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LONG TERM ENERGY STRATEGIES*

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Preface

The growing inertia of the energy sector and the market penetration phenomenon make long-term (25 to 50 years) energy forecasting increasingly mandatory. One of the greatest uncertainties is related to the energy demand, i.e. the product of world population (for which some long-term forecasts differ by plus or minus 50%) and of possible energy consumption per capita (for which other forecasts vary by as much as 500% or even more). As an illustration, this paper compares a basic (A. Weinberg, 1971) scenario, and regionalized scenarios. The broad range of figures obtained--from 38 to 300 . 10^9 kW(th)--puts in proper perspective the importance of the transition period and of the optimum choice among the various long-term energy alternatives.

Methods for comparing options--or preparing choices--are insufficiently developed: cost/benefit analysis (the most broadly utilized), impact matrix, preference functions. An impact matrix, WELMM (for Water, Energy, Land, Materials and Manpower) is being developed in the Energy Program at IIASA and is presented briefly in this paper. Preliminary results of comparing land and materials requirements for three different 1000 MW(e) reference power plants (coal, nuclear and solar) illustrate the interest of a better understanding of the systems aspects of harvesting and using energy resources on a very broad scale. Moreover, this kind of approach can be extended to other economic sectors outside energy and appears to be a useful tool for natural resource management and long term forecasting.

Abstract

Because of the long lead times in the energy sector and long market penetration periods, decision making must be prepared early. But uncertainties, and especially the uncertainty of future energy demand, make it a difficult task. Among possible methods of comparing energy options, the WELMM approach has been developed, and is introduced.

Long Term Energy Strategies

The growing inertia of the energy sector and the considerable size of financial commitments make long-term energy forecasting increasingly mandatory, both on a national or regional basis as well as on a global basis. Improper or untimely decisions will come to bear more and more heavily upon the community as a whole.

Yet forecasts are difficult to make because of three major uncertainties: The possible absolute level of the world population, absolute and relative levels of energy consumption per capita, and the structure of energy demand (energy mix and possible role of secondary energies).

NECESSARY TIME SCALE FOR FORECASTING

The first point is to get an idea of what can be considered a necessary time scale fore forecasting: 10 years, 50 years, 100 years? Depending on the people concerned--industrial, governmental, or scientific--there are variations in the acceptance of the expressions of short, medium and long term. Generally, in the Energy Program at IIASA, we consider the three periods from now to 1985, from 1985 to 2020-2025, and beyond 2025. Of greatest interest to us is the second period, from 1985 to 2025, which does not, however, mean that decisions do not have to be taken before this time. Indeed, they must be taken now or in the coming years.

Three examples will serve to illustrate why we consider 50 years to be a necessary time-scale unit for forecasting.

If we consider a single-unit commercial pressurized water reactor like those being built today, the time scale extends over some 50 years: 10 to 12 years from preliminary planning to start-up, 30 years of operating life (with long term requirements of natural uranium and enrichement supply) and possibly 10 to 12 years more for decommissioning and/or possible dismantling.

If we look today at nuclear developments as a whole, about 35 years after the first demonstration of a chain reaction, and after having benefitted in fact from the impulse of generously funded military programs and from exceptionally favorable development conditions (which we did not even appreciate at the time!), nuclear fission now accounts for about one to two per cent of the world's total energy production and consumption. However, it is still relatively far away from a completely succesful achievement as long as the fuel cycle is not fully and commercially implemented. This is clearly illustrated by Figure 1, which shows the timing of the development of the fission breeder over a time-span of at least 50 years, possibly more. The same would probably apply to high temperature gas-cooled reactors; the temporary commercial success of the General Atomic line of high temperature gas cooled reactor raised some hopes about a possibly faster path, but it now seems that we are back to an inevitable path of development aiming at a minimum 50-year developmental period.

1944	The principle of breeding, Fermi
~ 1948	Clementine, Los Alamos
~ 1955	EBR1; BR1, BR2
~ 1959	The oxide breeder, LMFBR
~ 1965	1000 MW(e) design studies
~ 1965-1975	Fuel and materials testing
~ 1972-1980	300 MW(e) prototypes, Phenix etc.
~ 1970-1980	Testing, proofing, licensing
~ 1980-1990	First 1000 MW(e) stations
> 1990	Commercial operation, fuel cycle

Figure 1. Timing of the fission breeder development.

How far, in fact, is this inevitable? Or, put another way, what is the possible share of "fate" in long-term energy strategies? This is very interesting to consider in connection with C. Marchetti's various market penetration curves for different energies [1]. In a broad general study, Marchetti has analyzed over periods longer than 100 years the market penetration of various non-energetic commodities and the mechanism of substituting an old good by a new one. Examples of this would be a different process for steel production, the substitution of butter by margarine, synthetic fibres, paints, etc. The application of this method to various fuels is shown in Figure 2 in the U.S. economy for wood, coal, oil, and natural gas; the time necessary to gain a 50% share of the market (or to lose it, as in the case of wood and partially in that of coal) varies between 52 and 135 years.

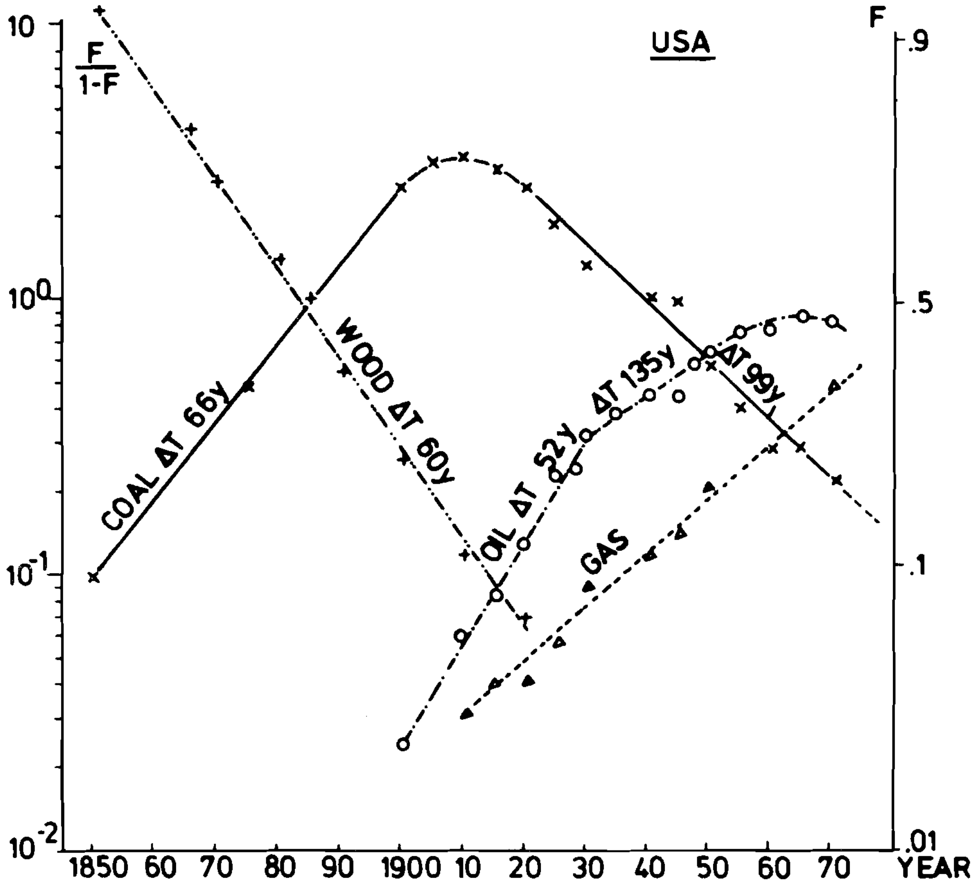

Figure 2. Fitting of the statistical data on primary energy consumption in the U.S.

This has been applied by C. Marchetti [1] and W. Häfele [2] to scenario analysis in demonstrating the possible growth of nuclear energy and its progressive displacement by some hypothetical future energy "solfus" (from solar and fusion) as shown in Figure 3.

In any event, what is important to realize is that mankind has this 50 to 60 year lead-time for a massive introduction of a new fuel technology. This can, however, be used both ways as far as decision-making is concerned. First, for planning the introduction of a new fuel technology such as the breeder or the very high temperature reactor (VHTR), 50 years at least will be needed, assuming that all the necessary steps and sectors are developed in time. We know today that more time may be needed if parallel or following sectors are relatively underdeveloped: This is the case in the reprocessing of irradiated fuels, the difficulties of which have been somewhat underestimated; it is hard to say now what negative influence this underestimation may possibly have on the overall penetration of nuclear energy.

