac{\$}{Mill\ BTU}$ (380 kV)	5.2 $\frac{\$}{Mill\ BTU}$ (5600h/Year)	13 $\frac{\$}{Mill\ BTU}$
Natural Gas	0.034 $\frac{\$}{Mill\ BTU}$	4.2 $\frac{\$}{Mill\ BTU}$ (1600h/Year)	5.2 $\frac{\$}{Mill\ BTU}$

After: H.G. Thissen, Jülich, F.R.G.
W. Buch, Salzgitter, F.R.G.

Relying on forecasts of the kind shown in Figure 1, and adding estimates on both the time of market introduction and the potential market shares of nuclear systems under consideration now, we arrived at the results given in Figure 2. For the reference case chosen, roughly 40 percent of the secondary energy produced in the year 2000 could originate from nuclear energy. One half of that quantity would be traditional nuclear electricity; the other half is made up of nuclear process heat for steel production and chemical reactions, of utilized nuclear waste heat for district heating networks, and of electrolytic hydrogen that could be produced by using the cheap off-peak capacity of the nuclear power plants.

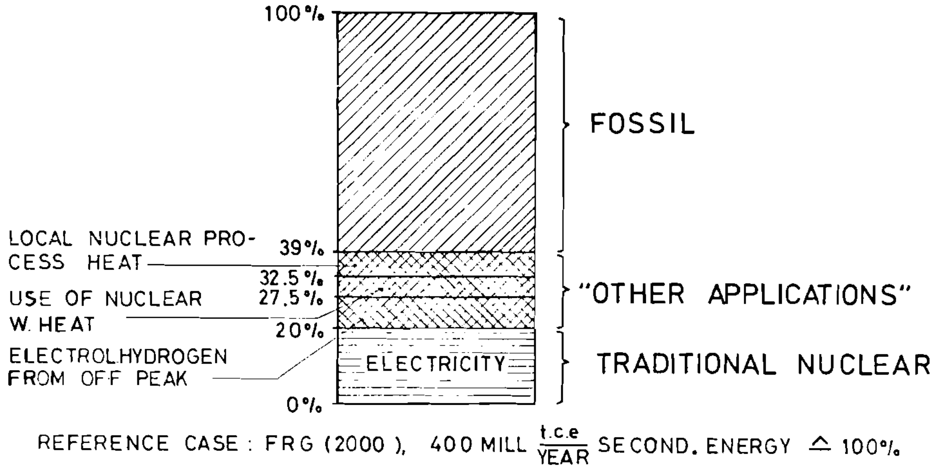

Figure 2. Projected shares of secondary energy originating from nuclear power.

As favorable assumptions were made for nuclear energy, a large fossil energy demand, totalling more than 60 percent, is not a very promising figure in the light of the oil and gas resources. The first question now is whether the nuclear share can steadily increase after the year 2000. The answer seems to be no, and the reason for this limitation can best be explained in going through the decision tree of Figure 3. This decision tree is embedded in the time power plane and is meant to evolve into these dimensions. Returning to our question which reasons will lead to a limit of the nuclear share, we will follow the sequence of decisions along the fat line.

We start with the assumption that a country has decided to develop nuclear energy as one if not the only primary energy input for its economy. If this question were to be answered with no, then other alternatives come in and similar decision trees must be considered. We will do that when we come to Figures 4 and 5. The next question is: nuclear power for electricity production, or also for other forms of secondary energy? Again this decision is practically taken by the development programs for nuclear process heat and nuclear ship propulsion. If for any reason the answer to industrial application of nuclear heat is no, then the nuclear share depends

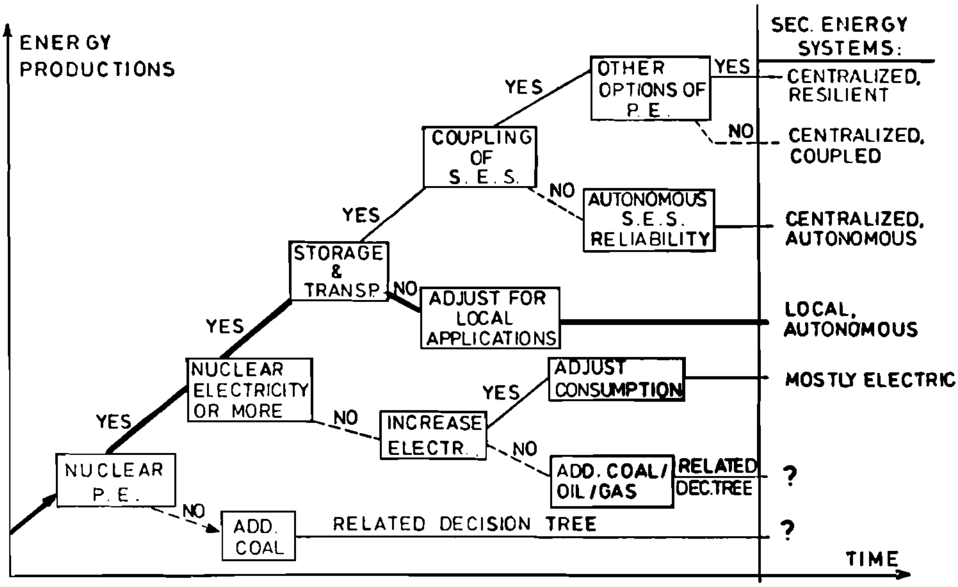

Figure 3. A decision tree for advanced energy systems.

on the question: can the electricity share in the secondary energy balance be increased? From Figure 1 we have seen that this share would possibly rise to 25 percent of the secondary energy demand in the medium-term future. Any further increase depends on the degree to which the consumer technologies requiring heat input can economically be fed with electricity. Here Carnot's law sets tough limits. In any case this evolutionary path leading to concepts of e.g. the all-electric city will not support the assumed goal of going nuclear.

Returning to the main branch of the decision tree and following the most likely decision, that nuclear energy will be used to produce other forms of secondary energy besides electricity, we face the question whether appropriate transmission, storage and distribution systems will be developed. Within the scope of a nationwide efficient supply system, and following the market trends shown in Figure 1, the obvious demand would be for a gaseous fuel that could accompany natural gas. Although the possibilities for a hydrogen society are investigated, the present direction of nuclear-based energy R & D indicates the general belief that such transportation and storage systems will not be implemented in the medium-term future. Indeed, most of the R & D programs try to adjust nuclear energy to local applications, such as steel production and district heating. Also closed cycle systems such as the German ADAM and EVA process have to be mentioned here. The most important problem limiting the nuclear share, if we follow this evolutionary line, is the mismatch between the economic size of nuclear plants and the size of the consumers. It is along this pathway that we arrive at the approximate upper nuclear share of 40 percent that was given in Figure 2.

For an energy supply strategy aiming at a larger share of nuclear energy, we can conclude that a phased development of transportation and storage technologies is a decisive point. Let us now follow the decision tree further up, assuming a decision were made in favor of truly large-scale systems for handling e.g. hydrogen, a mixture of Co + H_2 (that would have to be recycled in the form of CH_4) or hot water. The next question to be answered is: coupling of secondary energy systems or not? If not, then at least two autonomous secondary energy systems, one for electricity and one for a gaseous fuel, will have to be operated in parallel. Each of these systems must achieve full reliability. If they can be coupled the overall reliability will increase or become cheaper, and it will be possible either to store electricity by converting it into gas or to flatten the load variations by a controlled consumption at the consumer end. Such coupling has additional advantages. It will more easily allow the integration of other primary energy forms as they may come in. This is especially true for solar energy, which most probably can be transported over long distances only after conversion into hydrogen. Also the interlinking of very large energy parks with the consumers would be facilitated, via increasing both the combined load and the standby capacity.

So with the very last decision at the end of this pathway a really flexible energy system comes into perspective. Following such a path, we would not foreclose the utilization of primary energy forms other than nuclear energy, with which we started our decision tree.

Certainly Figure 3 does not include all aspects that might govern the evolution of nuclear energy as a main primary energy source. Still, it reveals the far-reaching consequences of early decisions, be they taken consciously or not.

DECISION TREES FOR NEW COAL

Let us now turn from nuclear and follow a similar exercise for coal. With respect to the present energy consumption level the global coal resources are very large indeed. A coal task force was formed at IIASA to investigate the possibilities of a global coal option. To put the various questions that arise into perspective, we have worked out two decision trees, for a coal option in a regional and in a global context. There are several reasons for this parallel approach: whether or not coal can be mined and utilized is subject to a variety of economic, ecologic and social conditions changing from country to country; furthermore, it is found in different qualities and, most important, in varying depths; and last but not least, the coal industry in some areas has a long tradition, and--rightfully or not--relies more on the experience gained in the past than on planning carried out in the spirit of a new venture.

Figure 4 contains a decision tree designed for a region of which an example would be Western Europe. It is assumed that the main coal resources are deep-lying hard coal, that a comparatively high standard of living exists and finally that the labor force is short.

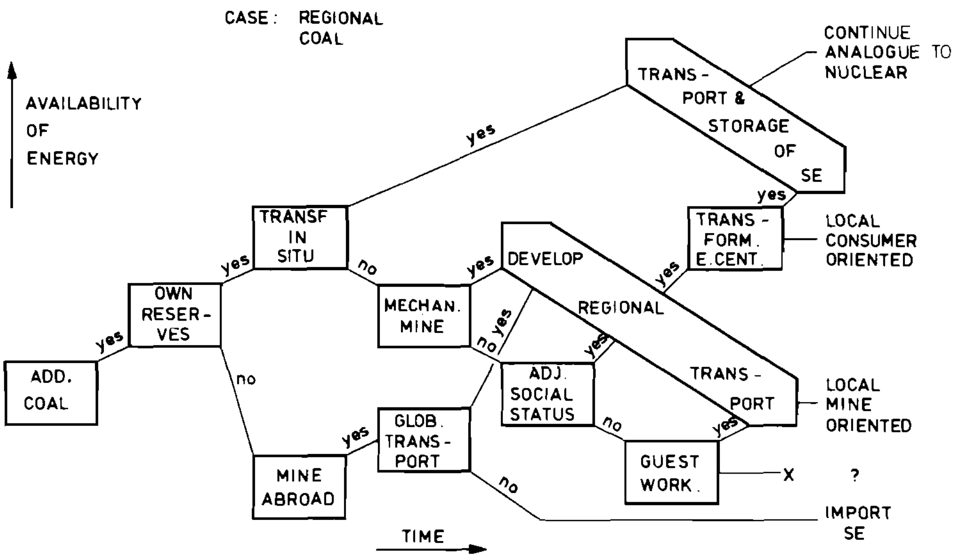

Figure 4. A decision tree for advanced energy systems. Case: regional coal.

In a similar way as we did with nuclear, we will start from the basis that a fundamental decision was made to develop "additional coal" as one, if not the only, primary energy input for the region considered. The term "additional coal" is used to distinguish the products of an innovated coal industry from the traditionally mined and marketed coal.

The first question is whether to use the domestic hard coal reserves part of which are already exploited. If not, mining operations abroad--probably exploitation of coal which could be strip-mined--must be envisaged. This path was introduced taking the development of crude oil as an example. Here the buildup of a global transport system for coal is a pending decision. If such a transport system, be it a fleet of coal ships or a pipeline grid for coal suspension, is not within the scope, there is just one possibility left. The coal mined abroad must be converted into secondary energy on the site. This secondary energy, preferably a liquid fuel, would replace mineral oil. If on the other hand a global coal transport should evolve, then the region considered would have to develop its own regional coal transport system. We will come to this question also along a different path.

If the second decision were made, in favor of exploitation of domestic coal resources, we must first check whether these resources can be transformed in situ, i.e. without the bottleneck of traditional deep mining. If not, we run into a sequence of decisions that definitely fix the maximum production volume of coal. The first question is, can the degree of mechanization of the mining operations be increased considerably? If not, the question must be answered whether the social status of a large number of miners can be improved considerably. If again the answer is negative, the decision must be faced to employ a large number of guest workers. Judging from past developments, we can say that going down the sequence of these three possible decisions will correlate with a decreasing coal output. To establish the dimension of the operations, we should realize an increase in the present coal output of a factor of 5 or even more within 30 or 40 years. A smaller increase would definitely not be in line with a pathway into a coal-based energy future.

For these quantities the development of a regional transport system for coal poses another major question. Such a transport system will allow building consumer-oriented energy centers for the conversion of coal into both electricity and gas, the forms of secondary energy that will be readily accepted by the future market (compare Figure 1). At the same time a regional transport system would be a necessary link between a global marine transport system and the coal transformation centers. If neither coal conversion centers nor a regional coal transport could be developed, local consumer-oriented or local mine-oriented coal conversion would certainly be a major hindrance for a coal option.

Let us return now to the question of in situ coal conversion. If such a technique were available in time, a direct feeding of a powerful secondary energy system, properly handling transport and storage problems, can be foreseen. Here again we arrive at a point that turned out to be of strategic importance in the decision tree for nuclear energy: the buildup of a modern secondary energy system that would largely decouple energy supply and demand. From this point on we can add the same considerations as in the case of nuclear, about increasing the reliability and flexibility of the system to accept other forms of primary energy.

One fundamental constraint for the large-scale deployment of new coal was not touched on so far: the CO_2 balance of the atmosphere. The basic intention of the decision tree in Figure 5 is to investigate which technological decisions will facilitate or hinder the solution of this problem.

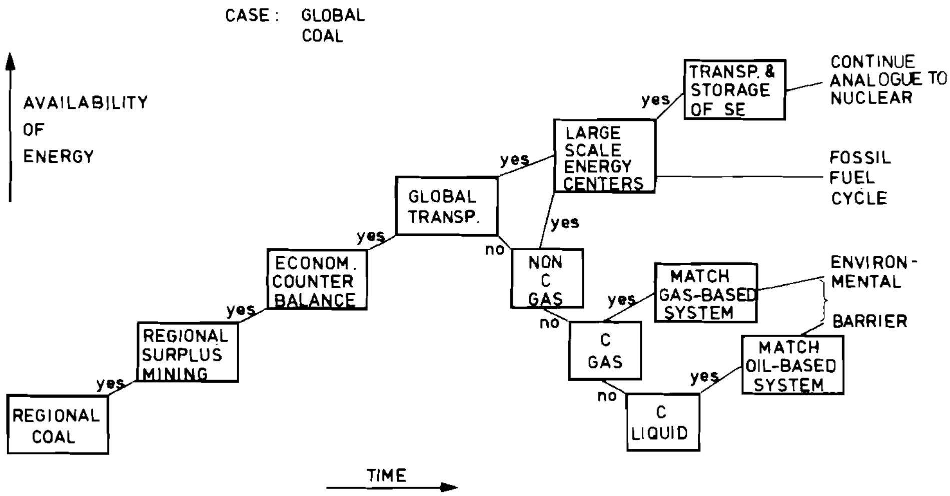

Figure 5. A decision tree for advanced energy systems. Case: global coal.

