Energy Systems (by Professor Wolf Häfele)

1. INTRODUCTION

Up to the present the production, transmission and distribution of energy has been considered mostly as a fragmented problem; at best only subsystems have been considered. Today the scale of energy utilization is increasing rapidly, and correspondingly, the reliance of societies on energy. Such strong quantitative increases influence the qualitative nature of energy utilization in most of its aspects. Resources, reserves, reliability and environment are among the key words that may characterize the change in the nature of the energy utilization problem. Energy can no longer be considered an isolated technical and economical problem, rather it is embedded in the ecosphere and the society-technology complex. Restraints and boundary conditions have to be taken into account with the same degree of attention as in traditional technical problems, for example a steam turbine. This results in a strong degree of interweaving. Further, the purpose of providing energy becomes more visible, that is, to make survival possible in a civilized and highly populated world on a finite globe. Because of such interweaving and finiteness it is felt that energy should be considered as a system and therefore the term "energy systems" is used. The production of energy is only one component of such a system; the handling of energy and the embedding of energy into the global and social complex in terms of ecology, economy, risks and resources are of similar importance.

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The systems approach to the energy problem needs more explanation. This paper is meant to give an outline of the underlying problems and it is hoped that by so doing the wide range of sometimes confusing voices about energy can be better understood. Such confusion starts already with the term "energy crisis". Is there an energy crisis or not? Much future work is required to tackle the problems of energy systems. This paper can only marginally help in that respect. But it is hoped that it will help understand the scope of the problem.

2. THE PHASING OF THE ENERGY PROBLEM

It is vital to realize that the problem of energy seems to appear in time phases. During these phases the detailed features of the energy problem will be quite different, sometimes even of an opposite nature.

One should distinguish the following three phases:

the short range phase	1970 - 1985
the medium range phase	1980 - 1995
the long range phase	1990 - 2050 (?)

The years given above are only approximate; the phases are overlapping and not so clearly defined. In the following a few explanations are given that may characterize these three phases and can perhaps make their introduction plausible (see Figure 1).

Fig.1 The Phasing of the Energy Problem

Short range 1970 - 1985	Medium range 1980 - 1995	Long range 1990 - 2050(?)	Thereafter
Energy prices	New technologies for the use of coal	Fast breeder	In addition
Oil import	LWR at a large scale	Hydrogen	Large scale uses of solar power ??
Security of supply	HTGR	Energy transportation at a large scale	
Conservation	Pipe lines	HTGR	
Capital funds	Floating islands	Nuclear complexes	
Siting	Local space heating by solar power	Optimization for embedding	
	Prospecting	Global monitoring	
	Pollution control at a large scale		

2.a. The Short Range Phase (1970 - 1985)

In the short range phase of the energy problem there will be certain shortages and changes in the fuel market, particularly in the market for oil and gas. Technological developments can help to adjust for this situation. However, this requires time, probably ten to fifteen years. Therefore it is just this lead time that determines the time range of the first phase of the energy problem, as during this first phase only existing technological and economic tools can be expected to be of help.

The most obvious problem of this first phase is the **supply of oil and gas**, particularly in the United States. Consider for instance the problem of oil prospecting. According to M.K. Hubbert [1] the amount of oil discovered per foot of drilling in the U.S.

has strongly decreased since 1938 and is now only 35 barrels/foot. Further, Hubbert assumes that the discoveries up to 1965 represent about 82% of the prospective ultimate total. The situation for gas is qualitatively similar, but this is not the case for coal. Other factors inhibit the easy use of coal [2]. There is not much hope that new resources of oil and gas can be readily discovered. An uncommonly large amount of capital would be required for such discoveries.

Energy conservation will therefore be a prevailing theme in the years to come. Increased efficiencies of energy conversion, the reduction of wasteful uses, better heat insulation in offices and homes and other measures will get continued attention. The existing forecasts for the demand of energy must then be re-examined considering such energy conservation. This will be especially so in the U.S. [3] where a change from affluence to conservation of energy will be experienced. In other countries such change will be less drastic but will exist.

Conservation can merely reduce, but not eliminate, the problem of oil and gas shortages. During the short range phase of the energy problem the U.S. has no choice but to **import** the necessary amounts of oil from the Middle East, which has about 50% of all oil resources outside the USSR and China. One has to realize however that Japan gets about 80% and Western Europe approximately 60% of its oil supply from the Middle East. The implications of these facts are outlined in detail for instance by Walter Levy [4,5].