However, from a general point of view, this penetration period will be initiated when the decision is taken to go ahead. This lead-time, which was not always understood nor accepted,

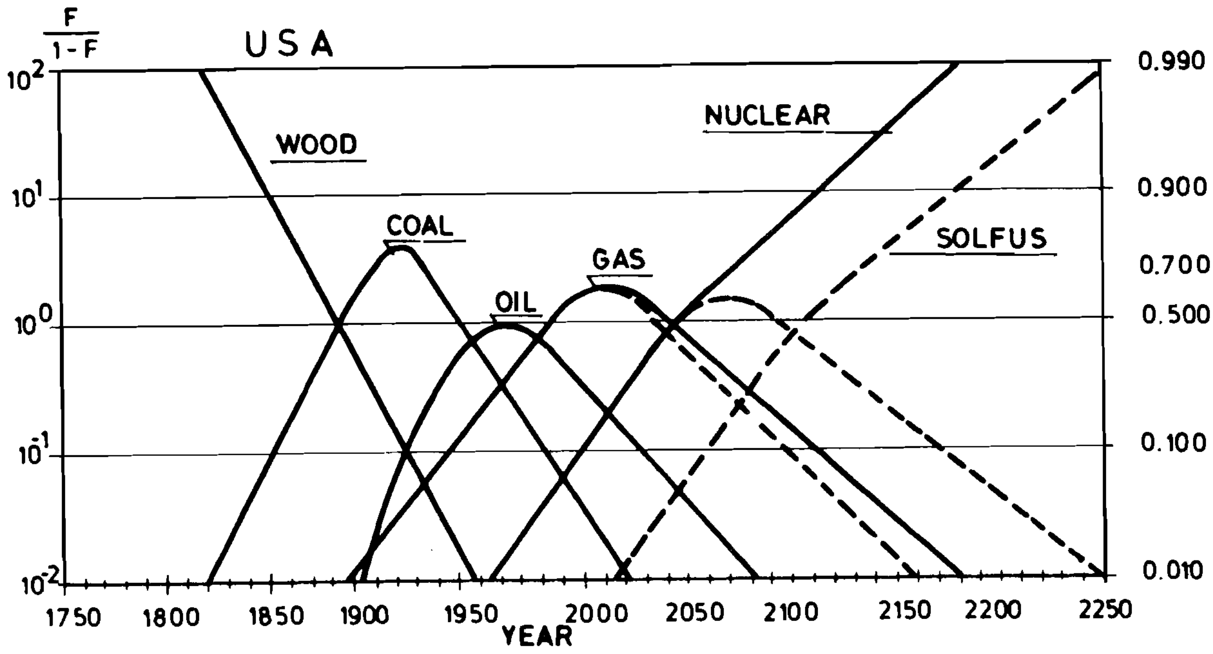

Figure 3. U.S. energy consumption from various sources.

can, however, also be used the other way, when an objective is fixed in time. For instance, in order to cover a certain percentage of total energy consumption through a new fuel technology at a given time, the time for reasonable decision-making can be inferred from such a lead-time. To illustrate this another way, it is worth considering the CO_2 problem as an example.

At IIASA we are analyzing the possibility of implementing coal production and use on a very broad basis, taking into account the very large amount of world coal resources--which may be still more considerable than presently estimated--and exploring, for instance, a two-fuel long-term strategy based on coal and nuclear fuels in comparison with other mono-fuel (all nuclear) or multi-fuel (coal, solar, nuclear, etc.) strategies. Assuming a ten-fold increase, or more, of coal consumption, it appears that one of the limiting factors could be the CO_2 problem, as studied by W.D. Nordhaus [3]. Possible CO_2 reservoirs are shown, together with their mutual rates of exchanges, in Figure 4. Depending on the acceptable increase of CO_2 concentartion above existing levels in conjunction with the risks of dramatic climatic effects, it can be seen from Figure 5 that a large-sclae action to remove CO_2

from the atmosphere--or to prevent its dispersion after combustion--must intervene between 2020 and 2050. C. Marchetti has suggested dumping CO_2 directly into the deep layer of the oceans. Other solutions can also be studied, but the main idea is the following: if it is really decided that coal use be implemented on a large world scale, it will also be urgently necessary to study this CO_2 problem in more depth because it could take a penetration lead-time of 50 to 60 years before one is able to implement the technological solution on the same large scale.

Incidentally, this would also show that the fuel cycle associated with carbon can be of major importance, similarly in some aspects to the nuclear fuel cycle.

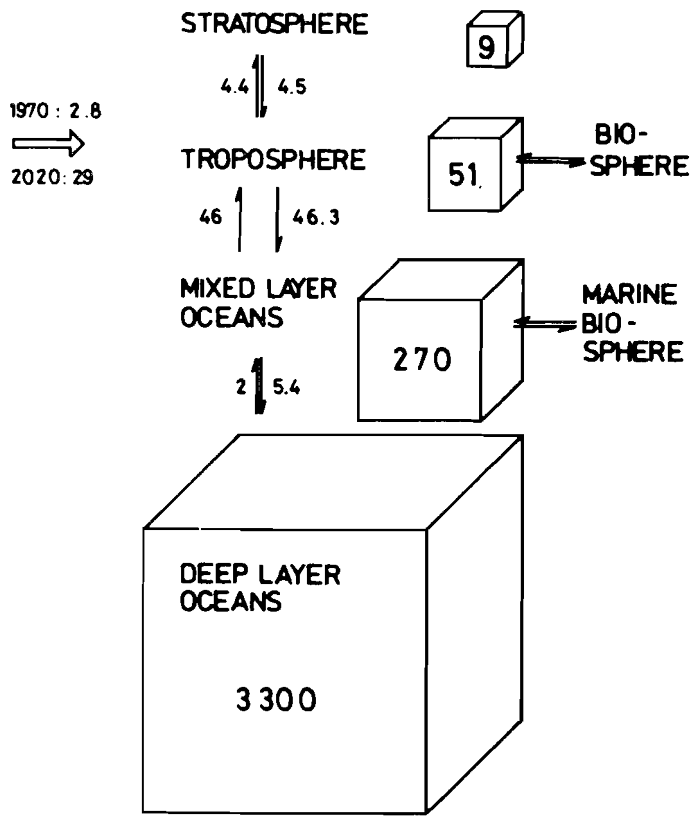

Figure 4. CO_2 ...irs and CO_2 flow - C contents in 10^9 t, C flow ra... in 10^9 t per year (1970 values) (Data: Ref. [4]).

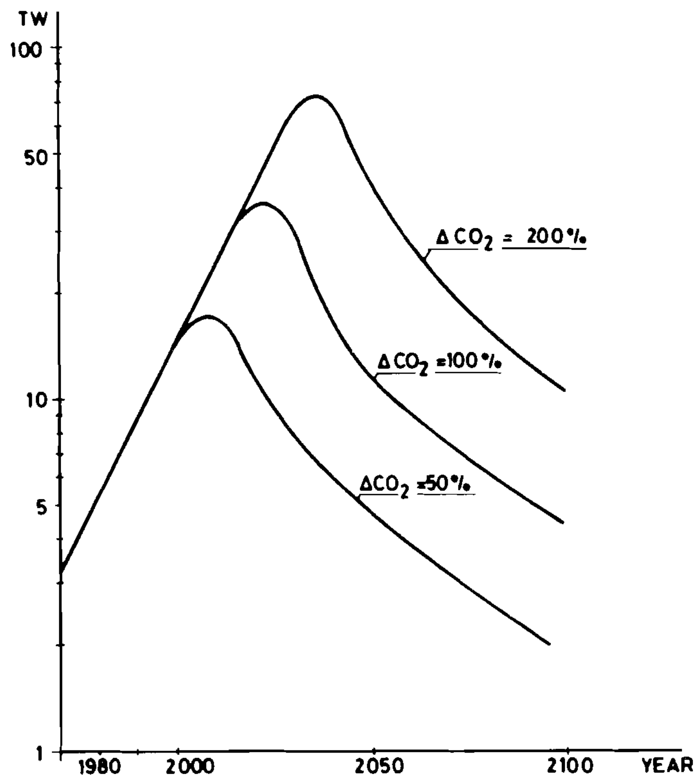

Figure 5. Necessary control of fossil energy consumption, if supplied in the form of coal, to stay below certain CO_2 levels in the troposphere (After W.D. Nordhaus, IIASA, Ref. [3]).

FORECASTING ENERGY DEMAND

Proceeding further, it is clear that the main aspect of the energy problem is the matching of energy supply and energy demand with the necessary assessment of all impacts, that is with a clear understanding of the embedding of energy in the various spheres:

- the atmosphere, i.e. interaction of energy with the climate;

- the hydrosphere, i.e. interaction of energy with global water resources;

- the ecosphere, i.e. interaction of energy with the environment; and

- the sociosphere, i.e. interaction of energy with society, the assessment of risks and, still more important, the perception of risks by individuals or by groups*.