Let us quickly go through the necessary decisions to achieve a global coal option. First of all, regional coal options have to be implemented; consequently those regions with large coal deposits must be prepared to produce more coal than is consumed inside their own economy. The second decision will certainly not be an easy one, if the requirements for land and water or the working conditions of the labor force in the mines are considered. As a very large fraction of the easily accessible coal deposits are located in countries such as the U.S.A. or U.S.S.R., we must ask whether developed nations in the long run will be prepared to mine and supply a product so difficult to handle as coal to the less developed parts of the globe. As a consequence of that situation, we must ask by which counterflow of goods or services an adequate economic counterbalance between coal-producing and coal-consuming regions could be achieved.

Assuming that a solution could be found for this problem, we are then at a salient point in our decision tree: whether or not to build a global transport system for coal. As we have seen in Figure 4, tackling the questions of a regional coal option, a global transport system would be expedited by the building of large-scale energy centers for the conversion of coal into secondary energy. A proper siting of these energy centers within the oceans or at least not too far from deep sea troughs will offer the possibility to dump the CO_2 directly without releasing it to the atmosphere. Here I specifically refer to Marchetti's work on global engineering. By means of large energy centers an adequate fossil fuel cycle could be introduced, by passing the problem of a CO_2 buildup. Following this line, a systems layout comes into the picture, which is very similar to that developed for a future nuclear option in Figure 3.

We now return to the point we have just passed in Figure 5 and assume that no large-scale global coal transport system would evolve. This might result from an early implementation of in situ gasification or liquefaction processes. Following the downward line, we must ask whether or not a gaseous fuel can be produced at the site of the mine that does not contain C atoms. If yes, we face the task of transporting say e.g. H_2 and CO_2, the first to the consumer and the latter to its final sink. Here again energy centers--partly different from those that are directly coupled with a global coal transport system--come in. For the sake of simplicity both types of energy centers were included in Figure 5 within one box.

If instead the decision were made to produce a gas or a liquid, or both, containing C atoms, we sooner or later will run into the global CO_2 problem. This is the more serious as synthetic natural gas and synthetic oil from a systems standpoint would fix the present consumption pattern. As viewed today, such a path provides the most ready means to match coal and the consumer demands which are shaped by mineral oil and natural gas. On the other hand, no simple and economically viable process is foreseen to prevent the carbon release to the atmosphere, once the carbon is distributed to the last small energy consumer.

CONCLUSIONS

We are not in a position to claim that the decision trees presented cover all relevant aspects of a possible future development of nuclear energy and coal. They need further improvement and certainly will have to be modified. Still, they turned out to be useful in guiding specific studies and in relating different standpoints. It is planned to establish similar decision trees for the other primary energy options: solar, fusion and geothermal. It is also planned to incorporate the largely different circumstances found in developed and developing regions which might give rise to alternative evolutionary pathways. Finally, we intend to use the concept of decision trees to explore a possible combination of primary energy forms within the framework of a long-term global energy strategy.

Reference

[1] Häfele, W., W. Sassin, et.al., "Applications of Nuclear Power Other Than for Electricity Generation." Paper presented at the European Nuclear Conference, Paris, April 1975. In conference proceedings, Enrichment and Special Applications, Vol. 13. Pergamon Press, Oxford, 1975.

6.4 On Strategies and Fate

Cesare Marchetti

The oil crisis brought interest and money into the field of energy studies and an immense pile of papers came out of it.

Now an analysis, though of only part of these papers, shows that they tend to be projected forward, trying to provide scenarios, models, consolation and fears to the dazzled reader. The widely contrasting results of these projections make one think that their methodological and data base might be shallow, so we started looking at the past history of energy consumption to see whether stable patterns and trends could be detected, in order first to use them as inputs for the extrapolations, and second to cross-check scenarios and models over them. As every student of science knows, a law--or a model, which might be interpreted as the clumsy stage of a law--must first fit the known experimental data before being used for predictions.

The first obvious thing to look at is the evolution of energy consumption. One might think that this is trivial, as everybody is doing it. The question is not so trivial if one observes that most books report fossil fuel statistics only, and too often only for the last 20 years or so. But fossil fuels are not the only source of energy and neglecting the rest leads to strong distortions of the secular patterns. In fact non-fossil fuel input for the world is now about 15 percent of the total, whereas a century ago, it was practically 100 percent. This means that a good part of the growth of fossil fuels is due not to an increase in energy consumption but to a substitution of fossil fuel for non-fossils. Extrapolation of such trends will presumably lead to forecasts on the high side as the substitution is already almost complete.

Figure 1 shows the trend for the total world energy consumption; it is astonishing that using the portion of the curve in the "quiet years," one can extrapolate e.g. from 1860 to 1950 using a growth rate of 2 percent per year. Such a low rate is again astonishing if one considers that the world population growth rate was around 1.5 percent per year during that period. Examining the behavior of the U.S.A., the leading industrial country even a century ago, one finds the same curve but with a growth rate of 3 percent (Figure 2), and one is tempted to say that after all the 2 percent is simply due to the terrible underdevelopment of humanity at large. But the 3 percent has a catch, as during that period the population of the U.S.A. grew at a rate of 1 percent faster than that of the world as a whole; and here we again have the 2 percent if we adjust for population.

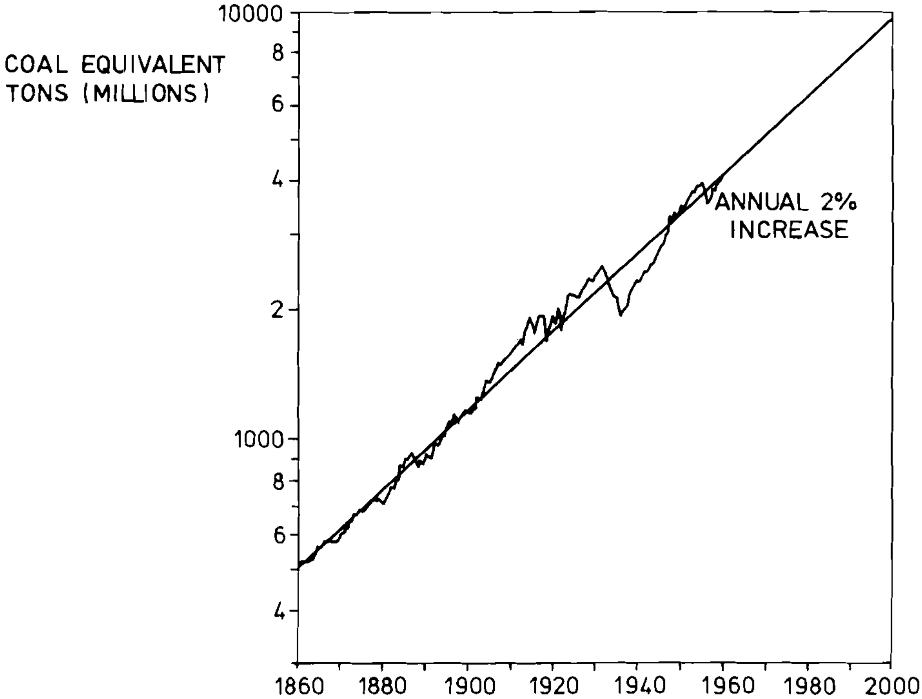

Figure 1. World energy consumption, including wood and farm waste.

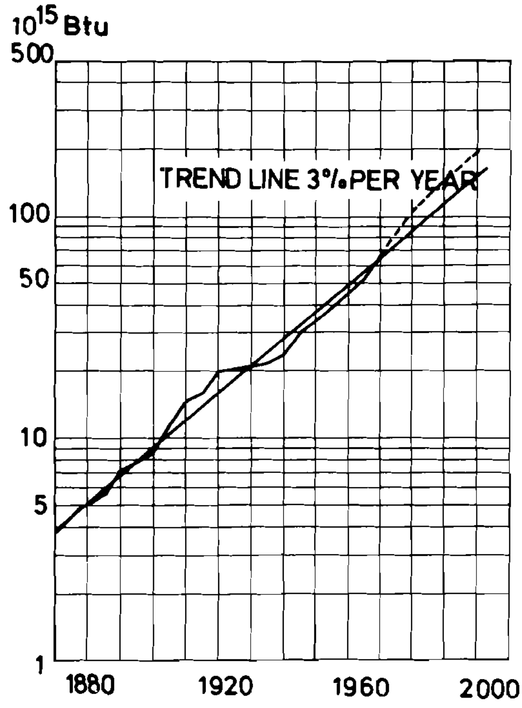

Figure 2. U.S. total energy consumption (After: Ref. [5]).

The evolution of per capita use of energy in the U.S.A. (Figure 3) again shows a strange behavior, and, against intuitive feelings, it only doubles in a hundred years. This says two things: that in the last century the U.S.A. just held a position in the world system they had conquered before, and that something important must have occurred during that period in the way energy was used. Figures 4 and 5 hint at what has happened. They show the evolution and efficiency of energy use for two important technologies: mechanical energy from fuels, and ammonia synthesis. The data are plotted in a peculiar way, as log efficiency/inefficiency, where efficiency is measured as a fraction of the theoretical efficiency, and the curves show the extremely regular progress toward better use of energy.

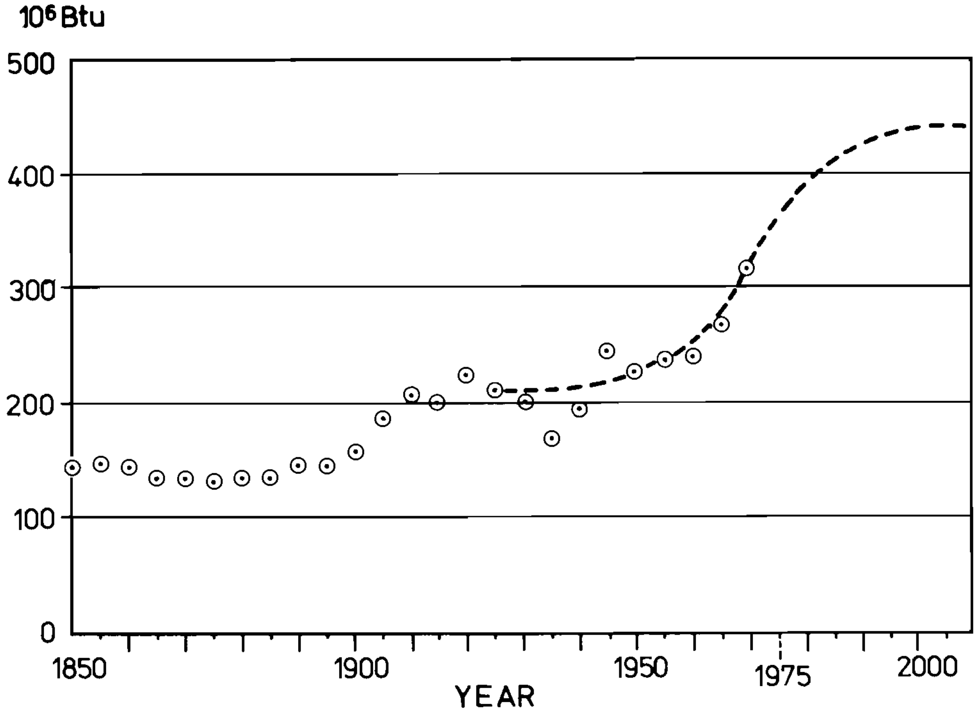

Figure 3. U.S. per capita energy consumption (Source: Ref. [6]).

Energy conservation is not a discovery of the last two years; it always crept into the web of technological evolution. Closer observation of the total energy curve shows numerous and sharp deviations, for some of which a correlation with economic and political facts can be found. These deviations may correspond to rates of change in energy consumption that can go from +10 percent to -10 percent per year, and can last for a considerable number of years.

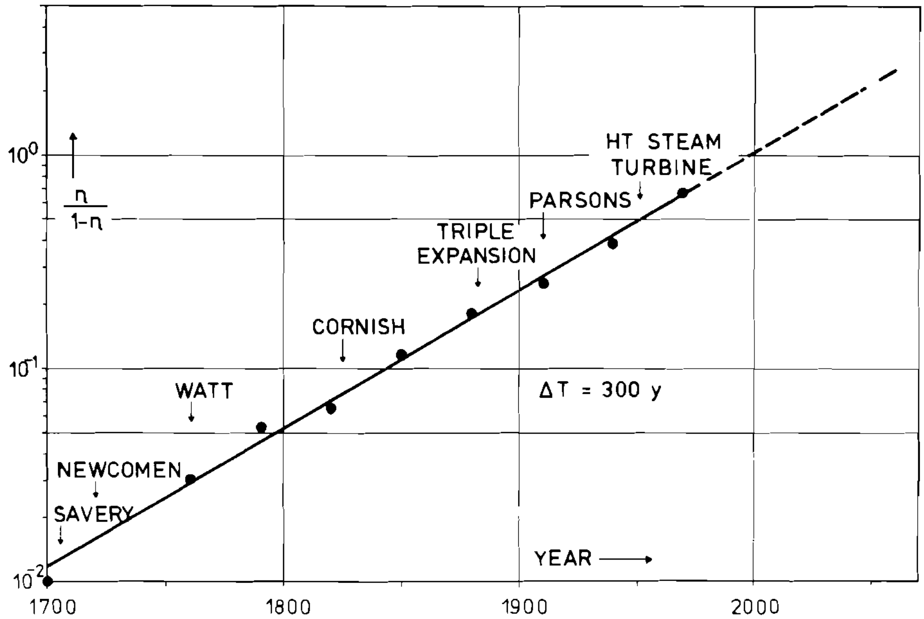

Figure 4. Efficiency of prime movers.

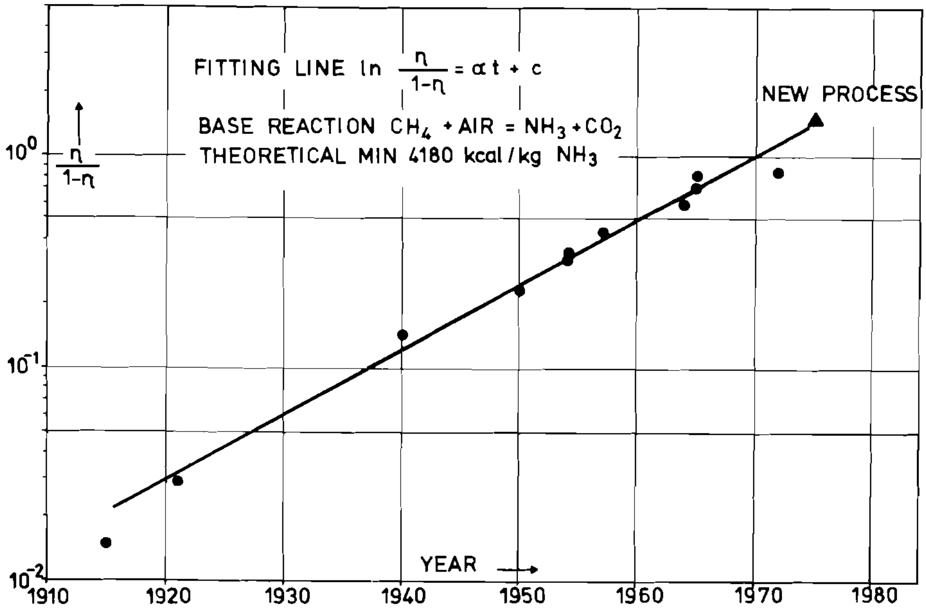

Figure 5. Efficiency in ammonia production (After: M. Slesser, University of Strathclyde, Glasgow).