Nuclear power will increase its share in the production of electrical power but this share will be limited because the lead time for the construction of a nuclear power plant is steadily increasing. In the U.S. eight to nine years lead time is not unusual. Further, one has to realize that all electrical power makes up only 25% of the primary energy demand and only as little as 10% of the secondary energy demand. Nuclear power will therefore have a smaller, but nevertheless important, impact on the overall energy problem in the short range phase than was previously expected.

There are many existing **regulations** for the use of energy: import, taxes, rates. Quite often these regulations have been arrived at from a fragmented point of view. Suboptimizations have taken place when energy was not yet a comprehensive problem. An example is the import quotas for oil in the U.S. In the Federal Republic of Germany, for instance, it is only now that a comprehensive plan for dealing with energy as a whole is being developed. Additionally, regulations for the protection of the environment are now being added at an increasing rate. To some extent it was nuclear power that initiated an awareness of environmental problems. Of course one realizes that nuclear power fulfilled only a pilot function there; the environmental problems being much more general. Nevertheless, the complications experienced in the licensing of nuclear power plants due to actions of environmental groups worsen the problem of a sufficient electrical power supply. Similarly, rigorous regulations for the emission of combustion engine pollutants tend to increase gasoline consumption. Therefore regulations probably have to be reconsidered from a comprehensive, systems point of view.

Some observers feel that, at present, there is overreaction to the environmental challenges. A particularly sensitive point is the siting of large industrial installations such as power plants, deep water terminals, refineries, and high voltage transmission lines. It is expected that the next ten years will bring a certain **equilibrium between environmental and economic requirements.** Such establishment of a reasonable equilibrium is probably characteristic of the short range phase of the energy problem.

Also **energy prices** will be put in equilibrium with the general economy of the next decade. The installation of new facilities like refineries, enhanced exploration for fossil fuel resources meeting environmental standards, research and development for energy technologies, and other requirements will all tend to increase energy prices. It remains to be seen where this equilibrium will occur.

Much has been published on these questions in the recent past. In particular an article by S.D. Bechtel [6] helps make necessary distinctions which will be mentioned here.

2.b. The Medium Range Phase (1980 - 1995)

As mentioned before, technology can help society adjust to new conditions and constraints in the problem of energy. The necessary lead time for the implementation of such measures determines the beginning of the medium range phase of the energy problem. This is the phase where technological adjustments can be felt. In order to see roughly where such adjustments have to be made it is important to realize that, as a rule of thumb, energy consumption splits into the ratios 1:1:1:1. That is, 25% of the primary energy demand goes into households and commercial buildings, 25% is for industrial purposes, 25% is for transportation and 25% is the primary energy demand for the generation of electricity. Because of conversion inefficiencies this last 25% constitutes only 10% of the secondary form of overall energy demands. Nuclear energy has been developed almost exclusively with a view to electrical power production. Even if nuclear power takes over the majority of electrical power plants (and it probably will) the problem of providing sufficient energy will prevail in this period, because it is not readily clear that an all-electric economy is a feasible solution. For example, it seems obvious that airplanes cannot fly on an electrical basis. Fossil fuels will continue to play an important role and, fortunately, there is much fossil fuel in the form of coal. The exploitation of coal has been constant or decreasing in the past. This is largely due to the present practices of mining, but improved standards and safety regulations plus a lack of research and development also contributed to the difficulties that coal industries have experienced in the past decade [2]. The technologies that have been mentioned above will therefore probably attack the problem of making use of coal by other means than conventional mining, the most obvious schemes being coal liquification and gasification and the transport of such fuel through pipe lines [7]. Such a scheme allows for a smooth transition from the use of natural gas to that of substitute natural gas (SNG). Gasification of coal requires process heat. It is therefore interesting to evaluate the potential of nuclear power for the provision of process heat. This could lead to an enhanced development of the High Temperature Gas Cooled Reactor (HTGR).

The problem of siting could also be the subject for significant technological advancements. The scheme of having serial production of nuclear power stations placed on floating platforms has to be mentioned here. This allows for cheaper fabrication under strict quality control provisions and helps to ease the ever-increasing difficulties of choosing sites for power plants and other technical installations in crowded areas. But other developments on the general problem of siting have to be envisaged too. Another goal for technological research and development could be abatement measures for the use of fossil fuels.
Also special uses of solar power have to be mentioned. For instance, local space heating in warmer climates falls into this category. Such special use of solar energy is already taking place today.