After having obtained some idea of the penetration lead-time for new fuel technologies, the second most important aspect of long-term energy strategy designing and forecasting is the assessment of energy demand. And this is the nightmare of energy planners...

Roughly speaking, energy demand is the product of population multiplied by average energy consumption per capita. Regardless of how one handles it, this product seems to be governed by some modified Heisenberg Uncertainty Principle... On a national basis, maybe, the population level is better known than the future average level of energy consumption. On a global basis, the population level itself is largely unknown.

Figure 6 gives the latest estimates of the United Nations, which level between approximately 12 and 13 billion people after the year 2100. However, such figures are contested as being either too low, as is done by some "Club of Rome" or "population explosion" experts, or else as being too high by, for instance, the French school of demographers. We know, in any case, that we cannot do much about this. One point, however, is worth stating: When study groups select values on the high side, it does not at all mean that they are enthusiastic promoters of these high values, but only that they prefer to err on the safe side of forecasting.

The second factor is the level of energy consumption per capita. Figure 7 shows the actual distribution for some nations. It is well known that there are dramatic differences between the various countries. But what about the future? Alvin Weinberg [6], one of the first, if not the first, to introduce such considerations for long-term energy strategies, quoted a very generous (but perhaps unrealistic...) average value of 20 kW thermal equivalent per capita (approximately 26 t.c.e. per capita), roughly twice the average American level of today. Presently, many scenarios are written with lower asymptotic values of 10 kW or simply 5 kW, which still represent an increase by factors of 3 to 6 compared to the present world average.

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*Because of its acuity, we should like to quote the following statement by N.L. Franklin of British Nuclear Fuels Ltd.:

"In view of the importance of the issues involved, a careful study of the reasons for the public hypersensitivity should rate high in national energy programmes. We should be foolish to continue the present policies of investment in super-safety, with consequent increases in energy costs, without a substantial effort to understand the part played by rejection of all technology, by specifically nuclear considerations and by media manipulation of news and comment, upon the public attitudes to nuclear facilities."

Such studies are the main aim of the joint IIASA/IAEA Project on Risk Assessment [5].

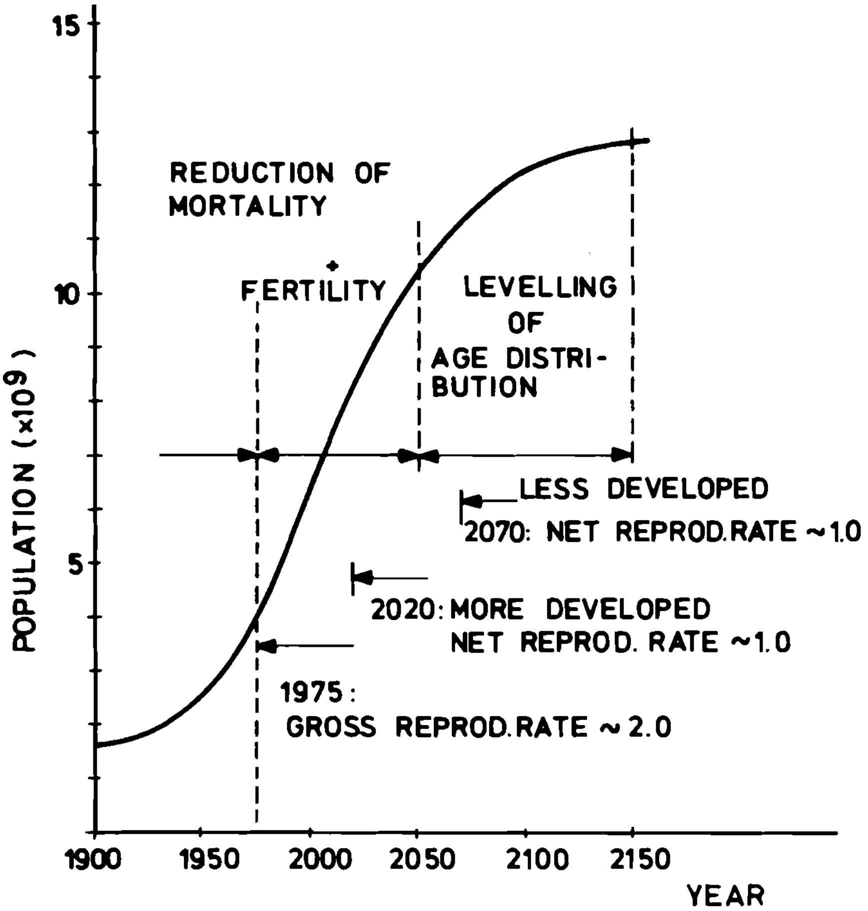

Figure 6. World population growth
(Source: UN World Population Conference, Bucharest, August 1974-Report of the Secretary General).

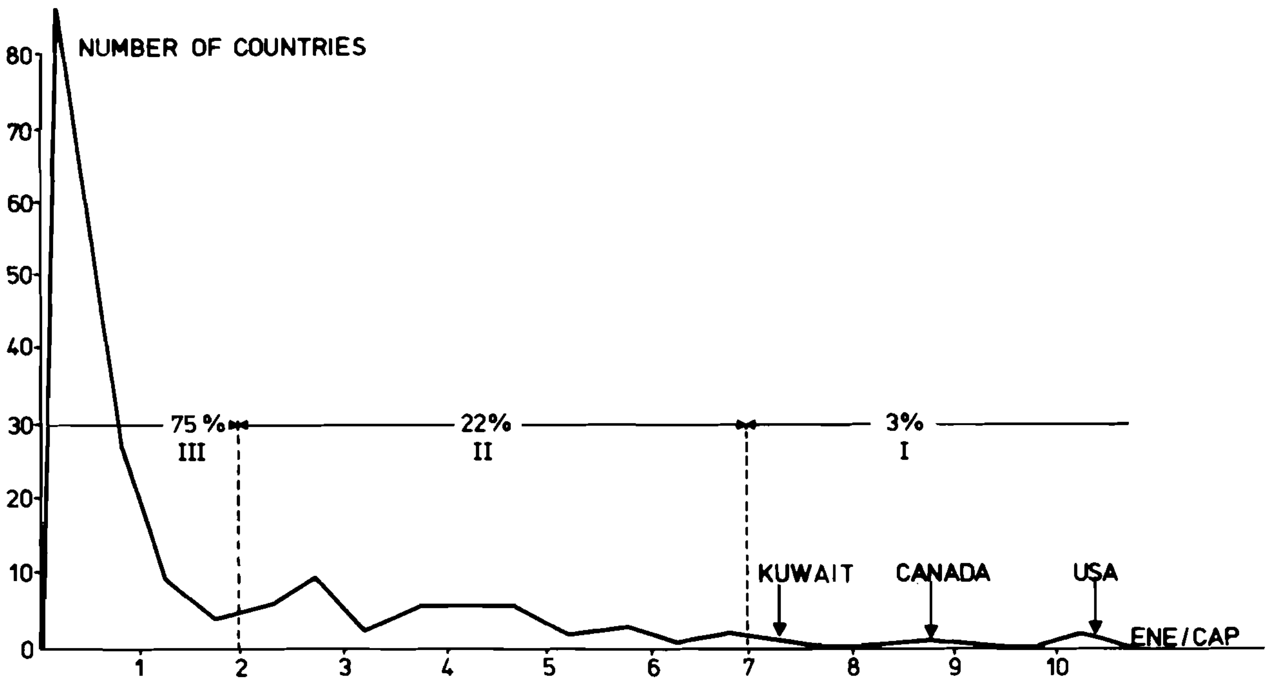

Figure 7. Distribution of world energy consumption, 1971 (178 countries) (Compiled from: UN World Energy Supplies 1968-1971).

If we look at the world as it is now and consider the next 50 or 100 years, the chances of a perfect equalization of revenues and/or energy consumptions seem relatively small. Some nations will develop or continue to develop, others may stabilize at best or even fall. For the U.S., for instance, to reach a level of 20 kW/capita, a simple doubling of energy consumption is assumed (but is it so simple?); this could be achieved with a constant growth rate of about 1.4% per year for the next 50 years, or about 0.7% for the next 100 years. However, for the less energy intensive nations to reach the same level, an almost 200-fold increase or a constant growth of energy consumption per capita of 10% to 12% per year for the same 50 years would be required.

To analyze such factors, we have explored various scenarios of world population growth and energy consumption per capita. Two of them are summarized in Table 1 and compared to that of A. Weinberg in 1971. Weinberg's world is highly egalitarian; unfortunately ours is not. In the two cases displayed here, 33% or 20% of the world population would consume 48% or 58% respectively of the total energy. In the lowest case, the world average energy consumption per capita has roughly doubled, but the increase is relatively small for 80% of the world population, which itself has been multiplied by a factor of between 2.5 and 3. But one of the most interesting results is the level of total energy used: 135 TW in the highest case, 38 TW in the lowest case; this is 6 times more than today (or 4%/year for 50 years), but 8 times less than Weinberg's forecast. This shows the range within which energy planners have to build up their strategies.