It would obviously be foolish to use these background noises for long-term extrapolations of the signal; I have the impression, however, that many people do precisely that by taking for their extrapolations the shallow base of the last 10 years and assume 4, 5, and 6 percent for the rate of world energy growth. They might learn something if they tried to explain first why the rate has been 2 percent for such a long time, and second why higher or lower rates did not obtain for long periods and finally cancelled each other.

The second point I want to bring to your attention is the extreme regularity with which a certain energy source is substituted by others. Substitution of one product or one technology by another has been the subject of study for many years, as the information is of primary importance for industry. The particular study that triggered our considerations was by J. Fisher and R.H. Pry of General Electric [1]. There the fraction of the market taken by a new product, F, is plotted versus time as the function ln F/1-F. Statistical data plotted in this way are beautifully fitted by straight lines over spans of time up to almost a century, even in the case of planned economies (Figures 6, 7).

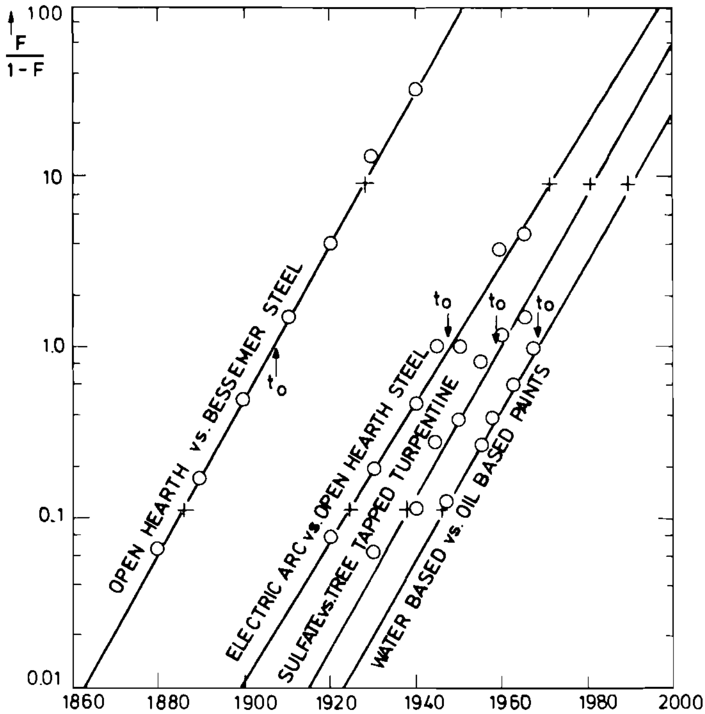

Figure 6. Market penetration curves in the U.S. (Source: Ref. [1]).

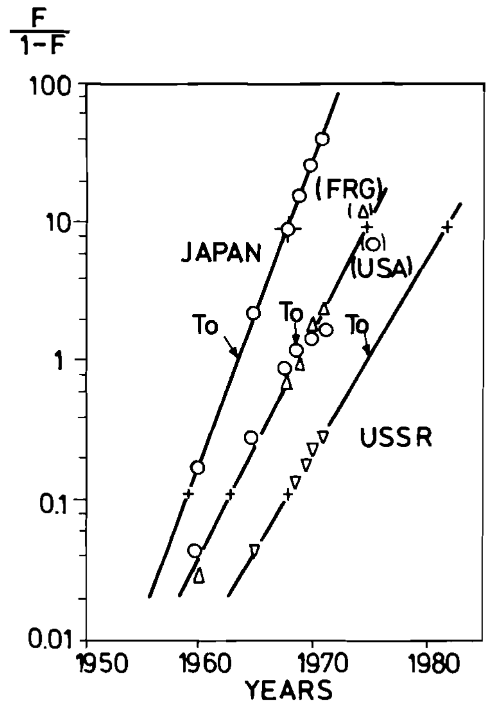

Figure 7. Penetration of BOF versus open hearth and bessemer steel (Source: Ref. [7]).

Assuming that after all primary energy sources are products fighting for a market, we plotted the statistical data for primary energy sources in the U.S.A. (and the world); the result is shown in Figure 8. As you can see, the graph is more complicated than the previous ones, where only one-to-one fights were shown and the curve for the losing product need not be drawn as it is perfectly symmetrical with that of the winning one. Now these curves can be fitted using a set of logistic curves plus some simple rules, and the only input necessary for long-term predictions of the evolution of the system is the initiation point (e.g. where the curve crosses 1 percent) and the slope for the newcomers.

Figure 9 shows that, using data before 1935, we were able to predict the fractional market share of oil in the U.S.A. up to 1970 with a precision of better than one percent.

This very simple fact of long-term predictability, i.e. of causes hidden in the deep past, puts a heavy burden on the credibility of all kinds of modelling based essentially on contingent interactions and short-term memory effects.

Who could resist believing that the saturation of the oil market share in the U.S.A. in the fifties was due to the closure of the Suez Canal and the consequent scare that the very

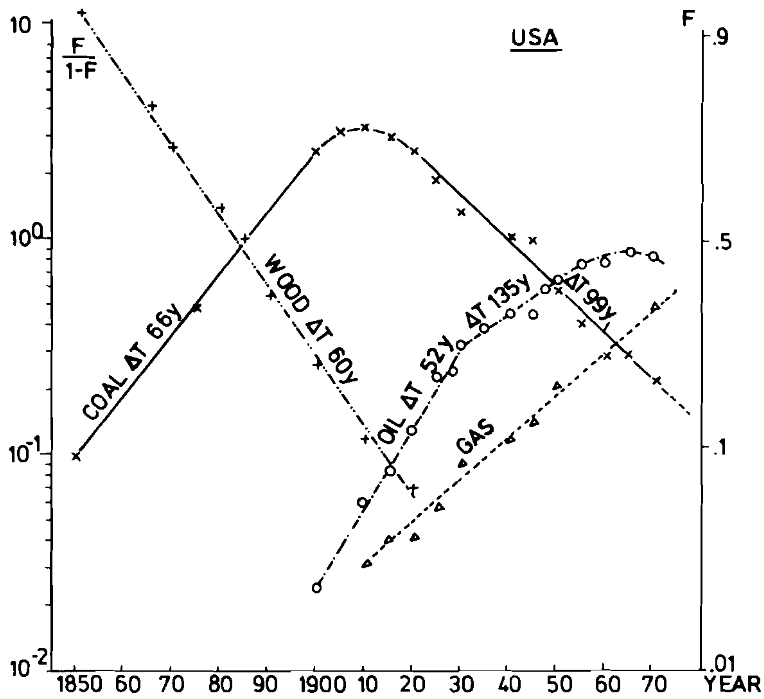

Figure 8. Fitting of the statistical data on primary energy consumption in the U.S.

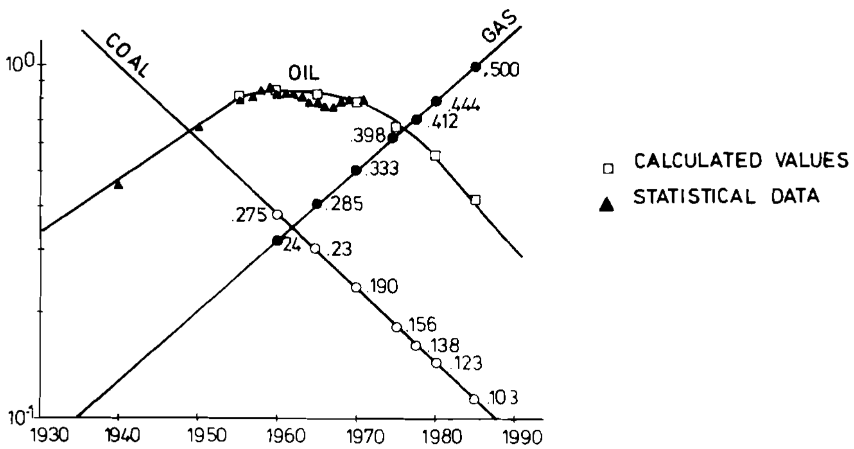

Figure 9. U.S. oil energy fraction calculated from 1930–1940 trend lines.

important Middle East resource was not so safe after all? Or that the saturation of the oil market share for the world in the middle seventies is a consequence of a sharp increase in oil price? But the facts seem to show that the real and quantitative cause of the two phenomena lies in the activity of obscure oilmen fighting for riches in wild Texas at the turn of the century. This is certainly beyond even a wild imagination and is objectively hard to believe; but the facts are there.

Turning now from the past to the future, these trends and rules, and othersthat may appear in a deeper analysis, put severe constraints on the playgrounds of modellers, scenario makers and strategists, and perhaps will lead them to devise a more restricted and coherent set of possible courses than they have done in the past. The models must in any case be able to interpret these invariants that proved to be so powerful and steady in the past. If not, planning, and the R & D that should support it, will be based on sandy ground.

The very stable trends we have shown, and in particular that of primary energy substitution, with its broad base of parallel examples in the market at large, appear to go unscathed through economic depressions, wars and central planning, and in our opinion greatly restrict the "decisional windows" of the strategists.

Two points will now be touched upon. One concerns the link between the freedom of decision we feel inside ourselves which the economists tend to assume as a sacred dogma, and the obvious determinism of many global outcomes. The second is what we can possibly do with the narrow channel left for decisions "free" on the global scale, and how actual R & D and industrial projection compare with that.

Concerning the first point, my first reaction as an old-time physicist is to draw an analogy between the somewhat free and unobservable behavior of single molecules and the beautifully clean pressure-volume relationship in a gas on a macroscopic scale. But this is only an analogy, showing that at the conceptual level the two things may not be contradictory. A general and deeper approach to the problem lies in the analysis of the properties of systems with a very large number of degrees of freedom. These systems tend to evolve globally through some kind of variational control which may be reduced to the existence of invariants, making the behavior of certain macroscopic variables appear deterministic [2]. The existence of such underwater controls in social behavior is vastly documented in a famous book of Zipf [3], from which I draw a curious and ambiguous example (Figure 10).

Everybody knows how important the choice of a mate for life is, and tries his best to make a good one. Now Providence and Fate have always been involved in this operation, but I feel more as a guarantee that the choice was good and meshed

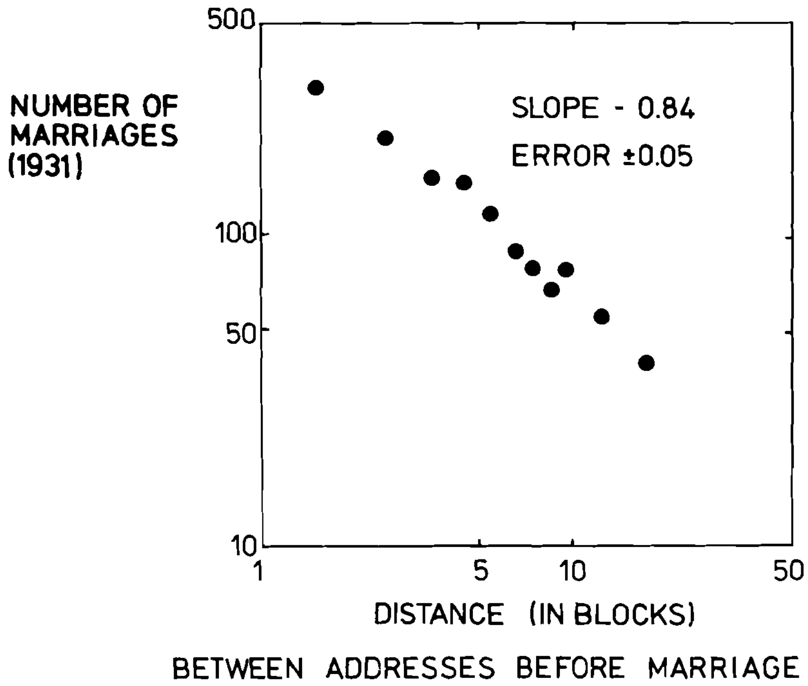

Figure 10. Marrying in Philadelphia (Source: Ref. [3]).

well in the cosmic fabric, than as a real limitation to personal freedom of choice. So it may come as a shock, looking at the bare facts, how rude and vulgar are the ways Fate operates. The probability of finding the proper partner is actually inversely proportional to the distance of his house to the power 0.8! As the number of potential partners living at a certain distance from a given house grows linearly with the distance, the mating probability follow almost precisely the inverse square rule.

Coming back to our more trivial problem of energy modelling and forecasting, we can say that we hope to be able to bridge the two views; but in the meantime we strongly believe that the deterministic patterns are a good guideline to sort realistic strategies from wishful planning.

The first example we will consider, just to take the bull by the horns, is that of coal. As reserves of coal are very abundant, many people take for granted that coal is going to play a renewed role in the energy picture of the next century, starting from some date that was originally around 1980 and is now becoming somewhat more fuzzy. These people should not forget that when coal started replacing wood, reserves of wood were very abundant too--and still are, as the primary productivity of forests is around 40 TW, with human energy consumption in the range of 7 TW; but something other than abundance is operative, moving things in one direction instead of another.

Now the coal line is moving down, and the market forces which keep the curve in that track--almost nullifying even the very serious U.S. effort during the last world war to build up production--may be too strong for the will of a planner or even a government (Figure 9). Following the rules, one could resuscitate coal by starting a new line; but this means severing all linkages with the family, i.e. starting a new industry, with new people, new technology, new products, and a new image!

The usual argument, that coal is cheaper than oil by some large factor, is a somewhat hollow one. Oil has always been more expensive than coal in the U.S.A., and in spite of that has regularly replaced coal even in the most straightforward and massive use of it, that of electricity production.

Let us assume that the "new" coal industry will be started for some reason. It will obviously require an increased level of coal extraction to start with. Coal extraction, as any other mining industry, including oil, cannot be improvised. Even if one uses only old technology, at least 15 years are needed for a well articulated mine to be brought to full operation starting from scratch, and let us say 25 years to have a certain number of mines in operation. We can make the reasonable assumption, up to a point, that in 25 years these new mines will have a conglomerate production of 5 percent of the world energy needs, i.e. something of the order of one TW or one billion tons of coal/year. We can also assume that the rate of growth of this industry will be the same for the coal industry in the U.S.A. 100 years ago, a rather strong assumption as the competition will be quite hard to beat.

The consequence of the introduction of this new industry is indicated in Figure 11, with a so-called SOLFUS operation, started around year 2000. Essentially only nuclear energy will be affected, but its level of penetration in the energy market will reach about 50 percent around the year 2050. In other words, all the effect of a coal comeback will be to stop nuclear energy growth, in relative terms (but probably not in absolute terms) around a century from now. This objective may be worthwhile or not--this is another question--but in any case it seems to be a far cry from the objectives that the planners set to themselves and try to sell. They are essentially:

- Reduction of oil consumption due to the substitution by coal. But as we see from the curves, oil will not be affected even marginally.