More important however will be the major adjustment of the economy and infrastructures of modern societies to the long-range phase of the energy problem. As fossil fuel resources are limited, in the long run one or two of the few existing options for the practically infinite supply of energy have to be prepared for. This probably requires adjustments. For instance, it might be necessary to change the boundary between the electrical and the non-electrical form of energy use or to consider more explicitly the relations between the availability of energy and the availability of water. Adjustments of that kind will have highly significant consequences.

2.c. The Long Range Phase (1990 - 2050 (?))

The main characteristics of the long range phase of the energy problem could be the following:

- One or two of the few existing options for a practically infinite supply of energy have been identified and fully investigated for large scale implementation.
- The global energy demand has been increased by at least a factor of ten. The developing nations are among those with the highest increase of energy consumption.
- Boundary and constraints for the global use of energy have been identified and modes for the production and use of energy that are consistent with such boundaries and contraints have been developed.
- The medium range phase of the energy problem has been used for a smooth transition into the long range phase.

The emphasis is more on these characteristics than on the particular date of 1995. Predictions of dates come out to be wrong more easily than predictions of the characteristics as such.

In the following more will be said about the above mentioned few options for the practically infinite supply of energy, and equally on the boundary and constraints for the global use of such amounts of energy. A detailed consideration for the long range phase is important because the medium range phase is expected to provide a smooth transition from the short range into the long range phase. We will therefore elaborate now in greater detail on more specific aspects of energy systems and on the existing options, boundaries and constraints for the large scale use of energy and will thereafter come back to considerations of the long range phase.

3. MODELLING OF DEMAND AND SUPPLY OF ENERGY SYSTEMS

In the past it was largely the demand of energy that was the driving force for the development of energy technology and the evolution of an energy economy. Other considerations were secondary and it was therefore possible to consider highly aggregated forms of parameters in the energy field, such as the increase in demand for electrical energy. Best known is perhaps the observation that this demand for electrical energy doubled every ten years. Such considerations were also very useful because these high aggregations led to fairly accurate results. Fluctuations in the components of aggregation seemed to cancel out each other.

Now one faces a situation that changes. In the short range phase of the energy problem the supply of certain kinds of fuels cannot meet the demands so easily any more. Ecological and other constraints, as outlined above, come into the picture too and can no longer be considered to be of secondary importance. It is therefore mandatory to come to more detailed evaluations of less aggregated parameters. This leads to the mathematical modelling of demand and supply of energy.

It seems possible to observe three aspects of such modelling: sensing, optimization and forecast.