In Weinberg's case, at equilibrium, total world coal resources of about 8,700 billion metric tons of hard coal equivalent, as reported in the Survey of Energy Resources for the last World Energy Conference in Detroit in September 1974 [7], would last about 20 years. In the lowest case, they would last 160 years. The difference is not trivial, and we touch here upon another factor, or let us say another difficulty, of energy forecasting, namely the energy mix. It is almost a difference in the nature of the problem whether to meet total energy requirements of 300 TW with only one fuel, with coal, for example, or to cover perhaps 20% of energy requirements of 38 TW with the same coal; the ratio jumps from 8 to 40, and the lifetime of the resources from about 20 years to 800 years, with an absolute level which will nevertheless be 3 times higher than present world production and consumption.

In the Energy Program we are exploring some "high" one-fuel scenarios because they are useful in providing us with limits, or constraints, as already mentioned for the CO_2 problem related to a large coal deployment. But of course, it is my conviction that we are in fact heading toward an energy mix of a few major fuels or resources, and that such an energy mix will probably differ largely from country to country. If the total level of energy supply depends on the final level of the energy demand, the distribution of this energy supply among various resources depends very much on the final uses of the energy demand and the preferred forms. By this we mean the secondary energies which will be used in the future: electricity, synthetic natural gas, methanol, hydrogen, etc.

Table 1. Global scenarios for energy consumption.

Cases	Number of people $x10^9$	In % of total	Energy consumption per capita kW(th)	Total energy used 10^9 kW(th)	In % of world total	World average per capita kW(th)
Highest	1.5	10 } 33	20	30	22 } 48	9
	3.5	23	10	35	26	
	10	67	7	70	52	
	15			135		
Lowest	0.5	5 } 20	20	10	26 } 58	3.8
	1.5	15	8	12	32	
	8.0	80	2	16	42	
	10			38		
"Weinberg" 1971	15	-	20	300	-	20

THE TRANSITION AWAY FROM A PURE FOSSIL FUEL ECONOMY

Our development has been based on an extensive use of fossil fuels. How long it can be continued in the same fashion has periodically been queried for political, economic or technological reasons. This question has been in the forefront since the oil crisis of 1973/1974 for political reasons as well as because of considerations about the final amount of fossil fuel resources, and especially that of oil, which is the most extensively used.

Due to the inertia in the energy sector, as illustrated above, such a transition will be a major undertaking which can proceed smoothly if properly planned and organized, or can be a source of unexpected troubles if insufficiently prepared.

To explore this basic problem, a model has been developed at IIASA by W. Häfele and A.S. Manne [8] (dealing mainly with the transition from a fossil to an all-fissile economy, the two secondary energies being electricity and hydrogen produced by LWR, FBR and HTGR). This model was improved and extended by A. Suzuki and L. Schrattenholzer to also include solar energy [9]. A few characteristics of this linear programming model are summarized below.

Constraints

1) Meet demand of each sector in each time period

2) Limited resource availability

   a) Coal
   b) Petroleum and gas
   c) Low cost natural uranium ($15/lb)

3) Nuclear fuel balance equations

   a) Plutonium
   b) U-233

4) Limited annual construction capacity for non-fossil technology

Figure 8 illustrates two possible types of growth for a "model society" and Figures 9 and 10 show preliminary results.

We are now using this model to explore other kinds of scenarios, including another multi-fuel scenario with nuclear and coal as major suppliers. Here coal is used as a raw material for the production of synthetic natural gas in high temperature gas-cooled reactors. Compared to hydrogen, this alternative could be less demanding on the industrial components and equipment for the utilization sector.

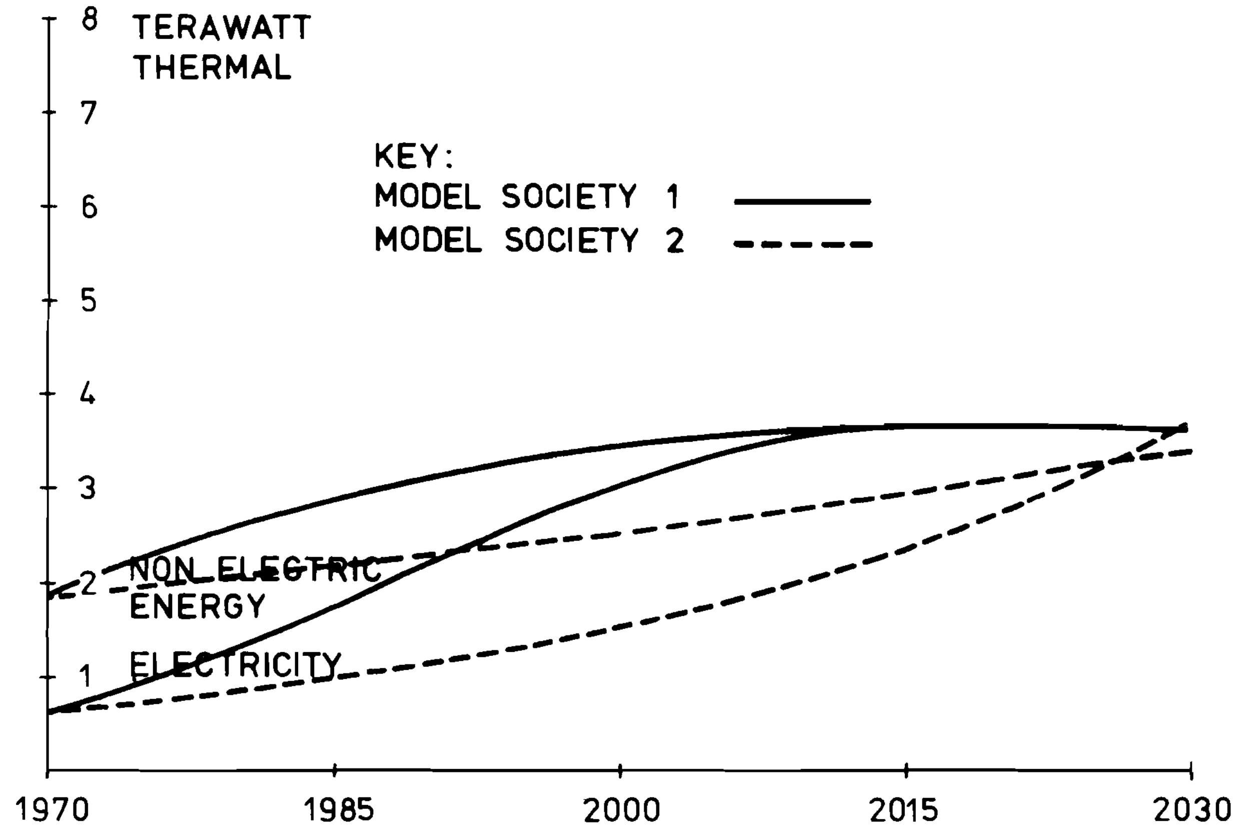

Figure 8. Exogenously-fixed demands.