- Reducing the "gap" for gas demand. Gas demand can be marginally reduced if the new industry starts early enough (year 2000 might be slightly late), and this is a way to fill the gap the other way around. The capacity of the natural gas industry to satisfy the demand left is a question for the resourceologists, but the prospects seem good.

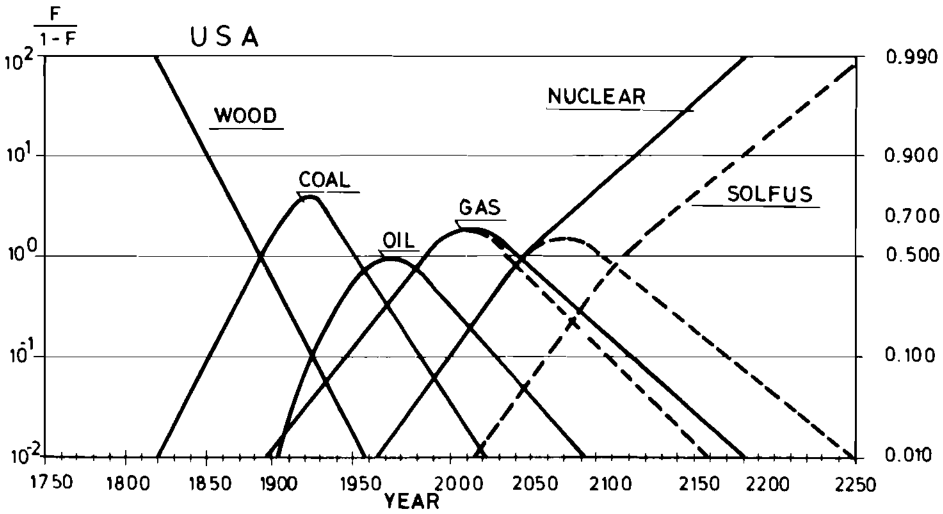

Figure 11. U.S. energy consumption from various sources.

- Cutting the ground from under the feet of nuclear energy. If this is done via natural competition, the operation does not seem to pay; in the year 2050, as the curves show, nuclear energy will provide more than 50 percent of the primary energy in spite of the "new coal." And it is hard to see the qualitative difference between a system deploying 35 TW nuclear, and one with only 17 TW. One could certainly ban nuclear energy, at least in theory; then all the burden would rapidly fall on natural gas (Figure 12), and resources could well become the limiting factor for the first time. But even then coal would not become decisive before the year 2050.

So the scramble for new energy sources, including solar and fusion and Lazarus resurrected from his tomb, is an investment for the second half of the next century, made on the basis of promises about effects ten years ahead in a business and administrative world that rarely dares to look beyond three years ahead. Also, accelerating the nuclear energy program (Figure 13) has effects, but different from those one would expect.

If we look at the constructive side of the analysis, we see that "fate" can be influenced perhaps mostly at the level of seeding, a fact well known to peasants for a few thousand years. As a new "line" appears to follow a fatal course after

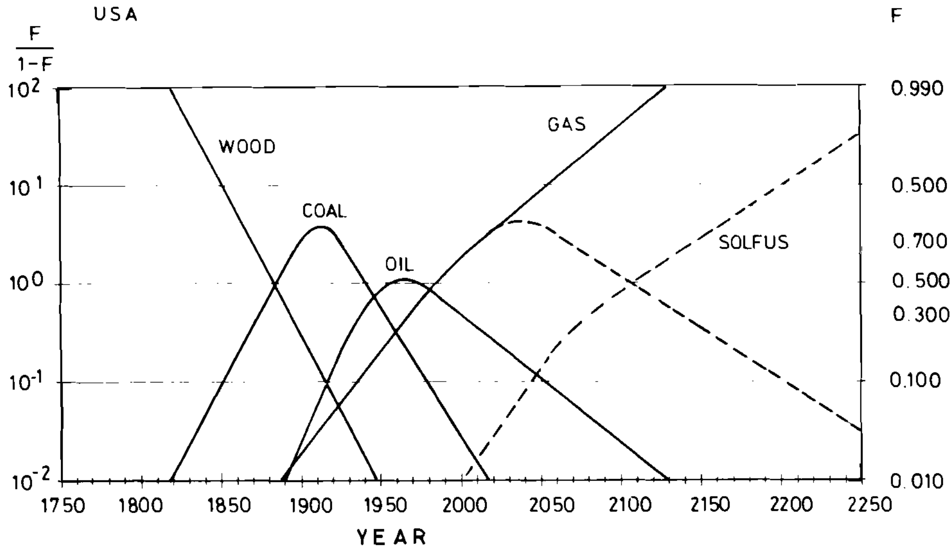

Figure 12. No nuclear energy – new coal year 2000.

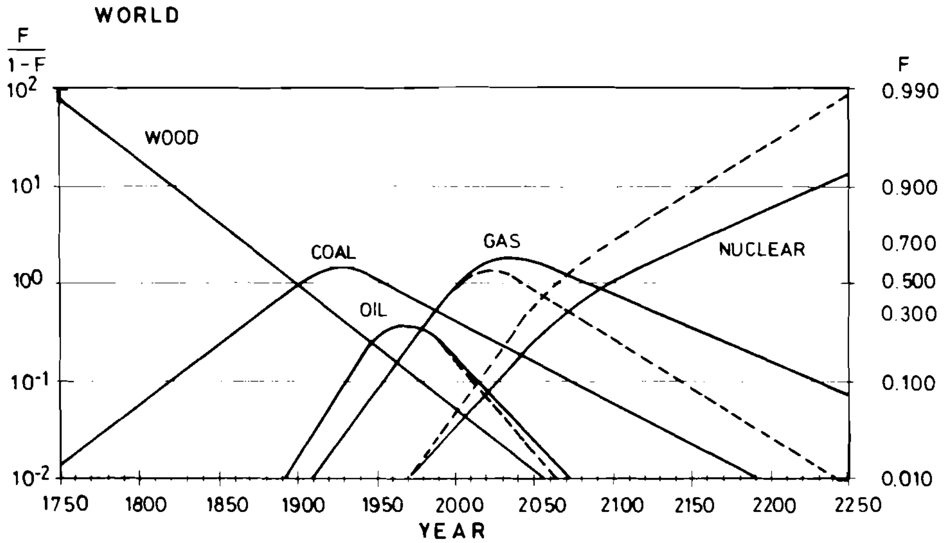

Figure 13. Effects of speeding up nuclear program.

it has penetrated a few percent of the market, what one can hopefully do is try to preset the starting point and the slope on the basis of the effects one wants to reach. This is still a moot point, as the causes of a certain slope and a certain starting point are unknown. A program of research on this problem is in fact envisaged for 1976 at IIASA with a grant from the Volkswagen Foundation. Analysis of past trends, however, indicates that fate may play a part here too. It is difficult to explain on the basis of external drives the almost perfect parallelism of the four substitutions shown in Figure 6, or the very close slopes of primary energy substitutions and the great independence from the type of economy (Figure 7). Certainly there are constraints there too, and presumably also for the point of start. The "decisional window" thus appears to be a narrow one, and the effects of decisions very delayed in time a truly hard challenge for prudent decision-makers.

Another element that must be introduced in the strategies, and often is not, is the predictable part of technological evolution. Industry, and particularly the chemical industry, currently uses learning curves giving the cost evolution of a manufacturing operation as a function of time or, much better, of the total integral amount of the good manufactured in that industry sector. As an example, three cases are reported from the field of energy processing, (Figures 14, 15, 16). The trends are clear and the double log does not hide the effect of major perturbations. The hump in the electricity price curve, for example, is due to overinvestment by the U.S. electrical industry during the hot twenties, followed by a sharp decrease in demand due to the great recession (Figure 14). In order to pay the capital charges the utilities had to increase prices. Figure 16 shows how able the oil industry was in overbalancing the inevitable decrease in resources through a more skillful technology, and how improbable a real oil crisis is, with a multiplication by four or five in prices, when the trend was so smooth. Natura non facit saltus!

It may well be that the trend line will bend up in time, but the statistical nature of oil deposits and of the technological progress make a sharp vertical bend very improbable indeed.

These curves show that there is a certain advantage in coming late: doubling occurs at shorter time intervals as the new industry tends to be more brisk and aggressive than the old. Thus a marginal advantage at the beginning may well expand rapidly. As the learning factors fall into relatively narrow ranges for large classes of manufacturing technology, one might try to search there for explaining the narrow range in market substitution rates.

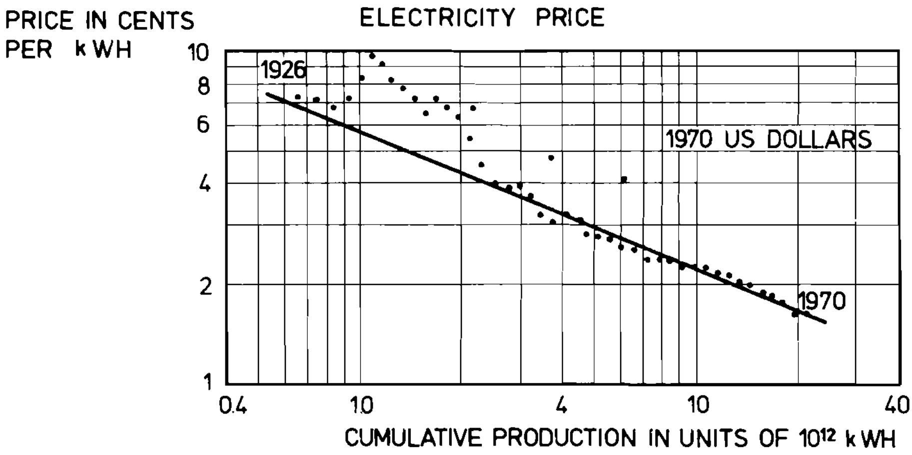

Figure 14. Trendline – 25% per doubling of cumulative production (Source: Ref. [6]).

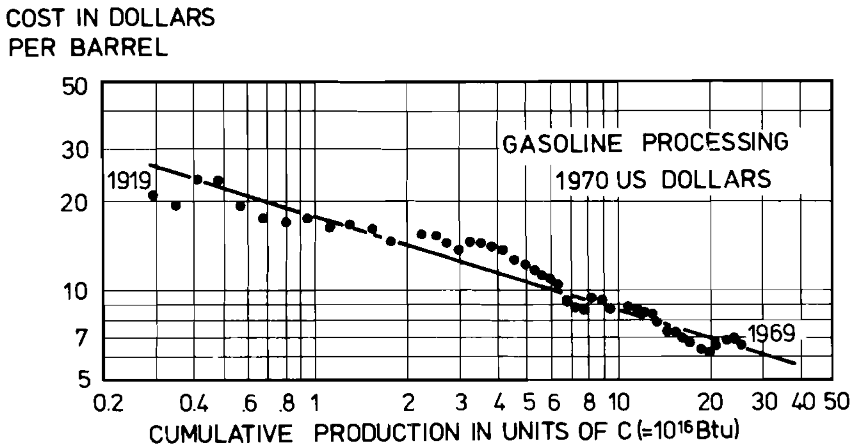

Figure 15. Trendline – 20% per doubling of cumulative production (Source: Ref. [6]).

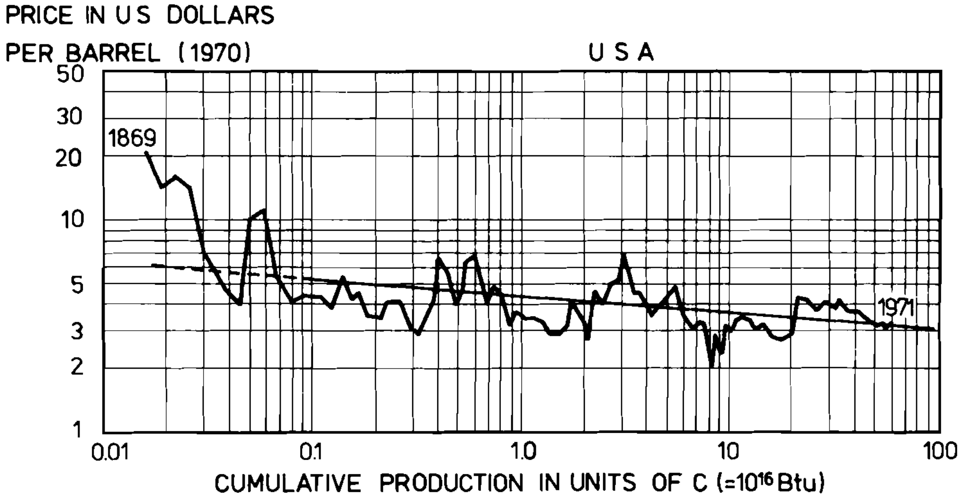

Figure 16. Trend of curve – 5% price reduction per doubling of cumulative production. (Source: Ref. [6]).

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Part 7: AFTER THE TRANSITION PERIOD?

7.1 Geoengineering and the Energy Island

Cesare Marchetti

PART 7. AFTER THE TRANSITION PERIOD?

7.1 Geoengineering and the Energy Island

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INTRODUCTION

The interest of politicians, businessmen, technologists, scientists and the populace at large is focused today on the problem of energy. Everybody agrees that energy is "necessary;" most tend to add "evil."

No objection to the necessity; but analysis of the motivation for regarding energy as evil reveals Freudian undertones. The rejection of technology perceived as a Faustian deal, after two-thousand years of passionate technological endeavor deeply ingrained in the Christian Weltanschauung, is a curious phenomenon to say the least.

This paper, although philosophically motivated, is not a philosophical essay. Together with two other papers, nicknamed in medieval style: "De consolatione tecnologiae," it tries to prove, in the spirit of St. Augustine, that the illness is within man, so that it is there that the cure has to be applied.

As doomtellers tend to wrap their bad moods in sophisticated technical arguments, we choose to sap their technical arguments for impending doom with homeopathic doses of simple technology.

The Problems

The literature describing the evil (one is tempted to say, the devilishness) of the energy system is very copious, and we will quote it only en passant. The list of the main problems is reported here briefly for reference.

Thermal pollution, especially at the energy conversion points (power stations and refineries), with effects on the biosphere and the microclimate, and possibly on a larger scale;

Chemical pollution, at all levels of energy manipulation: extraction (oil spills and acidic waters for coal); transportation (oil spills especially from ocean tankers); use (SO_2, NO_x, CO, miscellaneous chemicals, particles and fumes, ash disposal); particular emphasis on climatic effects of CO_2;

Radioactive pollution, at the level of the nuclear plant, of fuel transportation, of the fuel reprocessing plant, of fission product disposal, and of the fuels themselves (Pu);

Miscellaneous: soil subsidence due to oil, gas and coal extraction; devastations due to strip mining of coal; visual pollution in large-scale transportation of electricity; congestion due to road transport of fuels; noise; smells; home-made bombs by diversion of Pu;

Political: the very uneven distribution of resources--leaving e.g. Europe and Japan out in the cold, not to mention many emerging countries such as India--is an inevitable source of political stresses;

Financial: again, uneven distribution brings a heavy burden in the balance of payment of the have-nots, the once-only character of the resources automatically invites a maximization of their value through oligopolistic maneuvers.