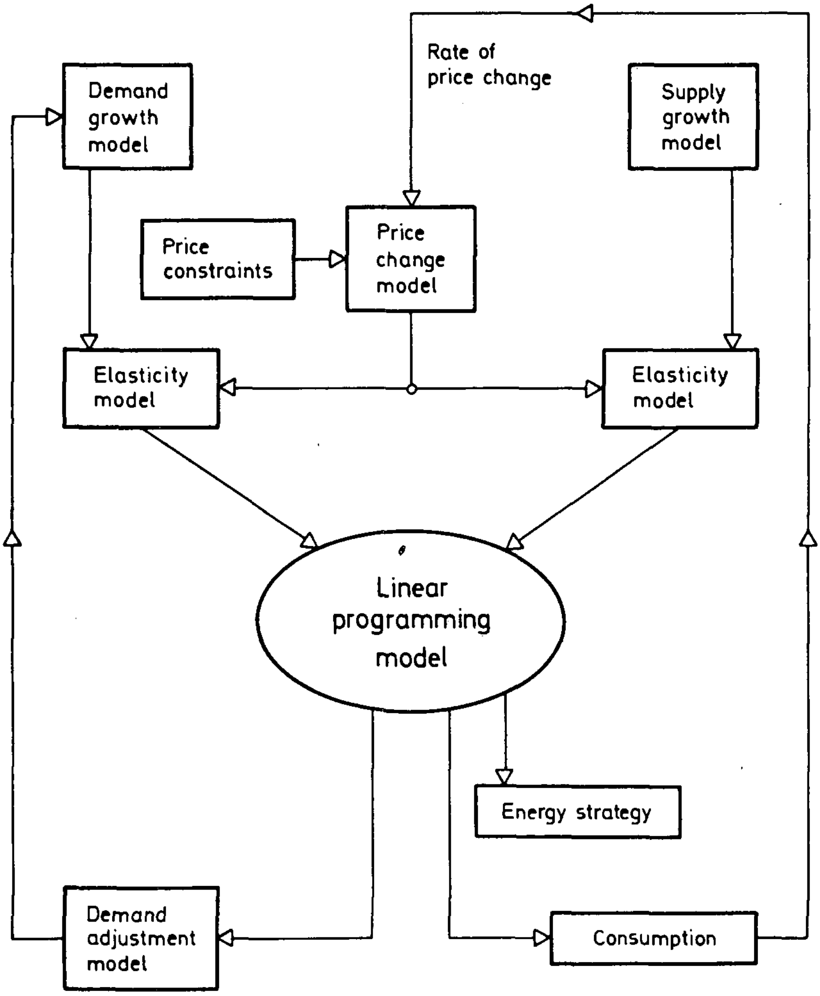
There are several things that must be sensed by modelling. It has been mentioned earlier that regulations in the energy field have sometimes been arrived at from a fragmented viewpoint; only subsystems have been considered. Modelling should lead to a more comprehensive point of view: What happens, if . . . . . ? It should be possible to evaluate certain policies and regulations by such procedures. This may be particularly true for the establishment of environmental and economical considerations, as has been mentioned earlier. But also in this respect, the complex problem of technology assessment can probably be brought in and, in this way, it might be possible to evaluate priorities for research and development. Undoubtedly there is a preoccupation in the community of science and technology for the production of energy but the handling and embedding of energy is probably more urgent in the long run. This could be more clearly assessed by modelling. Further, the impact of energy conservation could be better evaluated as to the problem of limited economic growth or no growth.

Optimization is an obvious objective for mathematical modelling. The best and timely distribution of fuel supply, optimal inter-fuel substitution and the optimal provision of capital come into the picture. Up to now the objective function was simply arrived at by the economic considerations of monetary prices and costs. It will be important by now to incorporate multiple objectives in the objective function that account for economic values as well as for environmental and social values. This leads into the much more general problem of comparing such values. Sometimes this problem is referred to as comparing "apples and oranges". More methodological work is obviously required here.

Forecast is the third aspect of modelling. The problem of forecast shall not be explained in greater detail. It is a widely recognized problem. Later in this paper we will elaborate on "system problems". Therefore the observation shall be made that the forecast of such problems will be of special interest if one wants to understand energy systems. A typical example for the modelling of energy demand and supply has been presented at a recent MIT Conference on energy modelling by Schweizer, Love and Chiles [8]. These authors consider a fuel allocation model as described in Figure 2. A model for demand of energy and its growth for various types of fuel in various regions and market sectors is used. The energy demand model is combined with a model on the various partial elasticities to serve as an input for a linear programming allocation algorithm. The same is done for a model of the supply, its growth and the elasticities involved. The linear programming algorithm then allocates demand growths to supply growths for a given objective function. The result is an energy strategy of meeting the demand growth with the connected price changes. Such an approach implies certain fuel interchangeabilities. This leads to the field of energy conversion and the related models for that. New technologies have to be considered here, but equally, also models for the energy policies that are under consideration. The over-all model, as described in Figure 3, can help to assess priorities for technological R + D work, for evaluating the

Fig. 2 Energy Allocation Model

(after Schweizer, Love, Chiles, Westinghouse Electric Corporation)



consequences of considering objective functions other than just minimum price, and they can help to evaluate the impact of certain policies.

A brief outline of the mathematics that is involved in that model is given in Table 1.

The process of designing such a model and numerical playing with it can help us to better understand the inherent features of the reality to which that model is applied. Of particular importance may be the identification of possibly existing various

Fig.3 Computer Energy Model

(after Schweizer, Love, Chiles, Westinghouse Electric Corporation)