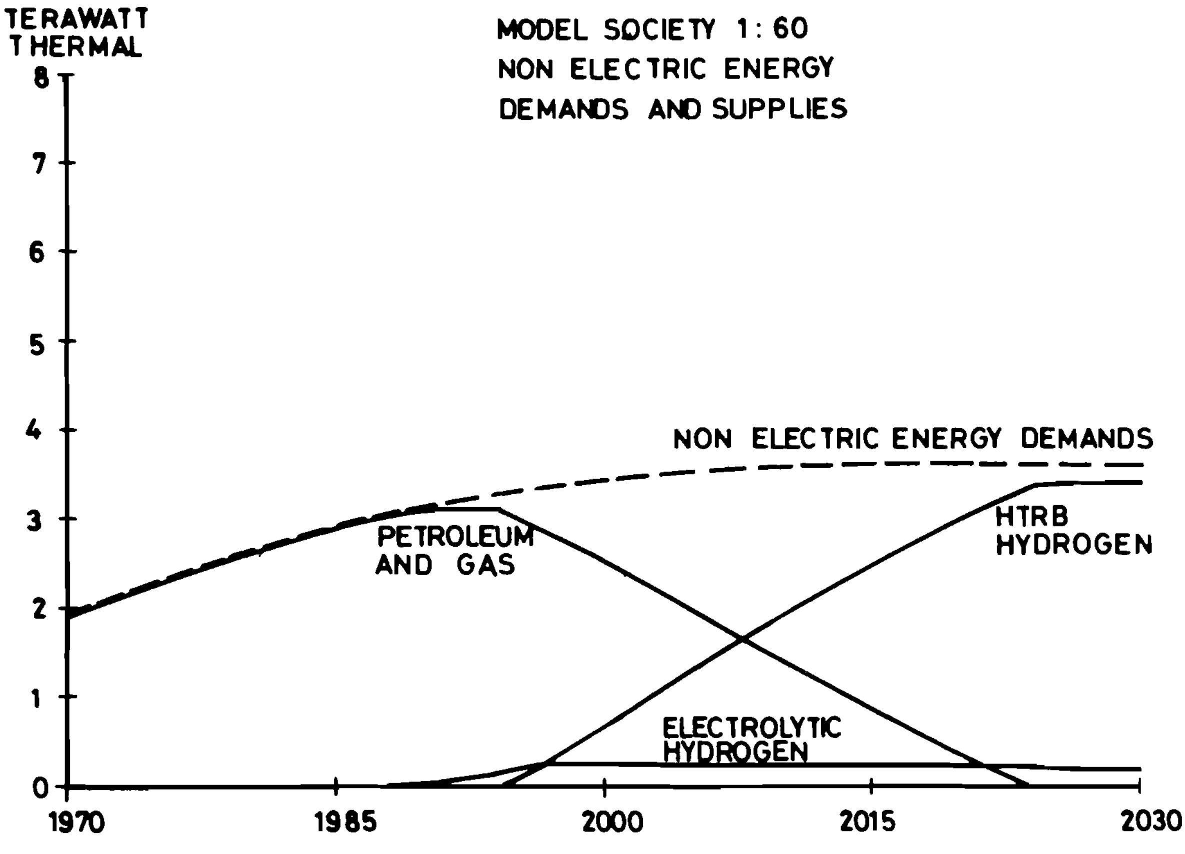

Figure 9. Model society 1.60;
non-electric energy demands and supplies.

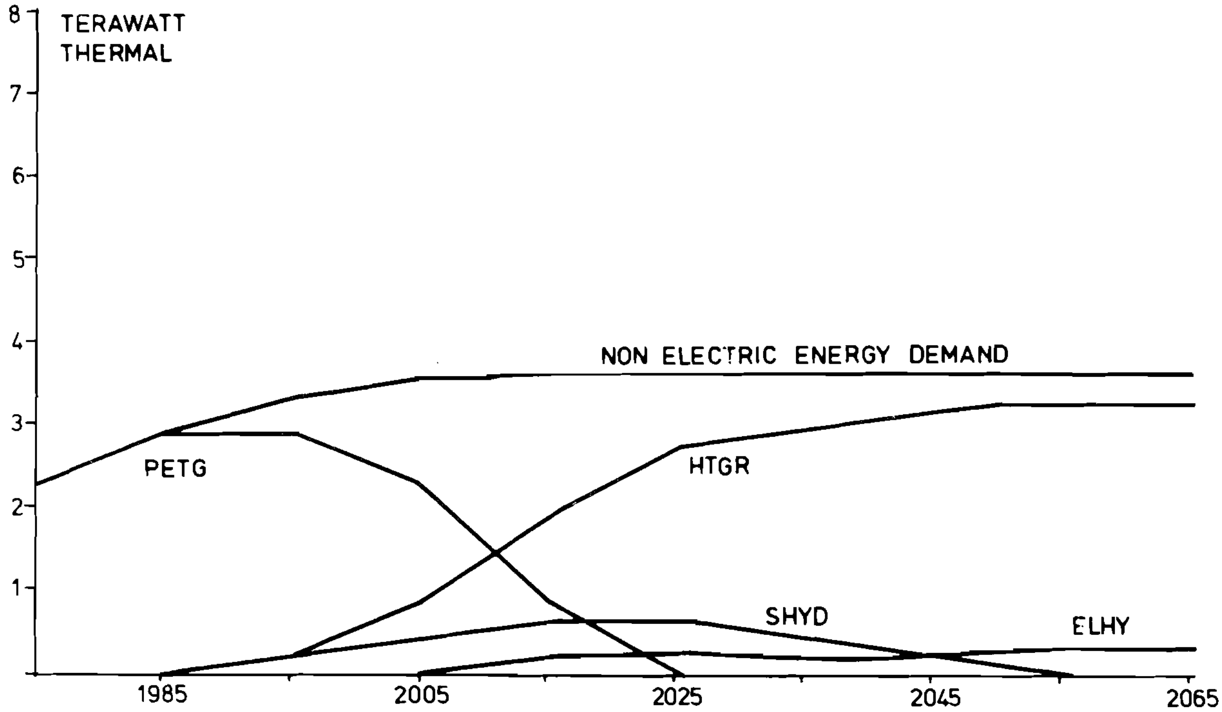

Figure 10. Model society 1.60;
60 years of petroleum and gas reserves,
non-electric energy demands and supplies.

LONG TERM ENERGY ALTERNATIVES

W. Häfele has summarized the five presently-known long-term energy alternatives or options for "unlimited energy supply" (Figure 11) with some assessment of their technological maturity and of their possible side effects.

It is clear, as illustrated by Figure 12, that these various alternatives have received quite different attention and support in the last 20 years. Although this is progressively being somewhat corrected, it is, in fact, very difficult to compare these various alternatives. These difficulties of comparison lie at two levels: First, the methodology for comparing "apples and oranges" [10] is still in its infancy; second, the knowledge of the technologies involved and the data available differ widely from one energy resource area to the other.

($1Q \equiv 10^{18}$BTU)	Resources	Technological Maturity	Side Effects
Coal	200Q	Mature at present scale To be developed for large scale	Unfavorable working conditions Land requirements CO_2 waste and other pollutions
Fission (Breeder)	$\approx 5 \cdot 10^6$Q	Sufficient for power plants Not yet sufficient for large scale fuel cycle	Storage of fission products Emission of radionuclides
Solar	∞	To be developed for large scale	Land requirements Materials requirements Climatic disturbance? Storage and transportation
Fusion (D - T)	$\approx 10 \cdot 10^6$Q	To be developed	Storage of activated material Emission of radionuclides
Geothermal	$5 \cdot 10^3$Q (?)	To be developed	Storage of waste? Emission of pollutants? Earthquakes?

Figure 11. Options for "unlimited" energy supply.

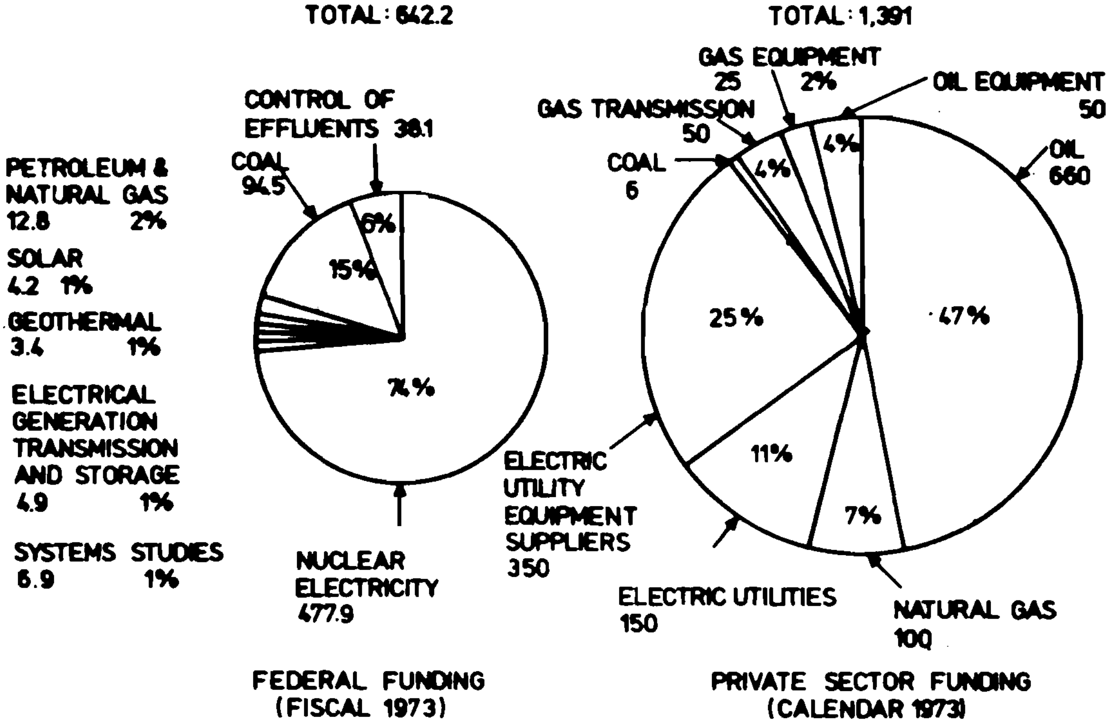

Figure 12. U.S. energy R & D expenditures, federal and private sectors, 1973 ($ million).