All these problems are serious; the inevitable growth of energy consumption under the sheer momentum of the system, and the very human expectations of the poor, may add enough yeast to make them leaven beyond control. However, redeploying the system as we will describe offers the possibility of solving most of the problems at once, in full accord with the economic, dynamic and technical constraints that a working system has to comply with.

Primary Energies and Energy Vectors

The distribution is important, as we shall see. Wood and natural gas are used as such, or with a minimum of manipulation, by the final consumer. Coal was used mostly as such until perhaps the Second World War. Now it goes mostly into the production of an energy vector, electricity, bearing no resemblance to the primary energy. Oil is following a middle course. Refined products bear less and less resemblance to the crude, although they still belong to the same chemical category, that of hydrocarbons. Nuclear energy, with present technology, is transformed only into an energy vector, electricity.

A brief analysis of the electrical system will help to visualize the strong relationship between the properties of the vector and the structure of the system.

Electrical nets sometimes extend over continents. Europe, connected from northern Sweden to Sicily, is a good example, but electrical energy is in general transported only over small distances: the mean distance the kWh travels in Europe is only 100 km. We can say that electricity is a vector with poor transportability.

Electricity is generated in power plants whose specific cost decreases and thermal efficiency increases with size. The economies of scale tend here to follow the fairly common rule of 2/3, i.e. the cost of the plant grows with the 2/3 power of its size.

The third element of the game is availability of the net. The customers demand very high availability--perhaps 99.9 percent--far beyond that of the simple electric generator. Electrical energy not being storable, the matching between the availability of the simple generator and that of the net is obtained by excess generating capacity in the form of standby.

The whole system is optimized in order to deliver the kWh at a minimum cost. Economy in generation pushes toward large power plants. Economy in standby investment pushes toward small generating plants, so that an accidental outage can be compensated with a small standby. Economy in transportation calls for dispersed generation--again a trend toward small generators.

The interplay of the three factors leads to subnets with an area of influence of about 100 km and with a maximum generator size of about 10 percent of the power of the subnet.

This very simple image is confirmed by almost a century of statistics. Electrical energy consumption has doubled roughly every nine years; the same happened to the density of energy use inside the subnets, whose extension grew with the technology of electricity transportation, with a doubling time of about 22 to 23 years. Combining the two rates one obtains a doubling time for the power of the subnet of six to seven years.

Now the power of the largest generator since the beginning of the century has doubled every 6.5 years through five orders of magnitude!

Similar patterns occur for primary energy. The poor transportability of wood has relegated it to local markets and an artisan level of production. Oil, on the contrary, has magnificent transportability by pipeline and tanker, and the market has developed at world level. Gas has good transportability by pipeline, but poor by tanker, and the gas systems have developed only at continental levels. Coal sits somewhere in the middle: the system has developed essentially inside national boundaries with marginal external markets. The ore carrier based on the model of the oil tanker and the LNG tanker evolving from it, are slowly improving the position of coal and gas from a systemic point of view.

In a nutshell, transportability makes the market larger, and this feeds back to the economy of scale for generation and transportation, making the system self-priming for economy.

Flexibility in use works in the same direction. If coal can be used only to make electricity, that is the upper limit of its market. Oil is the most flexible at present due to the protean quality of its chemistry. Natural gas comes second, being excellent for fixed installations only, although, technologically, it could be used also for transport.

We should now say a few words about storability. The transportation system has the task of matching production and consumption spatially; storage helps to match them temporally. The importance of storage is well illustrated by the electrical system, where electricity cannot be stored as such. In such systems the utilization factor is roughly 50 percent, in spite of an availability factor of the system probably in excess of 90 percent. Lack of storage is then reflected in an over-investment in generation and transportation.

We think we have now laid the logical framework to draw the identikit of the ideal energy carrier: it is *flexible*, *transportable*, *storable* and, last but not least, *non-pollutant* in all the senses listed at the beginning.

Primary Energy Market Dynamics

Substitution of new technologies, products, ideas, for old has for long attracted the curiosity of the economic analyst.

A simple function describing the development in time of the competition between two products for a certain market has been given by J. Fisher of General Electric. Assuming that the various primary energies are just different products competing for the energy market, we plotted the evolution of their market shares in the same way and found a similar behavior.

This representation has the merit of providing a mechanistic visualization of extremely complex and slow phenomena, giving clues both to the time constants of the evolution of the system, and to whom is going to sweep the stakes in the next round. It is our firm opinion that the perception of these forces and constraints must be at the center of any long-term energy strategy. It sounds like wishful thinking to assume that rules which have operated for so long, in so many different fields and economies, and through so many perturbations will be suddenly superseded.

In this frame nuclear energy appears the most probable king of the roost for the next round. The nuclear industry is vast, and the economy established; the fraction of the market which seems empirically to mark the non-return point seems well within reach. This does not mean that solar in its various denominations, fusion, and miscellaneous has no future. It means only that they are too late to rob nuclear of the *next* round. Thus, the capacity to accommodate the characteristics of these possible new energy sources, and the flexibility to fit the phase-out requirements of the classical ones, would add a touch of perfection to the energy system we are going to describe.

Nuclear Reactors and the Hydrogen Economy

A nuclear reactor is a machine capable of producing heat from fissile nuclei, and to transform fertile nuclei into fissile ones.

Its important characteristics for our purposes are the following:

It is very sensitive to economies of scale. Investment costs for the *nuclear island* tend to grow with the square root of the power of the reactor;

The influence of the *raw* fuel material, U or Th, on the final cost of the heat produced is small in the case of current reactors and negligible with breeders. In other words, the cost of the heat generated by the reactor is essentially technological, it is a *process cost*;

The by-products, radioactive materials, are very toxic, almost impossible to degrade, very long-lived, difficult to dispose of and potentially very powerful explosives.

The old way to deal with plagues is the lazaret, and it is still valid today. But to realize the maximum concentration in primary energy plants in the frame of an economic optimization, one has to dispose of an adequate energy carrier, flexible and transportable. Electricity will not do, as we have seen; consequently, nuclear reactors are built in the backyard, so to speak, and the fuel reprocessing plants, in order to be of economic size, have to collect irradiated fuel elements to be transported for thousands of miles through the normal infrastructure. *It is this intricate meshing between the sociosphere and the nuclear energy system at the very root of the "evil" of nuclear energy.*

The most logical step to emerge from the impasse is to find an energy vector of adequate properties. It should have the properties of natural gas to realize a concentration of nuclear reactors at continental level, and those of oil for optimization at world level.

The Hydrogen Vector

This vector was identified some years ago, and it is hydrogen produced by water decomposition. The vast literature already accumulated on the subject indicates that gaseous hydrogen transports essentially as natural gas overland, with the outlook of finding the cryogenic technology to transport it over the sea maturing through the present intensive development of LNG tankers. Furthermore, hydrogen has a very high level of flexibility--i.e., capacity to satisfy the requirements of the various submarkets, given proper lead times--and of ecological compatibility. Buried pipelines are the most unobtrusive system to transport energy, and the only product of H_2 combustion that can be considered a pollutant, NO_x, can be kept at very low levels with some care in design. No "secular" pollutants such as CO_2 are produced. Leakages of hydrogen as gas or spillages as liquid are non-polluting in the most absolute sense.

To make a long story short, if we are able to interface nuclear reactors with hydrogen as the energy vector, then the nuclear energy system can be redeployed at continental level, with a dozen sites per continent and the potential of little coupling with the sociosystem; and finally at world level, with practically complete decoupling through a proper choice of sites.

In the following we shall make an attempt to describe one of these energy centers at world level. It will be an island, both to stress the decoupling and for other more technical reasons. It will contain reactors with total power of the order of the TW(th), and will ship LH_2 to continental terminals. From a systemic point of view, the analogy with a large oil field is almost perfect.

On the New Primary Energies and the Hydrogen System

For meshing the new energy sources into the hydrogen system, *fusion* reactors are perfectly substitutable for fission reactors. Their economics too is very sensitive to scale. As the characteristic of the energy source, the plasma, is different, the hydrogen production system could be a novel one. In any case, that developed for HTGR's would be usable.

Solar energy deployed on a large scale has the problem of storage and most probably transportation over long distances. The transportability and storability of hydrogen are envied by solar energy developers. Here too, the possibility exists of using just the thermochemical watersplitting cycle developed for HTGR's, as concentrations can produce temperatures of the order of 800-1,000 $^{\circ}$C with relative ease. The electromagnetic nature of the radiation, however, and the fact that nature solved the problem a couple of billion years ago by decomposing water into hydrogen and oxygen with chlorophyll, are stimulating research for ad hoc cycles. Low temperature photochemical cycles would have the advantage of making concentration unnecessary.

For *hydropower* in remote areas, or power stations based on ocean thermal gradients, both producing mechanical energy, the technology currently proposed to make this energy transportable is water electrolysis and LH_2 (or NH_3).

For the *old fossils*, market penetration curves show a relatively limited life ahead, independently of resources. During this period, the market demand structure will require products richer in hydrogen than the fossils--e.g. synthetic natural gas (SNG) versus coal. This means that hydrogen, if available from non-fossil sources, will be used to upgrade oil and coal. The interaction then operates the other way around.

The ecumenical character of the hydrogen economy thus provides the perfect frame for the energy island we are going to describe, embedding it into an inevitable evolution.

THE ENERGY ISLAND: BASIC OPTIONS

We are listing here the basic options of our energy island together with some of the arguments supporting the choice. The time horizon being the end of the century, technologies in full development now, such as that of LNG tankers, are assumed to be mature.

Installed Power: ~ 1 TW(th)

The level of installed power comes from the present world energy consumption of ~ 7 TW and the systemic requirement that no more than 10 percent of the eggs be in the same basket. In case one island is shut off for some reason, the other nine should shoulder the extra load. This can be done by some overstretching of the plants, and by the excess capacity always present in systems growing by large blocks. The cost of the hydrogen being due almost entirely to capital charges, it will be a good tactic to use always <u>all</u> the capacity available and store hydrogen in exhausted gas fields in the continents.

Reactor Type: HTGR, Pebble Bed Type

Due to its high thermodynamic potential, heat from these reactors is the most suitable to operate chemical systems, and in any case permits the highest efficiencies. The choice of the pebble bed version stems from the opinion that it is more suitable for scale-up than the prismatic one.

Reactor Mix: HTGR Burners plus Breeders

The system can operate with HTGR only. Breeders can be added to get a mean conversion ratio of one. In this case the system does not grow, but burns all the uranium and thorium introduced. The great systemic advantage would be that the necessary uranium could be extracted from the cooling water.

Reactor Size: 200 GW(th) Horizontal Vessel, Straight or Toroidal

From discussions with pebble bed reactor developers, it seems that the real bottleneck to large size is only the maximum diameter available for the pressure vessel. We got around this difficulty by using a horizontal vessel, straight or toroidal (Figures 1 and 2). With current diameters for the vessel, a diameter of 100 m for the torus and the usual core power densities we obtained the figure indicated. The size of such a reactor is certainly mindboggling to nuclear engineers, as would be the sight of a 1,000 MW generator to Thomas Edison, for whom a giant generator was in the range of hundreds of kw.

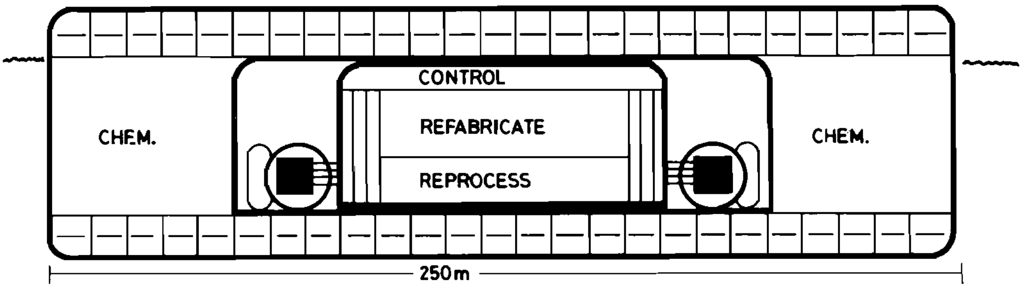

Figure 1. Diagrammatic cross–section of nuclear barge (dimension 250 x 250 x 40 m). All the nuclear region, including the reactor, has a toroidal shape.

In the extreme case of one-island-one-reactor, the economies of scale could give a further reduction of two in the specific investments and consequently in the cost of the heat generated, but obviously the system would be much stiffer. Another reason for the preference for a reactor of this size is that it matches the economic scale of a reprocessing plant. The fuel cycle then can be completely contained in the reactor building.

<u>Reactor Mounting: Prestressed Concrete Barge</u>

The concept of barge mounting has many advantages. The reactors can be built in a shipyard, by a stable organization in a rich technological environment. The site can be changed

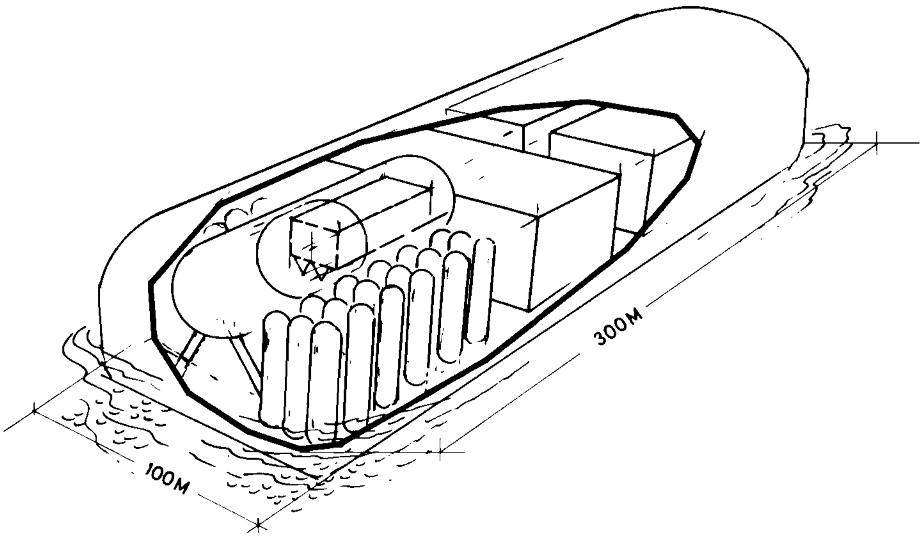

Figure 2. Linear scheme for the nuclear barge.

following redeployments and reoptimization of the system. Final disposal of plants after the end of their useful life can be rationally organized at proper sites. The technology of large (prestressed) concrete barges is under rapid development, especially given the demand for offshore drilling of oil. They have expected lives of more than 50 years. The barges we are talking about are in the displacement range of millions of tons.