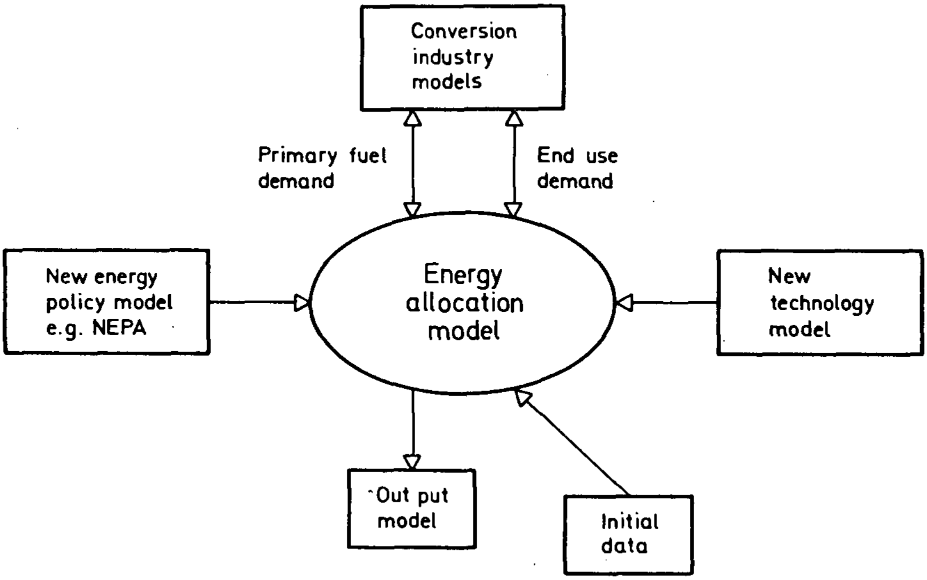


Table 1 Dynamical Energy Allocation Model

$\delta P = \sum_{ik} \delta P_{ik}$ $\quad \delta P_{ik} \equiv$ Growth of prices of K-TH fuel to be paid by I-TH industry

$\delta D_i = \sum_k d_{ik} \cdot \delta P_{ik} = \sum_k \beta_{ik} \cdot \frac{D_{ik}}{P_{ik}} \cdot \delta P_{ik}$ $\quad \delta D_i \equiv$ Growth of minimum of total fuel consumption of I-TH industry

$\beta_{ik} = \frac{\delta D_{ik}}{D_{ik}} / \frac{\delta P_{ik}}{P_{ik}} \equiv$ Partial elasticity (known from elasticity models)

$\delta S_k = \sum_i s_{ik} \cdot \delta P'_{ik} = \sum_i \gamma_{ik} \cdot \frac{S_{ik}}{P_{ik}} \cdot \delta P_{ik}$ $\quad \delta S_k \equiv$ Growth of maximum of total supply of K-TH fuel available

$\gamma_{ik} = \frac{\delta S_{ik}}{S_{ik}} / \frac{\delta P'_{ik}}{P'_{ik}} \equiv$ Partial elasticity (known from elasticity models)

$P'_{ik} = P_{ik} - g_{ik} \cdot P'_{ik} \equiv$ Supply costs of K-TH fuel to I-TH industry

LP - Problem : Minimize growth of total prices δP with respect to variables δP_{ik} and constraints D_i and S_k.

Note : Criterion of optimiziation could be different (E.G. Growth of pollution);
Additional constraints could be considered (E.G. Resources)

levels of the system considered and the degree of coupling between these levels. For instance, the construction of a new power plant is a part of the electricity supply system of a considered region. Such an electricity supply system in turn is part of the general supply system for all forms of energy and so on. Now it may be interesting to consider for instance the problem as to whether a change in the boundaries of the system in question influences the various conclusions that can be made, or in other words: the degree of coupling of the system considered with systems of higher levels [9].

A remark must be made on data input. Mathematical models are of value only if the necessary input data are available. Evaluations for the asymptotic solution of the energy problem require global considerations. The type of data that are required for this must be identified. The problem then is to make the degree of aggregation of raw data compatible. Furthermore the required data may be available for the domain of economy, but of equal importance are data for pollution, thermal waste heat, sociological data or, in other words, data that allow for the more general objective functions that have been mentioned earlier.

4. LONG RANGE ENERGY DEMANDS

In the following we will deal with large amounts of energy. It is therefore useful to introduce the unit of $Q = 10^{18}$ BTU. In Table 2 the equivalent of Q in several units is given.