Comparing "apples and oranges" is a difficult task. Figures 13a and 13b present three different methods which are being studied at the Institute and which are partially used for comparing energy alternatives: benefit-cost analysis, matrix methods (some examples will be presented hereafter for the comparison of energy resources and their harvesting) and preference theory.

Concerning technologies and data, question marks for geothermal energy illustrate the nature of the problem. Although the resource base of geothermal energy--e.g. the latent heat stored in the top 10,000 meters of the earth's crust--is very impressive, how much of this can really be recovered is a hard question to answer.

When we restrict ourselves for the following to coal (or, on a broader basis, to carbon fuels) fission fuel and solar, it becomes interesting to compare these three resources. To do this, we have developed a matrix method called WELMM:

Methodology	Aggregation of impacts into scaler index	Assumptions on desirability	Assessment
Benefit-cost analysis	Almost everything	Uses monetary units; compares impacts in this unit	Uses economic data
Matrix methods	Usually not	Assumes non-comparability	No desirability assessment
Preference theories	Everything	Relationships explicit and rigorously defined	Assessment

Methodology	Examples	Experience
Benefit-cost analysis	Benefit-cost analysis	Much in U.S.
Matrix methods	Planning balance sheet Goals achievement matrix Environmental impact matrix Factor profile	Some - in vogue now
Preference theories	Indifference surfaces Value functions Utility functions	Limited

Figures 13a and b. Methodologies for comparing energy alternatives.

WELMM

Water

Energy

Land

Materials

Manpower.

The WELMM approach assesses the various impacts of energy deployment on water resources; on land; on the energy balance (or energy analysis, i.e. the energy expenditures which are necessary to produce energy, leading to the ratio of net energy to gross energy contents); on the materials balance; and on the manpower requirements. As far as possible, we consider not only direct requirements but also what we call indirect requirements (for instance, the energy embedded in materials) and the "investment" or "capital" requirements (the energy embedded in infrastructure and buildings, for example).

Figure 14 shows a comparison of the energy content of some fossil fuels with fissile fuels. The scale covered by fissile fuels extends over 10 decades, from pure uranium for the breeder (the mines of which are the tailings of enrichment plants...) to uranium from sea water for the light water reactor. It is interesting to observe that the Tennessee uranium shales (at 60 ppm U content) compare with coal if used in light water reactors (LWR's). Presently, uranium ores of 0.2% or 2,000 ppm are mined and used in the world in LWR's. One of the biggest problems with nuclear development (assuming that it will overcome some of its present difficulties) is related to uranium resources and their use: How large are the resources and how long will they be used in converters? It is worth remembering that, comparing uranium mining to copper mining, for instance, the average grade of copper ore mined in the U.S. has decreased by a factor of 7 (from 4% to 0.6%) in less than 70 years. If a similar decrease, or possibly a more severe one, were to take place for uranium, we believe that the mining problem would become extremely acute. For the time being, the more necessary the introduction of the breeder seems the more its future appears to be clouded or uncertain.

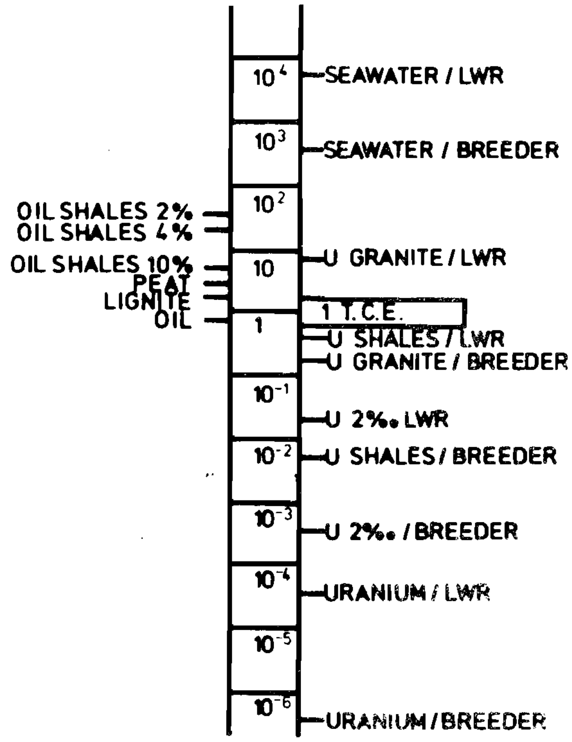

Figure 14. Gross energy content and mining scale.

Table 2. U_3O_8 requirements for different reactor mixes.

Case		Cumulative U_3O_8 consumption to year 2020 (thousands of tons)
1.	No breeder, HTGR constrained to no more than 25% of total nuclear capacity	5,726
2.	No breeder, HTGR unconstrained	4,760
3.	Delayed LMFBR introduction (1991)	3,091
4.	LMFBR constrained to 200 GW(e) in year 2000, introduced 1988	2,878
5.	LMFBR constrained to 400 GW(e) in year 2000, introduced 1987 (base case)	2,332
6.	No constraints on LMFBR or H GR, LMFBR introduced 1987	2,262
7.	Total energy demand reduced by 50% by year 2020; LMFBR introduced 1987	1,849

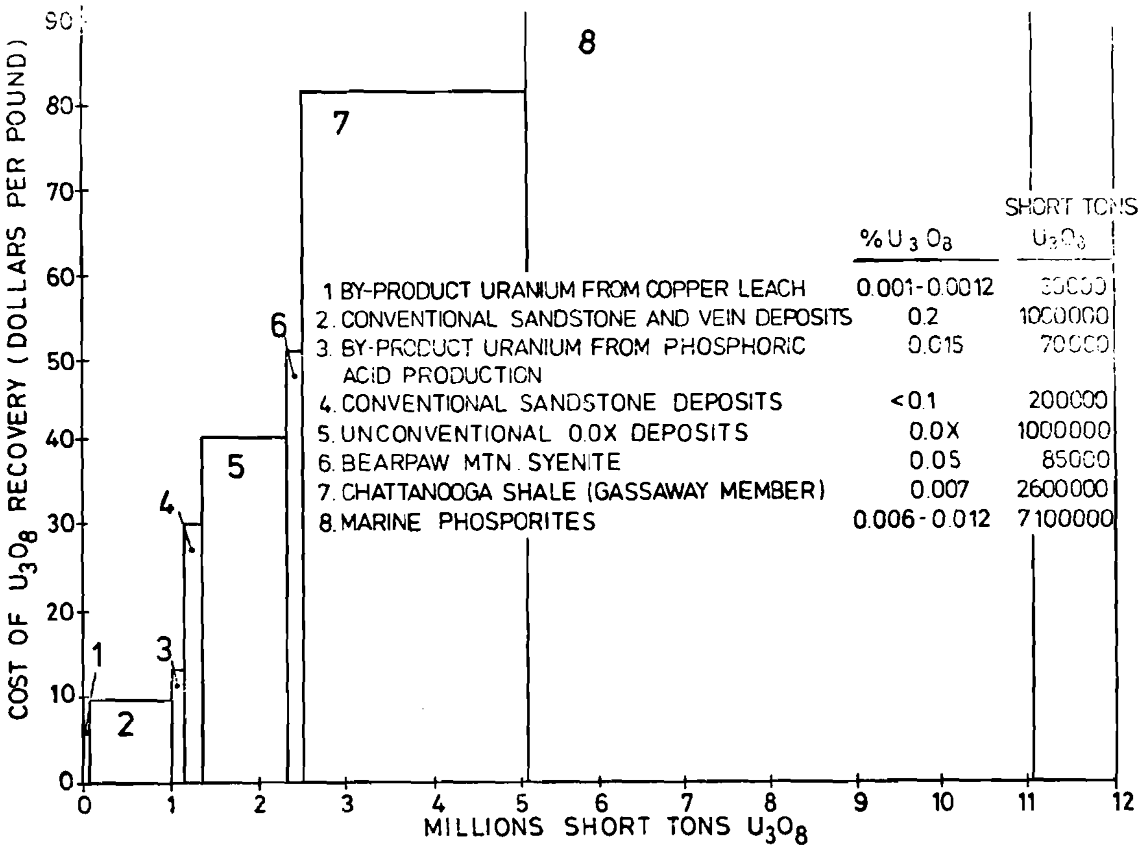

Figure 15. Estimated U.S. uranium resource availability.