The Site: Equatorial Atoll (Canton Island)

The requirements for the site appear to be satisfactorily fulfilled by Canton Island:

- The atoll provides shelter for the barges, and sufficient draft in the lagoon.

- Deep cold waters for cooling purposes are easily accessible.

- The lagoon is large enough (~ 10 x 15 km) to accommodate a complex infrastructure, possibly including the uranium extraction plant, be it chemical or biological (Figure 3).

- The area is outside the hurricane belt, and atmospheric perturbations in general tend to be mild.
- The island is located in a region where introducing heat at the surface of the ocean is expected to induce a negative feedback, i.e. a reduction of the solar input by an extension of cloudiness (Figures 4, 5, 6, 7, 8).
- The island, being located in a region of constant air subsidence, should have a desert climate. Dampness is known to be a heavy burden for people working in the tropics.
- The basalt core of the island is considered a suitable place for the final disposal of fission products and radioactive material (Figure 9).

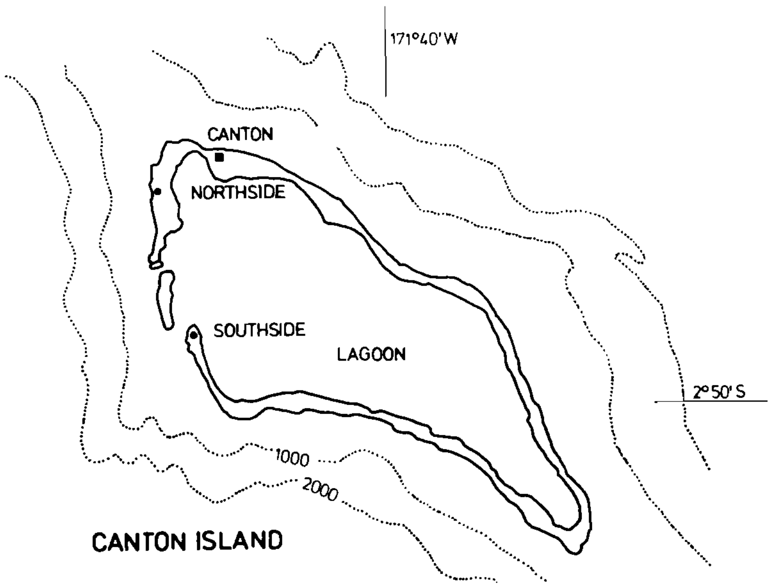

Figure 3. Outline of Canton Island with bathymetric curves. The maximum is about 15 km.

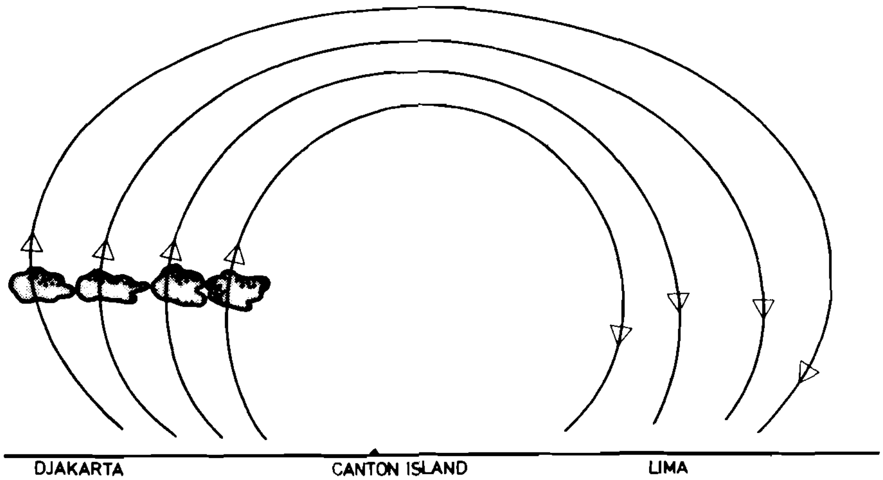

Figure 4. Schematic diagram of the atmospheric "Walker Circulation" along the equatorial Pacific. An equatorial ocean current runs in parallel with the low–altitude circulation branch. Hot, humid air rising in the western branch generates clouds, reducing solar input due to the great difference in albedo with the open ocean. The extension of this cloud is controlled by the temperature of the oceanic current, and indirectly by waste heat rejected into it. The system appears to have a built–in negative feedback, tending to compensate waste heat rejection with reduced solar input.

Figures 5 & 6. Synthetic cloud cover maps integrating 15 days satellite observation. The effect of the descending and horizontal branches of the "Walker Circulation," to keep the ocean cloud–free, is evident as the stable cloudiness in the ascending branch.

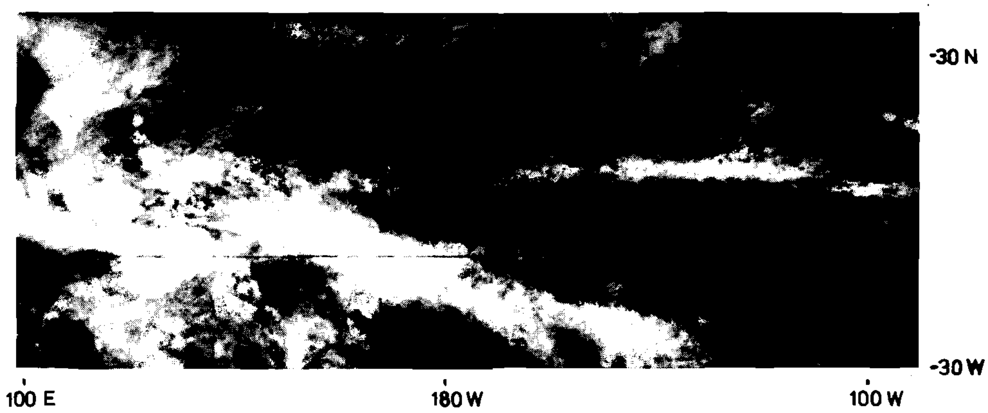

Figure 5. Mercator projection average – March 16–30, 1967.

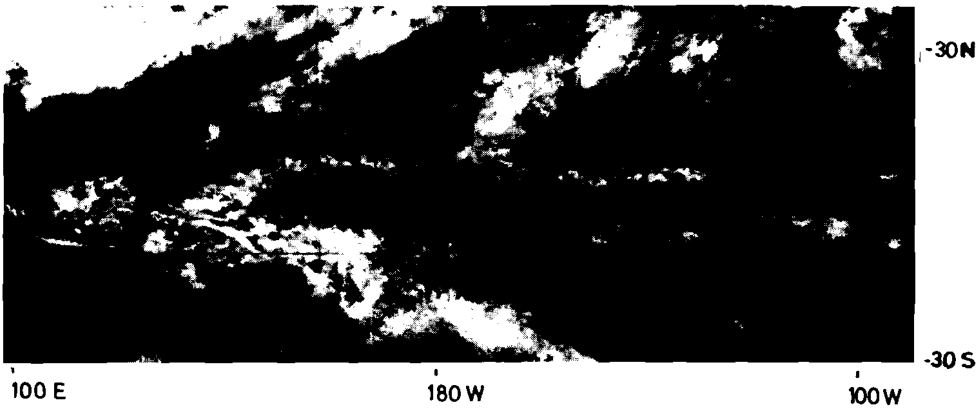

Figure 6. Mercator projection average – January 16–30, 1967.

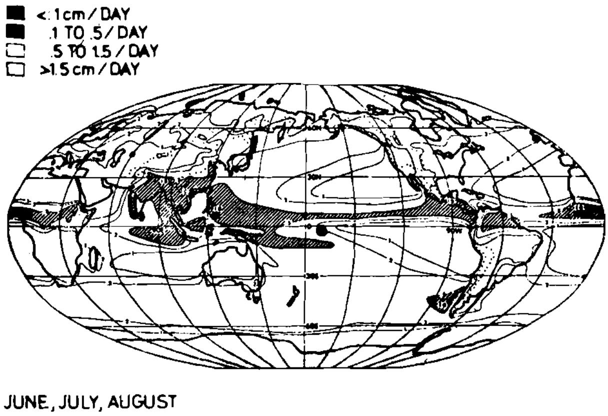

Figure 7. Annual mean rate of precipitation, also confirming the satellite–picture pattern. The position of Canton Island is indicated with a black circle. The hub of the circulation shifts somewhat from year to year, so that Canton Island, which sits toward the eastern limit of its excursion, occasionally gets a tropical rainy season.

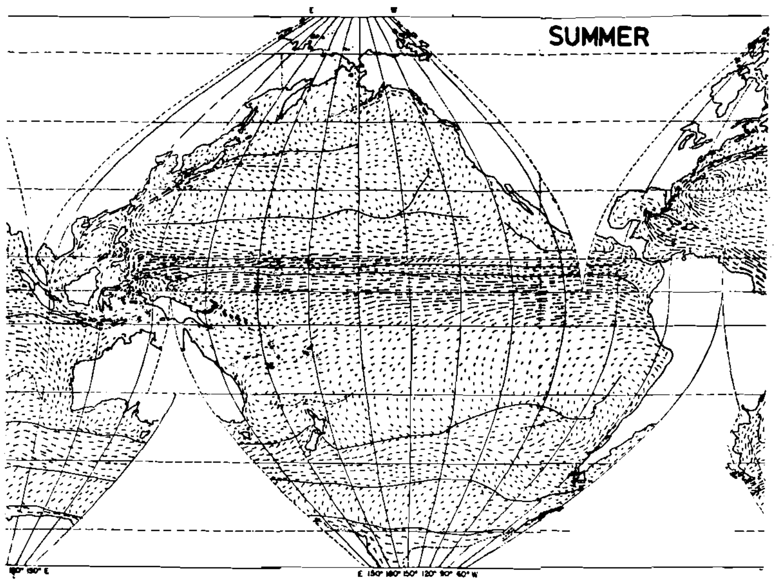

Figure 8. Ocean surface current patterns. The length of the arrows gives an indication of their stability. Canton Island appears to be in a zone of stable east–west currents.

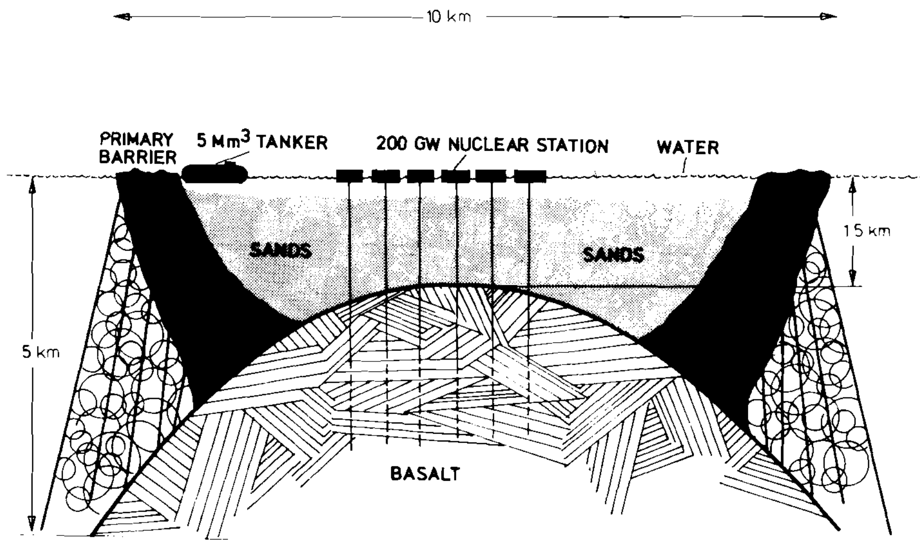

Figure 9. Scale view of Canton "Energy Island" with its presumed geological structure. The full lines under the power station barges represent permanent, drilled radioactive waste sink holes, and the dashed extensions the free trajectories of the sinking capsules.

Waste Heat and the Cooling System: Using Water from the Deep

The system takes full advantage of the thermal gradient of the ocean, making a fine art of what is usually the brutal rejection of waste heat. By pumping water at the proper depth, temperature differentials with surface waters can reach 20°C in most equatorial regions and at Canton Island in particular. This means one can reject cooling water at surface temperatures, or lower. In the first case a thermal plume--with the consequent potential damage to the biosphere or others--will not appear. These waters will, however, be nutrient rich, which will generate intensive algae and fish growth, characteristic of upwelling. In the second case, cooling water will sink to its equilibrium buoyancy level in the thermocline. The equatorial ocean currents will carry this water over long distances, and the heat will be finally released to the atmosphere where strong winds and low temperatures will thin out the thermocline.

This possibility of modulating time, geographical position and rate of heat transfer to the atmosphere provides a rich interface with the work of meteorologists and climatologists, many subtle ways becoming possible for getting rid of the heat with a minimum of disturbance on the geosystem. One of the methods for minimizing the effects on weather and climate, requires water to be rejected at temperatures slightly higher than surface waters.

Cooling Water Circulation: Penstocks into the Thermocline; Thermal Gradient Pumping Optional

A one TW(th) plant with 50 percent efficiency requires a flow of cooling water in the range of 1-10,000m^3/sec. 1,000m^3/sec for a simple pump and pipe is well within the practice of large hydroprojects. Our scheme considers about 10 penstocks lowered to a depth of 200 to 400 m along the steep border of the atoll. Each will be powered by an axial bulb pump, of the type used in tidal plants. The head is due to friction, dynamic losses and some difference in water density, and should be in the range of 2 to 3 m of water. As ocean thermal gradient machines appear to be under successful development, one could operate the pumps using an ammonia cycle through the surface water, and the pumped water which has a temperature of 10-20°C lower.

This bootstrap operation would guarantee a water flow even in case of a major shutdown of the reactors on the island, and might also provide some reserve capacity for essential services.

The Fuel Cycle: Fully Contained in Reactor Building

The most important characteristic of the fuel cycle will be its complete containment in the reactor building. This is a natural consequence of the size of the reactor and has no economic penalty. The reprocessing and fuel fabrication should be mostly automatic, based on sol-gel and coated particles. We assume that carbon too is recycled. In this scheme *fissionable* material, including plutonium, is always mixed with radioactive products and *never comes out as such.* The reactors being of the continuous charge type, no large stocks of fuel will be present at any time. Stealing of plutonium appears intrinsically very difficult, as it means stealing radioactive fuels.

The Hydrogen Plant: Thermochemical Westinghouse Sulphur Cycle, or Water Electrolysis

The Westinghouse sulphur cycle, based on the thermal decomposition of sulphuric acid followed by the anodic oxydation of sulphurous acid, has been taken as reference for its great simplicity and promise (Figures 10, 11, 12, 13).

The ideal configuration would be that of a power cycle, using SO_3 and its decompositon products as working fluids, interfacing with the reactor. SO_2 could then be fed umbilically to the chemical plant, located on another barge, to be used in conjunction with electricity to produce hydrogen. In this way the chemical plant would be in a sense disconnected from the nuclear system, the interaction being through storable chemicals. It is probably appropriate to have the H_2 liquefaction plant associated with the chemical plant, LH_2 being transported to the ocean terminal by shuttle barge or better by pipeline.