Table 2 Energy Equivalence

$1\ Q \equiv 10^{18}$ BTU $= 2.52 \times 10^{17}$ kcal
$= 1.05 \times 10^{21}$ joule
$= 2.93 \times 10^{14}$ kWh (th)
$= 1.22 \times 10^{10}$ MWd (th)
$= 3.35 \times 10^{7}$ MWyear (th)

Table 3 Energy Consumption

USA	1970	0.07 Q/a	
USA	2000	0.16 Q/a	
World	1970	0.24 Q/a	(4×10^{9} people, 2 kW (th) /capita)
World	2000	2.1 Q/a	(7×10^{9} people, 10 kW (th) /capita)
World	2050	6 Q/a	(10×10^{9} people, 20 kW (th)/capita)

In Table 3 a few figures are given that characterize the consumption of energy. It should be noted that the world consumption of energy in 1970 is roughly 1/4 Q/year whereas the consumption for the year 2050 could be 6 Q/year. This is a factor of 25 larger than the value for 1970. The figure of 10^{10} for the population is an unsophisticated straight-forward guess and could be heavily debated. It should be realized however that this figure does not imply exponential growth. A key figure, on the other hand, is the value of 20 kW/capita. This figure has been introduced by Weinberg and Hammond [10] after having studied in somewhat greater detail the future conditions of a civilized society. A break-down of that figure is given in Table 4. Again it should be noted that also in the kW/capita figures no exponential growth of any kind has been assumed. The point that has to be made here is that we have to consider the life conditions of future decades, when the population will be high and that recycling of resources, particularly water, will probably be necessary. In order to better understand such future life conditions sophisticated scenario writings and life style descriptions are required; but the argument goes further. Figure 4 [11] demonstrates the fact that at present the use of energy is very non-uniformly distributed over the globe. Contrary to that,any

Table 4 Energy Budget for a Steady-State Civilization *

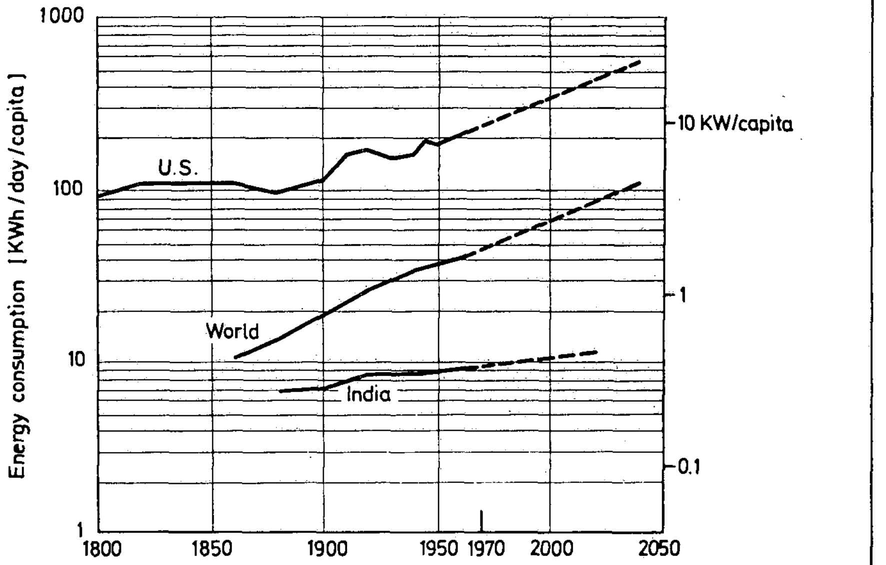
		kW (th) /capita
Present U.S. level		10.0
Adjustment for the future		
Steel, Aluminium and Magnesium production	0.1	
Recovery and recycle of scarce elements	2.0	
Electrolytic hydrogen	2.5	
Water by desalting (100 gal/day) *	0.3	
Water transport to cities	0.1	
Air conditioning to cities	0.3	
Intensive food production	0.2	
Sewage and waste treatment	0.5	
Total adjustments		6.0
Contingency		4.0
		20.0

* (Weinberg, Hammond, Global Effects of Increased Use of Energy, Geneva, September 1971)

consideration of asymptotic solutions of the energy problem must start from the assumptions that the provision of power per capita will be equal for all of the world population; and further, the actual value of that figure will correspond to the highest figure in question, for instance the figure for the U.S. It is impossible that a non-proliferation of high power installations per capita can ever come into effect. Eventually the same comfort for all of the world population must be feasible and accessible, at least potentially, and that means that any asymptotic solution of the energy problem must be based on that assumption of equality. On the basis of these few conceptual considerations alone, one can see that the demand for energy as compared with today's values will be significantly larger, at least 10 times but probably more.