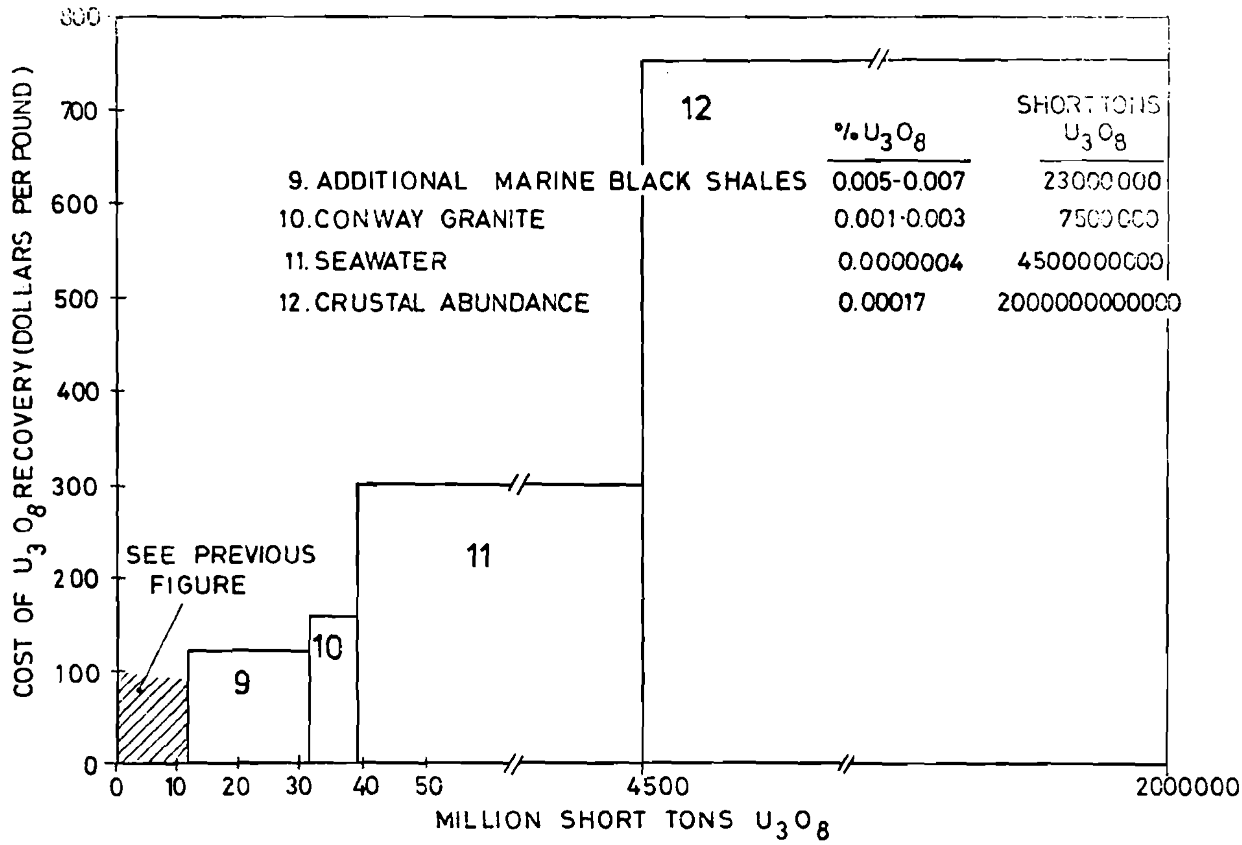

Figure 16. Estimated U.S. uranium resource availability in relation to U.S. crustal abundance.

It is interesting to compare uranium requirements to uranium resources. Table 2 shows a recent assessment of uranium requirements for the U.S. [11] based on various assumptions, including reprocessing and recycling. There is a factor of 3 between high and low values. Figures 15 and 16 show an estimation of U.S. uranium resources [12]. It is worth mentioning that a much more detailed estimation has been launched by the U.S.A.E.C. NURE program (Natural Uranium Reserach and Exploration Program), with results expected for 1980.

It appears today that insufficient efforts have been devoted to the two ends of the nuclear fuel cycle, reprocessing (and the problem of radioactive waste disposal) and uranium resources, compared to the amount of efforts made with regard to the reactors themselves. In a sense, we can say that this statement is also generally true for most of the energy resources, and possibly also for many of our natural resources.

Looking at a general scheme of classification for energy (or mineral) resources, for instance at the U.S. Geological Survey-Bureau of Mines' diagram (often referred to as the McKelvey diagram) (Figure 17), there are many categories of resources ranging from the proven economically recoverable reserves to the farthest subeconomic speculative resources in undiscovered districts. For industrial purposes, the proven reserves are the most important. They are the daily ingredient of business, and they are generally secured on a 20 to 30 year, and at best 50 year, basis compared to the present level of consumption. For U.S. coal, for example, proven reserves represent about 1.7%, or 50 billion metric tons, on an estimated total of about 3,000 billion tons.

But it is clear that, for long-term energy planning or strategies, or for the purpose of choosing between two possible alternatives such as coal or uranium, our knowledge of the energy resources is far from adequate. For uranium, we do not have even the slightest idea of possible figures for the total amount, apart from reference Figure 16--which does not mean much--of the abundance of uranium in the earth's crust. There is a good chance that "the uranium is there" [13]; but where, in which form, in which amounts? Recently doubts were expressed--for instance, by the O.E.C.D./I.A.E.A. Working Panel on Uranium--that it can be found in time to meet the future requirements, and figures of 20 billion dollars have been mentioned just for exploration in the coming decades [13].

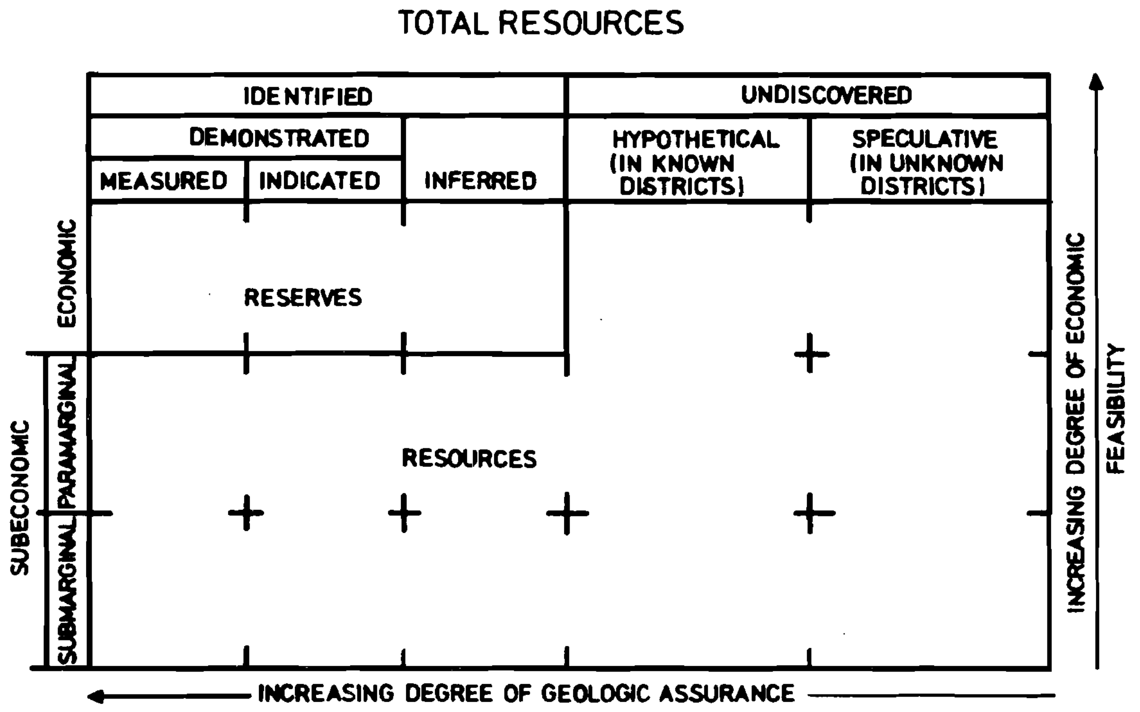

Figure 17. USGS-USBM reserves/resources classification, 1974.

LARGE SCALE HARVESTING OF ENERGY RESOURCES

No less important than the problem of assessing energy resources is the problem of harvesting them. We are devoting a special effort to this topic, especially with the WELMM matrix method, as already mentioned.

As pointed out by A. Weinberg, let us recall that about 80% of the "demandite" (generic name for all the material which is mined out of the ground, excluding water) consists of CHx, i.e. of fossil fuel; of the remainder, 11% is SiO_2 and 4% is $CaCO_3$; iron represents only 1.1% (but 86% of the "avalloy" which is effectively used by man). Of the total value of metals and non-metals, thus excluding fossil fuels, 5% only is produced by underground mining methods, and 95% by open-pit mining, dredging and solution evaporation.