The second option is an electrolysis plant (Figure 14). The scale of the reactor, however, makes the electric interface somewhat inadequate; e.g., 40 generators of 2GW (the largest now is 1.3GW) should be arranged around the reactor.

A description of the Westinghouse sulfur cycle and of an electrolytic plant is given in the illustrations.

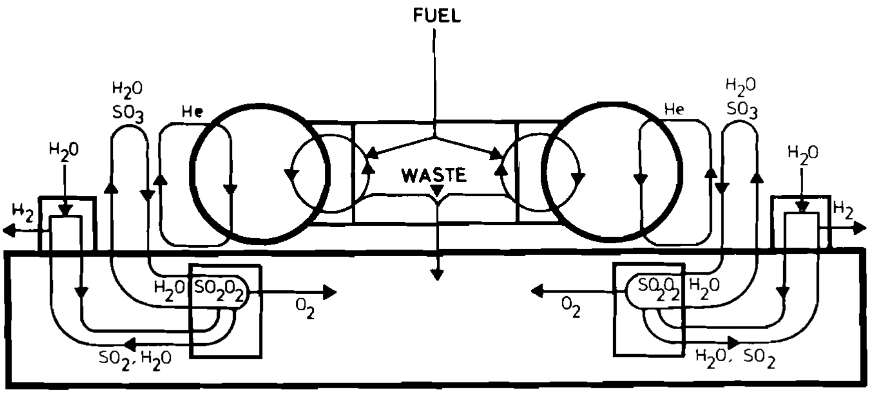

Figure 10. Materials flow of the plant. The fuel cycle, including reprocessing, refabrication and waste disposal, is contained in the central part of the system, on the inner side of the reactor torus. The chemical cycle is external. Waste heat will be rejected mainly from the lower chemical boxes.

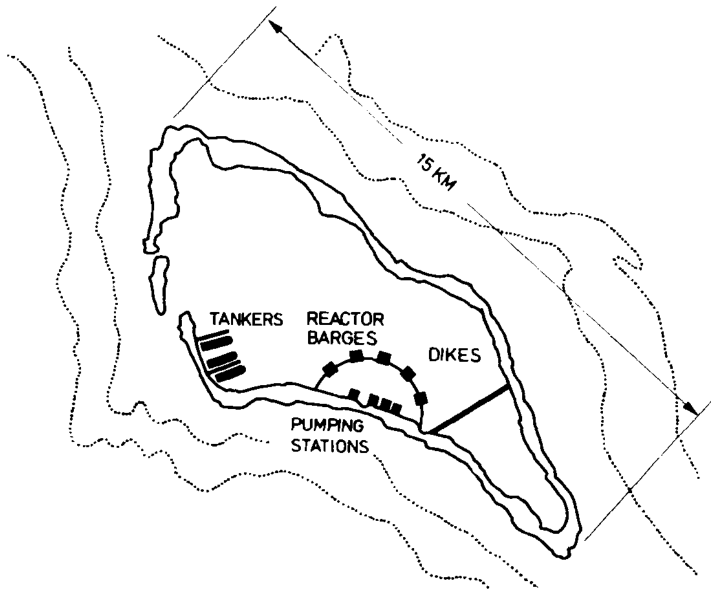

Figure 11. Plan view of Canton Island, with the installations drawn to scale. Each barge represents 200 GW(th) of primary energy.

BASIC REACTION $H_2SO_4 \xrightarrow{<850^{o}C} H_2O + SO_2 + O_2$ ΔG 48kcal

<u>CLOSURES</u>:

- ELECTROLYSIS $SO_2 + 2H_2O \xrightarrow{+0.17V} H_2SO_4 + H_2$ ΔG 9kcal

- RARE EARTH $SO_2 + 2H_2O + Me \longrightarrow H_2SO_4 + MeH$ $\Delta G>9$kcal

  $MeH \longrightarrow Me + H_2$

- IODINE $SO_2 + 2H_2O + I_2 \xrightarrow{100^{o}C} H_2SO_4 + 2HI$

  $2HI \xrightarrow{300^{o}C} H_2 + I_2$

Figure 12. The chemical processes: three variants of the "sulphur process" for decomposing water using nuclear heat. The basic reaction, that of thermal cracking of sulphuric acid, is common to all three. In the first case (developed by Westinghouse), the closure is by electrolytic oxydation of sulphurous acid. In the second (studied by Pechinéy), the closure is through the formation of rare earth hydride, decomposed thermally to yield hydrogen. In the third (developed by General Atomic), the closure is via the formation of hydrogen iodide, to be decomposed thermally. The free energy necessary for the closure, is about 9cal/mole H2.

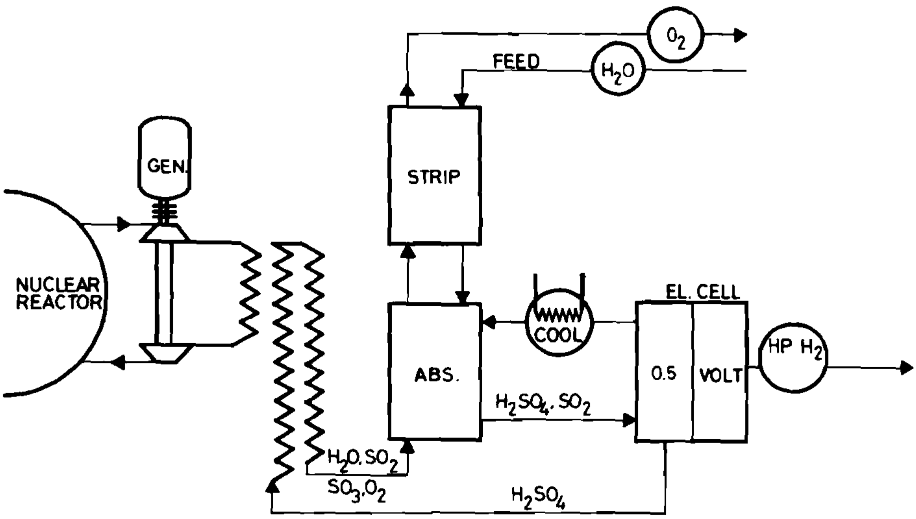

Figure 13. A possible block flowsheet for the realization of the Westinghouse sulphur cycle. Sulphuric acid is decomposed thermally, and SO_2 + SO_3 are stripped in an absorption column where the electrolyte of a cell is circulated. SO_2 is transformed into SO_3 electrolytically.

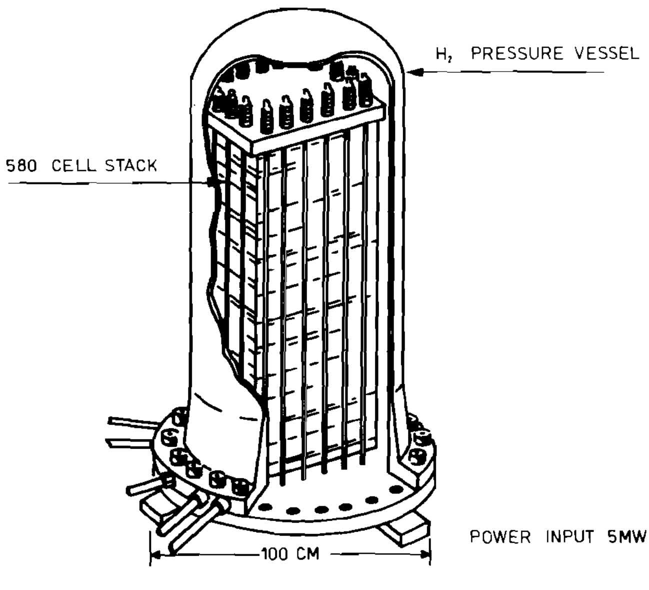

Figure 14. Block scheme and dimensions of a General Electric solid electrolyte electrolysis cell of 5 MW.

Hydrogen Transportation: LH_2 in Tankers, or Catamaran, or Prestressed Concrete Barge

The use of cryogenic tankers appears the best option to date. Cryogenic tankers up to 150,000 m^3 are under construction to transport LNG. If demand exists, rates of growth as for oil tankers, which had a doubling time of six years for tonnage, may be technically feasible. This would produce the Mm^3 tanker in the late nineties.

The volumes of LH_2 to be transported are very high, due in part to the low density of LH_2 (~ 0.07). A TW island would produce ~ 10^9 m^3 of LH_2/year. Assuming three tankers under charge all the time, with a charging time of 24 hours, this would call for 2 Mm^3 ships. This large size is not particularly distressing. The low density makes for low draft. The design we prefer is that of a double cylinder prestressed concrete catamaran, with the cargo partly in the hull, partly in the deck (Figure 15). The low draft should permit access to many sites on all continents. Perhaps the best strategy would be to locate the first continental energy centers on sites that can later be transformed into ocean terminals, in order to use the infrastructure of the center after the power stations are scrapped. This would feed back into the decisions to have the power stations at these centers fixed or mounted on rafts. The second solution is to be preferred as it permits reoptimization of the system by reshuffling the stations and clearing the site if necessary.

Assuming that the continental sites will by then have been reduced to ten per continent, a tanker would visit a site every second day, a very reasonable rate.

Some consideration has been given to the case of an accident leading to spillage and fire of hydrogen. Certainly no pollution is going to ensue. Experiments done, obviously on smaller scales, show that hydrogen evaporates with extreme rapidity, mixing and dispersing in the atmosphere. At the boiling temperature of $20^{\circ}K$, gaseous H_2 is still less dense than air. Hydrogen fires are far less dangerous than oil fires, because they last for very short times and because their flame is almost radiationless, radiation being the most important vehicle for flame propagation in oil and hydrocarbon fires.

Cursory attention has been given to the alternative transport of hydrogen by special airship, carrying it partly as gas and mostly as LH_2. At first sight the system does not appear particularly attractive.

Fuel Procurement: World Market; Extraction from Sea Water

The first option is obvious except for the fact that we assume implicitly that enrichment plants are not on the island. This is mainly because we warmly hope that the proper

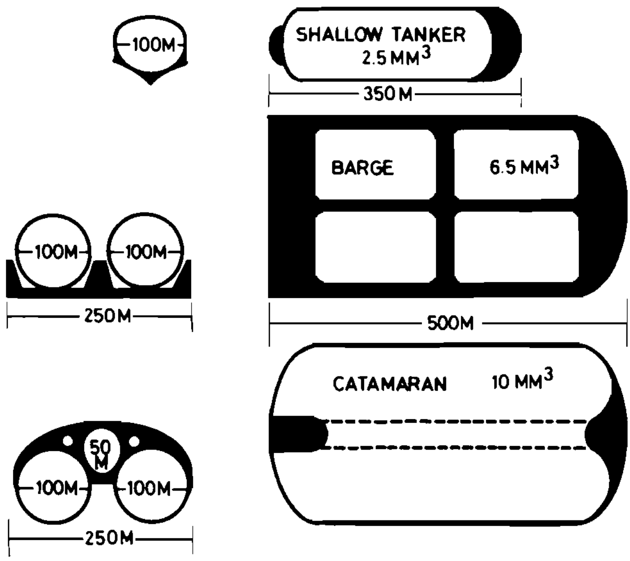

Figure 15. Some vertical and horizontal cross–sections of possilbe LH_2 tankers are indicated. The shallow tanker represents the level of present technology from the point of view of naval construction; the largest cryogenic tanker that could be built today is about an order of magnitude smaller.

breeder, preferably a gas breeder, will be ready in due time. In that case the system would consist of a mixture of breeders and burners with a global breeding ratio of one. Consequently, only natural uranium and thorium should be imported. The annual consumption for a 1-TW island would be in the order of 500 tons/year.

Now an amount of uranium several times this large is carried by the cooling water of the plant. Consequently, great attention should be paid to the development of methods for extracting uranium from sea water. Studies made in Britain in the sixties and more recently in Japan will lead to building the first extraction plant, using inorganic absorbers, in the eighties. A parallel development is going on in Germany, where algae have been bred that are capable of fixing uranium with great selectivity (enrichment factors up to 10^5). In both cases the lagoon of the atoll would constitute an ideal container for the extraction plant.

The fact that the cooling water is pumped from the deep under the thermocline and released at a substantially higher temperature insures that the depleted water will not be recycled, a serious danger for extraction plants operating in shallow waters.

If the breeder-burner combination and the uranium extraction can be economically realized, then the island would become sort of a bootstrap operation eliminating the ecological and political problems of uranium procurement.

Waste Disposal: Selfsinking Capsules

After actinide separation and recycling, waste will be concentrated at levels of 10 to 20 percent in volume of fission products. With a container of linear dimension of the order of a meter, heat generated by fission products is then capable of melting the ground in which the container is buried; if its density is higher, the container will sink for tens of years at initial rates of the order of meters/day (Figures 16, 17, 18, 19). The system automatically provides the necessary cooling by melting of the rock, and sealing by its solidification above the capsule. Each reactor on the island should have a disposal shaft, drilled through the coral overburden and reaching the basaltic core of the island. The shaft will be instrumented and filled with salt so that descent can be monitored for the first year or two and the capsules are recoverable in principle during that time.

We believe the system to be tamperproof and consider final non-retrievability as the best insurance against criminal use of fission products or inadvertent removal by future generations.

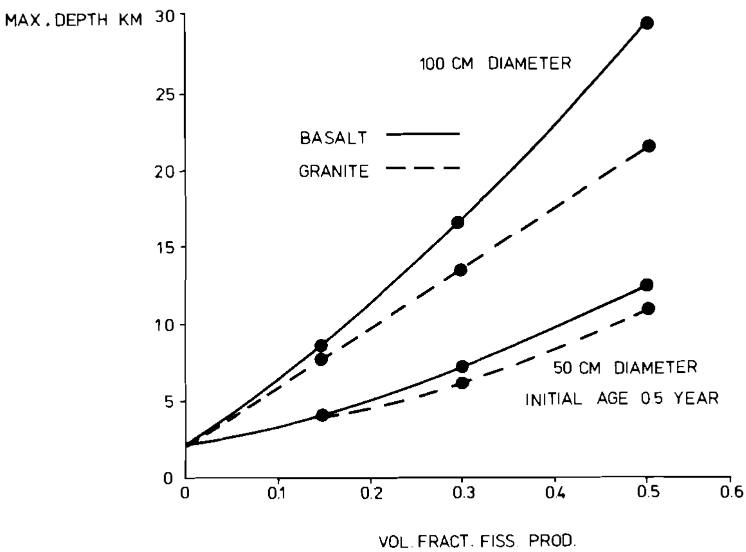

Figure 16. The final depth of penetration of capsules containing fission products, sinking into basalt and granite, that is molten by nuclear decay heat, is given as a function of capsule diameter and volume concentration of fission product, for an initial age of the products of six months at the starting point.