Fig. 4 Growth in Energy Demand

Source : Ch. Starr [11]



In a previous chapter a time scale for the three phases of the energy problem has been given. The third phase, the long range phase, has been characterized by the fact that one or two of the few options for practically unlimited fuel supply was chosen for implementation; fossil fuel cannot be employed on a large scale any more. As we will see in the next chapter this happens when the energy consumption reaches a few Q/year. This in turn depends largely on the size of the world population and the rate at which the developing nations are keeping up in their standard of living. This may happen sooner or later than 1995 and the long range phase of the energy problem will then appear accordingly sooner or later. The date of 1995 is therefore only indicative,as has been mentioned above.

The relevance of such considerations can be felt if Figure 5 is considered. It demonstrates the linearity between the energy use/capita and the gross national product/capita,and the continued linearity if the recent increases in these figures are evaluated. There is debate today as to what extent this linearity is a necessity and this in turn leads again to mathematical modelling. Much work has to be done there.

One more observation must be made. The linear relationship of Figure 5 seems to underline a simple scheme that is given in Figure 6. The circle of fuel supply and its price levels will indicate a constraint but otherwise there appears only energy and the gross national product. This was a reasonable scheme as long as the previously mentioned restraints and boundary conditions were of secondary importance. But this changes now.

Fig. 5 Commercial Energy use and Gross National Product

● 1968 after Stat. Yearbook of UN (1970)

○ (1961/1962) after Ch. Starr Energy and Power, 1971 S.4

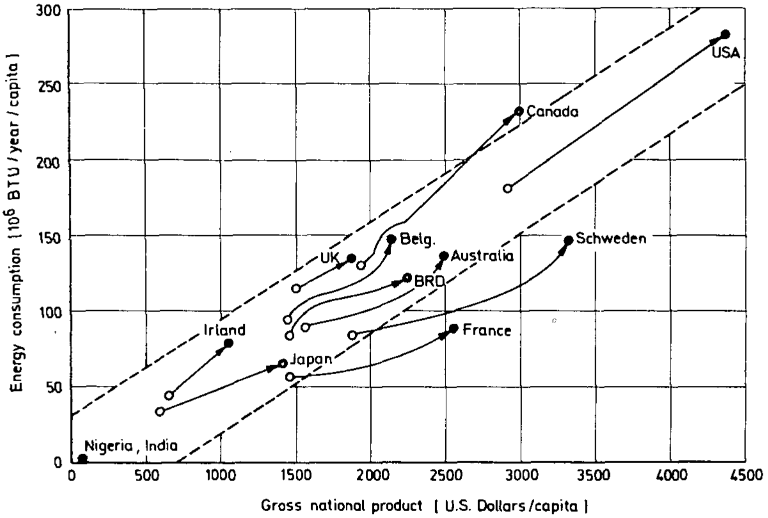
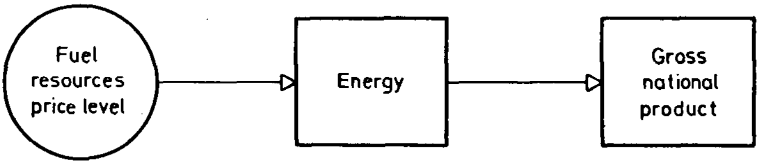


Fig. 6 A Relationship between Fuel, Energy and Gross National Product



5. ENERGY RESOURCES

The fuel that has been exclusively used up to now is fossil fuel. In view of future phases we have to compare fossil fuel resources with those from other sources.

5.a. Fossil Fuel

Widely different figures for fossil fuel resources are reported and discussed today. The reason for these discrepancies is the simple fact that it is difficult to clearly define an obvious upper limit for declaring deposits as resources. Earl Cook [12] makes the observation that there are three methods of forecasting the availability of resources. One is the economic method that simply projects historic trends and demand elasticities together with technological trends and simply concludes that if under such conditions one would look for fuel, it will be there. This was perhaps a reasonable approach in the past when the scale of energy production was small if compared with global yardsticks. Here we are concerned with a different order of magnitude of the energy problem. The next method is the geologic-analogy method which is supply oriented and not demand oriented as is the economic method. Extrapolations are made on the basis of geological considerations. The third method is the exploitation-history method of M.K. Hubbert [13] that takes into account the history of the production curve, the proved-reserve curve and the curve of discovery per foot of exploratory drilling. The last two methods seem applicable for our considerations here.