One of the most striking phenomena of the last decades has been this development of open-pit or surface mining for energy resources also, as illustrated by coal and uranium today and by future plans for oil shales and tar sands. For example, in the U.S. in 1973, 70% of the uranium reserves were underground and 19% were open-pit (the difference is accounted for by various other sources); but only 36% of the production came from underground, and 62% came from open-pit.

It is probable that world-mining will continue its dynamic growth, growing faster than true production because of the harvesting of lower grades and deeper deposits--and possibly also smaller ones. Only open-pit mining seems able to answer this growing demand, while we are waiting for new underground mining methods to be effectively developed. Such methods include automatization (already very high in some coal mines), remote control, tele-operation, solution mining or in situ processing (for coal, oil shales, etc.). The potential of open-pit or surface mining can be illustrated by the lignite exploitation in the Rhine area F.R.G., on sites such as Garsdorf (300 m open pit, in operation) and Hambach (600 m open pit planned for 1980), and by uranium mining in Wyoming, U.S.

Yet open-pit mining raises many problems, such as the disturbance of underground water equilibrium, land requirements, material handling, etc.

Land requirements have been estimated (Figure 18) and used for a rough comparison of three energy alternatives: coal, solar and nuclear (Table 3). A similar comparison has been made for material requirements (Table 4). It is interesting to note that land and material requirements are comparable for the three options if nuclear developments lean on the LWR and on uranium ores of even lower grade, but are changed by one or two orders of magnitude when based on the timely introduction of the breeder.

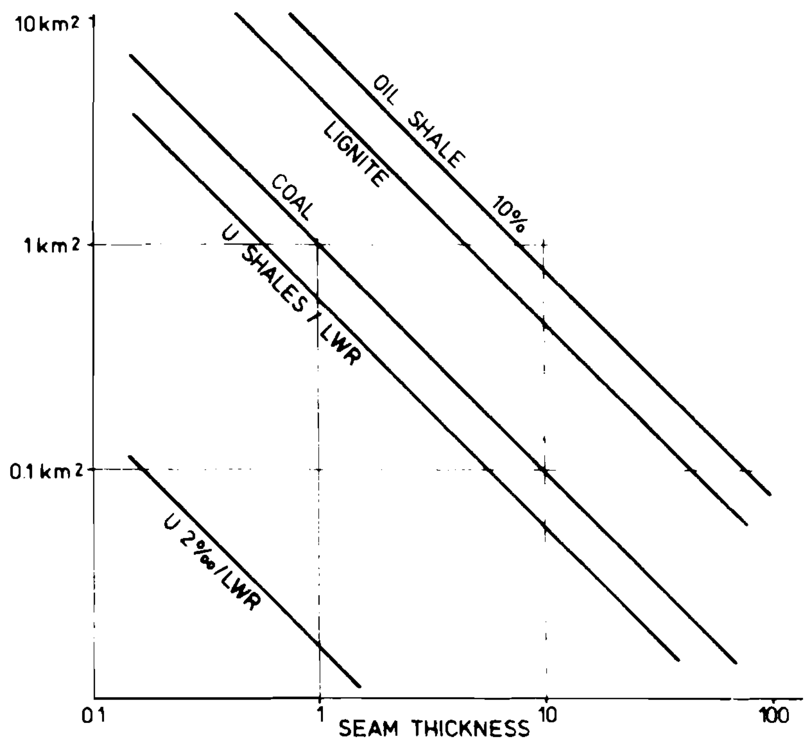

Figure 18. Land disturbed for producing 10^6 t.c.e.

Table 3. 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 $\eta = 0.2$	30	Permanent
Nuclear	Site LWR-U Shale (high-voltage line)	2 m seam 10 m seam	0.08-0.05 37 7.5 (20)	Temporary (non-exclusive)

Table 4. 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)

In fact, one does not always realize the possible dimension of the material handling problem which can be associated with nuclear development. Table 5 illustrates the waste problem associated with using uranium ores of low content, and Table 6 shows what the resulting impact would be for two given scenarios.

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

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

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

OBJECTIVE FUNCTIONS FOR ENERGY SCENARIOS

Because it was the simplest, and because there was a strong tendency to stress purely economic factors, objective functions have generally concentrated on discounted costs. At IIASA we are also exploring possibilities to minimize pollution (i.e. to internalize this factor in our model) and also to minimize impact on natural resources in the broad sense, that is, to include not only mineral resources but also water, land, etc. Of course, the consideration I have developed to illustrate the problem of harvesting energy resources--because I think that insufficient attention has been paid to it--can and must be extended to the whole energy cycle, from the resource in the ground to the final energy use.

In reality, the decision-making process is not limited to the choice of the primary energy resource because there are also various alternatives for the large scale development of any advanced energy system, as shown in Figure 19 for nuclear energy [9]. Bearing in mind the necessity to minimize discounted cost--and as far as possible, capital requirements because of growing competition for capital availability and conceivably even risks of capital shortage--and also to minimize impacts on the environment and natural resources, one important problem is the consideration of secondary energies. With the increasing cost of energy, some trade-off must be achieved between energy (and natural resource) conservation and the simplicity of final energy use. This points to the search for the most efficient systems. I think that in this field yet too little effort has been devoted to the possibilities of directly using the heat produced by nuclear reactors*, and to the study of secondary energy systems based on direct-heat transportation, storage and use, as well as on chemical energy sytems [14]. In this respect I consider that the development of high temperature reactors has a very high potential. The coming years, even maybe the coming months, will be crucial for them. Taking into account the penetration lead-times mentioned at the beginning of this paper, let us hope that we will not "foreclose the option".

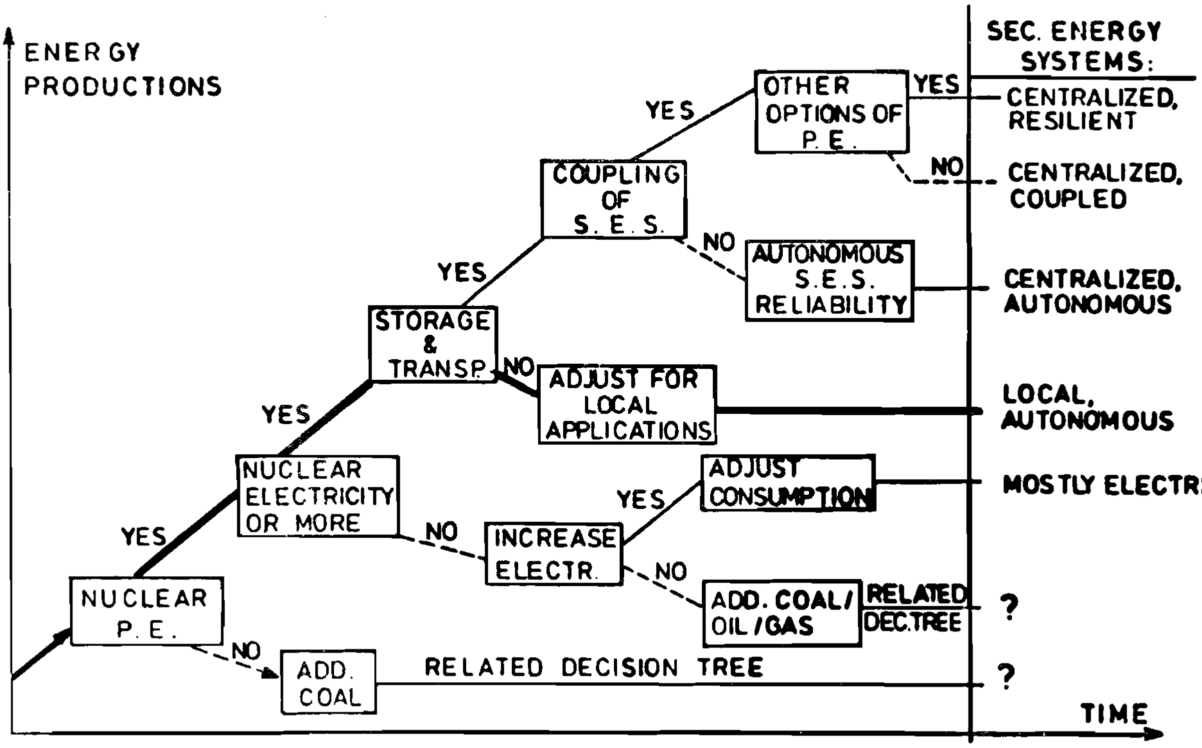

Figure 19. A decision tree for advanced energy systems.

*notwithstanding the incentive to increase the efficiency of electricity production.

Finally, looking at the future availability of mineral resources, H.E. Goeller and A. Weinberg [15] point out that iron ore no doubt is one of the most abundant mineral resources. If iron ore is associated with a low cost energy source they foresee together that mankind can meet many of its materials' needs with iron and energy. One scenario could associate steel and the very high temperature reactor, which are two typical Japanese products.

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