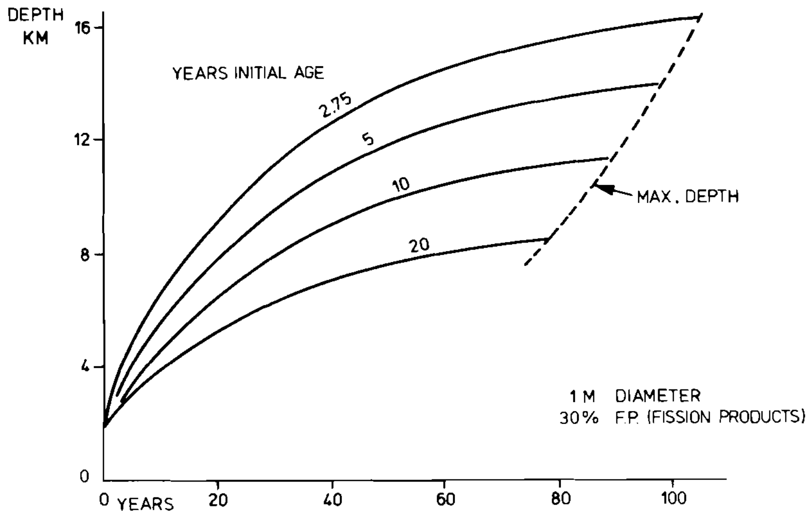

Figure 17. As in Figure 16; the maximum depth is given as a function of the initial age of fission products (time after fuel extraction from nuclear reactor) for a given capsule diameter and fission product volume concentration.

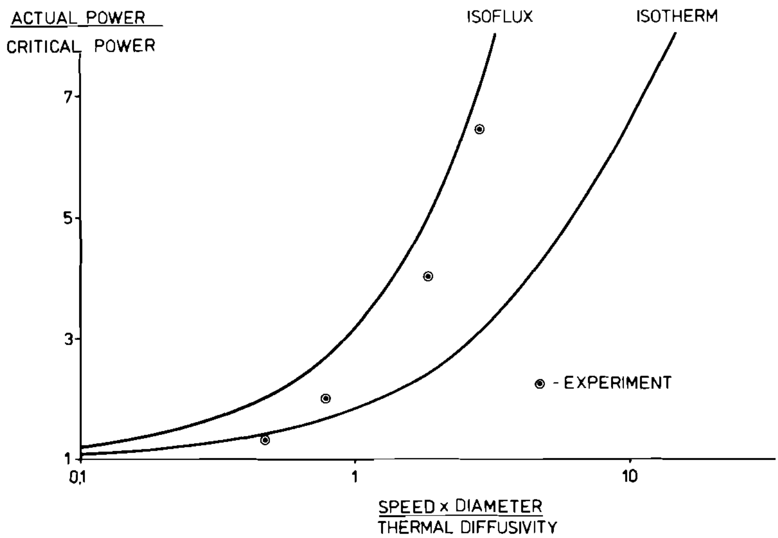

Figure 18. Sphere sinking in paraffin: experimental data for checking the sinking capsule equations. Isoflux sphere assumes local heat flux independent of local surface temperature; isotherm sphere assumes local temperature independent of heat flux; physical case will be between the two.

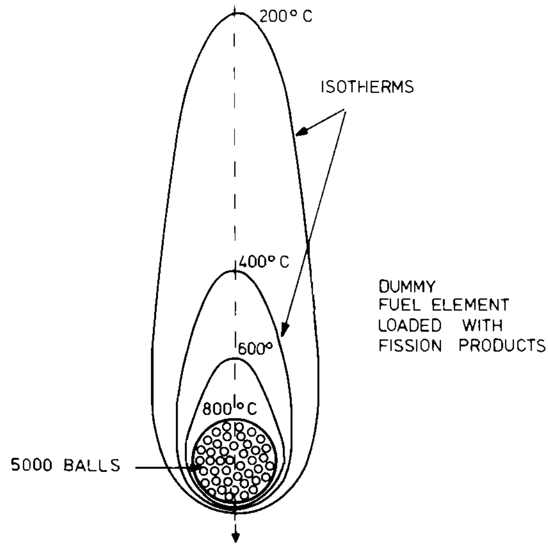

Figure 19. "Cooperative" sinking capsule, proposed because of the difficulty of building a large sphere capable of mechanically and chemically resisting the hard environment of molten rock under pressure: a large sphere is replaced by a large bunch of small spheres, made with the same technology of the fuel elements of a pebble bed nuclear reactor.

The Operation: Ad Hoc Multinational

The scale and complexity of the operation, on the technical, commercial, financial and political side, can well absorb the potential and the ambitions of an ad hoc multinational. Multinationality would come from the market served, from the source of finance and control, from the staffing. It is an essential requirement for the final deployment of the scheme.

The model can be that of an oil company, fading somewhat into the image of a public utility. Investments of the order of $100 billion are well within the capability of such organizations. The system will presumably be manned by engineers only, in the range of 1,000 people. With an investment of $100 M/man, salaries could be high, selection rigorous, turnover brisk. With so restricted a staff, however, most of the repairs and maintenance would have to be made by substituting plug-in components.

We preferred this solution, where most of the technical problems of maintenance and repair are "externalized," because it helps the system to stay open in various senses.

The Resilience: Hierarchical Storages

The problem of the resilience of the system, i.e. its capacity to provide end service despite accidental or provoked disturbances, is of great importance intrinsically as well as psychologically, as people are more and more frightened of depending on very complex, disruptable, uncontrollable and in large measure not understandable systems for the very core of their life and welfare. The extreme concentration in energy generation capacity, perhaps greater than that naturally deployed by the oil system, makes the question of resilience a must. In our view this can be obtained by simple means, so well integrated into the working of the system that the added cost will be marginal.

First, storages in the water table can be realized at the level of the village or city. They may hold the full consumption for a month or so, and a survival consumption perhaps three to four times as large. A well developed pipeline net also provides a form of short-term capacity and of resilience, due to its great redundancy.

Second, at the level of regions, nations and continents, exhausted gas fields can provide the necessary capacity for consumption periods of the order of years. One storage only, that of Gröningen in Holland, full of hydrogen would hold about three years of energy consumption for the European Community.

As the introduction of new capacity will be made in large lumps, dimensioned on the expected demand of a few years ahead, a certain amount of overcapacity will be present most of the time. System costs being essentially of capital origin, it will be natural to produce at full capacity and store the product, as in the structures indicated above. The hierarchy of storage and control will give the interested parties ample time to react.

For the system as a whole, the possibility must be taken into account that one of the island is permanently shut off. This means having a "stretch" capacity in the others of 5 to 10 percent, which does not seem a particularly difficult constraint. Electrical and chemical plants often get that by a slight deoptimization of the operating conditions.

FROM HERE TO THERE: THE TIME SCALE

The structure we have described--defined elsewhere as "target island" to stress its final and attractive character--has to be viewed in the perspective of an evolutionary process.

The first step is the development of a proper water splitting process. Once the right candidate has been spotted (1975), realization of the first plants will go very fast as petrochemical developments have shown. In the second step (1980), type and siting of reactors will very probably follow the pattern set by the electrical industry, and the hydrogen produced will serve essentially the chemical market. The third step (1990) will see energy centers (50 MW(th) reactors) located on the seashore or on nearshore islands with an embryonic continental system pattern, since the transportability of hydrogen and the possibility of using part of the natural gas infrastructure, will call for the center to radiate over a large area. The fourth step (~ 2,000) will be the island supplying "merchant hydrogen" to the energy centers which will start operating as terminals. What happens now with LNG versus natural gas establishes a suggestive analogy.

These steps should be considered not as discontinuities but as first of a kind. Market penetration and substitution will follow the well known leisurely logistics, many techniques being present at the same time.

CONCLUSIONS

The options we have listed make a self-consistent set, and provide the basis for solving to a large degree the many problems currently related to the use of energy and listed at the beginning. For each of the options the necessary technology already exists, perhaps being applied in other fields, or is under development. In a few cases it has been explored only at laboratory scale; but in the author's opinion, its feasibility and economy is only a matter of development.

The claim we made at the beginning, that the extra technology is added in homeopathic doses only, may appear a severe understatement, but we think it is not if we look at the question in the proper time horizon. What we mean by this is that most of the developments would have taken place anyway during the next 25 to 50 years, and what is left, the "addition," may be obtained through a mild stimulation of the system. To be more precise, nothing is envisaged in the scale of the development of nuclear energy, although the consequences of this deployment may be even more far-reaching.

What we were aiming at was a topological description of the system. The geometry, i.e. the design, can take many forms, and is obviously the task of an engineering company more than a systems analysis institute such as IIASA. The few sketches we have included serve the purpose of clarifying a concept rather than providing an outline for the design.

We are also aware, as already noted, that such a complex configuration will not be born whole but will grow in stages, from the inland chemical reactor, to the offshore nuclear park, to the island. This allows time not only for the technology, but for the perception of the problems to mature.

The present struggle for power between multinationals and geographically bound political power will very probably lead, in the medium term, first to international legislation to regulate the operation of the multinationals, and later to a kind of world authority, with limited but sufficient power to deal with them on an equal footing. This configuration strongly resembles medieval Europe where the multinational of the time, the Church, crossing the most variegated frontiers of local power and inevitably interfering with it, was finally balanced by releasing some of the local power to the institution of the Holy Roman Empire, somewhat thin in power but sufficiently articulated to cope with the problem at the proper level.

ANNEX

Background Information on the IIASA Energy Project

It is vital for IIASA to establish a broad interface with the world and to interact in many ways; written communication is only one mode of interaction. The Energy Project has sought this interaction, and in fact its work is thriving partly because of the manifold exchange with other institutions. Although ample reference was made to this interaction in the Introduction, it seems worthwhile to add a brief survey of our attempts to broaden this interface.

As can be seen from the tabular representations that follow, we have established relations with several universities, including the Royal Swedish Academy of Engineering and the Technical University of Vienna; a joint seminar series has been arranged with the University which has attracted a broad audience also from outside. In this way we hope to establish closer links with the local intellectual community. Our relations with industry are widespread. We consult with General Electric and with Siemens; we have working relations with the Electric Power Research Institute, Palo Alto, California; and relations with the Shell group have been established. We have mentioned the relations with our partners in the Coal Task Force, namely the Institute for Organization, Management and Control Sciences at Warsaw, Poland; the National Coal Board at Harrow, Middlesex, the U.K.; Gesamtverband des Deutschen Steinkohlenbergbaus, and the Bergbauforschung both at Essen, F.R.G.; the Ministry of Fuels and Energy, Prague and the OKR Group at Ostrava, C.S.S.R.; and the U.S. Geological Survey.

Our collaborative scientific links are diverse. They extend to institutions such as the British Meteorological Office (BMO) at Bracknell, Herts.; the National Center for Atmospheric Research (NCAR), Boulder, Colorado; and the Siberian Branch of the Soviet Academy of Sciences at Irkutsk. We are cooperating with the Kernforschungsanlage at Jülich, F.R.G., on the survey of energy models; with the Bureau de Recherches Géologiques et Minières (BRGM), Orléans, and the Institut Français du Pétrole (IFP), Paris, on energy resources; and with Electricité de France, Paris, on the impact of energy production on other resources. We have visited our partners in Prague, C.S.S.R., and in Sofia/Varna, Bulgaria, and there reported on the status of our work. (The present Energy Status Report was presented at Varna, Bulgaria, in October 1975.) The scheme of task forces and the joint project with the IAEA have been described. Also, there have been some consulting activities. Against the background of a nation-wide debate on the energy problem with emphasis on energy conservation and nuclear energy, we made presentations in Sweden to a parliamentary committee and to the Royal Academy of Engineering. Other consulting activities included preparing a major base paper on nuclear energy for the Austrian government.

Another important channel of communication is invited papers for presentation at major conferences. Through these papers, we have reached a broad audience, and significant follow-up activities have resulted. Some of the major studies covering wide areas are shown in the list of accomplishments that follows; a comprehensive list of papers appears in the IIASA publications index. We are also preparing two conference volumes and have prepared one major survey. We have written the linear program for transition strategies and have made operational the large global circulation model of the BMO at Bracknell, Herts.

There are of course other modes of interaction; our list is not complete but it may serve to indicate the scope of our attempts to establish rich interactions with the outside.

External Relations

Interactions/Joint Ventures

Fusion/Fission Task Force: University of California, Berkeley
University of Wisconsin, Madison
Kurchatov Institute, Moscow
Nuclear Research Center, Karlsruhe

Coal Task Force: U.K., F.R.G., Poland, C.S.S.R.

IAEA

Joint Project: Risk Group

Consulting

Sweden: Situation of Nuclear Energy
Austria: Situation of Nuclear Energy
Solar Energy

Academic

Royal Swedish Academy of Engineering	-	general
University of Karlsruhe	-	economic studies
University of California, Berkeley	-	solar energy
Technical University of Vienna	-	joint seminar

Industry

Institute for Organization, Management and Control Sciences, Warsaw, Poland

National Coal Board, Harrow, Middlesex, U.K.

Gesamtverband des Deutschen Steinkohlenbergbaus, Essen, F.R.G.

Bergbauforschung, Essen, F.R.G.

Ministry of Fuels and Energy and the OKR Group at Ostrava, C.S.S.R.

U.S. Geological Survey

Electric Power Research Institute, Palo Alto, California

General Electric, San Jose, California

Shell Austria, Royal Dutch Shell, Deutsche Shell AG

Siemens AG, F.R.G.

Scientific Links

Global Circulation Models: BMO, NCAR

Econometric Analysis: Irkutsk

Risk: Paris

Status Report: Varna

Energy Models: KFA, Jülich

Energy Systems: Prague

Energy Resources: BRGM, IFP (France)

Accomplishments 1975

Invited Conference Papers

Nuclear Energy and its Alternatives	Häfele et al.	Nürnberg
Applications of Nuclear Power Other Than Electricity	Häfele et al.	Paris
Market Penetration and H_2; Primary Energy and H_2 Production	Marchetti	Caracas
Methodology for the Evaluation of Environmental Risk	Linnerooth, Otway, and Pahner	Boston
Social Values in Risk Acceptance	Linnerooth, Otway, and Pahner	Boston, Asilomar
Energy Strategies	Häfele, Sassin	Bucharest
Transport and Storage of Energy	Marchetti	Bucharest
Long-Term Energy Strategies	Grenon	Japan
Solar Energy Conversion and the Federal Republic of Germany - Some Systems Considerations	Weingart	Stuttgart

Survey Work

Proceedings of Conference on Energy Demand

Proceedings of Conference on Resources

Survey of Energy Models, No. 2

<u>Computer Programs</u>

Extension and Applications of the Häfele/Manne Model

Global Circulation Models: 2 Numerical Experiments

<u>Studies</u>

Large-Scale Nuclear Fuel Cycle
Avenhaus, Häfele, McGrath

Factor Energy Demand Analysis
Charpentier, Sassin

East-West Econometric Energy Demand Comparison
Tsvetanov

A Critique of Recent Modelling Efforts to Determine the Values of Human Life
Linnerooth

Solar Energy Task Progress Report
Weingart