In Table 5 we present information that was given by V.E. McKelvey and D.C. Duncan [14] and M.K. Hubbert [13]. The large difference between the lower and the upper limit in the case of the McKelvey-Duncan data, and the data of M.K. Hubbert that are in between, illustrates the above remarks. It should again be noted that the upper values are no limit in a physical sense. In the case of coal, for instance, the figure refers only to resources above a depth of 1800 m.

Oil resources are somewhere between 2 Q and 20 Q. It was outlined in the last chapter that consumption rates of a few Q/year must be anticipated in the not so distant future. The figures in Table 5 therefore indicate that such consumptions cannot be based on oil, it must be coal instead. There the resources are larger by a factor of ten or so. It is there-

Table 5 Energy Content of the Worlds Supply of Fossil Fuel

in units of $Q \equiv 10^{18}$ BTU

	According to V.E. Mc Kelvey and D.C. Duncan [12]		According to M.K. Hubbert [13]	
	Known recoverable	undiscovered and for marginal	eventually recoverable	%
Coal	17.3	320	192	88.8
Crude oil	1.73	23	11.1	5.2
Nat. gas	1.95	20	10.1	4.7
Nat. gas liquids	0.21	3.2		
Tar - sand oil	0.23	6.3	1.7	0.8
Shale oil	0.87	77	1.1	0.5
Total	22.5 Q	450 Q	216 Q	

fore indeed reasonable to make coal a possible corner stone for the medium range phase of the energy problem. It could last for a few decades if simple, straight-forward algebra were applied. One has to think, however, of the conditions that would characterize harvesting of coal on a large scale. It requires world-wide major operations. As we will see, this leads to system problems, that is, side effects that were secondary when the harvesting of resources were modest will become first order effects. For illustration the problems of surface mining could be mentioned. Similar remarks should be made also for the case of shale oil.

Much effort is required to identify such system problems. It is not sufficient simply to point to a single, and yet not so large, resource figure. The time period during which one can rely on coal might therefore be more limited. This underlines the statement that the medium range phase would be primarily a phase for smooth transition.

5.b. Uranium and Thorium Resources

The remarks on the difficulties of having meaningful estimates of fossil fuel resources apply equally to resources for nuclear fission reactors; i.e. uranium and thorium. There are many publications on this subject and in the middle sixties the question of uranium reserves was heavily debated [16]. It should be realized however that all the figures at that time referred to known deposits or deposits that could be discovered with a high degree of certainty. Further, only uranium prices of up to 30 $/ pound of U_3O_8 were considered. In order to appreciate this one has to know the relationships between ore costs per kWh and busbar costs for various types of power plants. They are given in Table 6. An increase of ore prices from 10 $/pound to 30 $/pound would increase, in the case of a light water reactor, the busbar costs by about 0.001 $/kWh. Such considerations set limits to the discussions of the sixties. However, at that time the main consideration was the commercial competition between nuclear and fossil power. In the context of today's energy considerations in general, and this paper in particular, this is no longer the only valid viewpoint. Therefore in Table 7 we have also given estimates based upon higher uranium prices. At 100 $/pound the cost increase for electrical power from LWR would be about 0.005 $/kWh and the resources would still be only a few hundred Q. These are quantities that are comparable to fossil resources. Nuclear

Table 6 Busbar Cost Sensitivity to Ore / Fuel Costs

Fossil fuel	0.5	(at $\approx \frac{50 \text{ cent}}{\text{million BTU}}$)
Light water reactor	0.1	(at $\approx$ 10 $ / pound of U_3O_8)
Breeder reactor	0.001	

Table 7 Uranium Resources

in units of $Q \equiv 10^{18}$ BTU

(Figures are taken from or are consistent with V.E. Mc Kelvey and D.C. Duncan [12] , exept if otherwise indicated)

	Known deposits		Unappraised and undiscovered resources	
	Light water reactor b.)	Breeder reactor c.)	Light water reactor b.)	Breeder reactor c.)
up to 10 $ / pound of U_3O_8 a.)	0.7	70	≈30 d.)	≈3000 d.)
up to 100 $ / pound of U_3O_8 a.)	—	—	$(2-10)\times10^2$ e.)	$(2-10)\times10^4$ e.)
up to 500 $ / pound of U_3O_8 a.)	—	—	5×10^4 d.)	5×10^6 d.)
Ocean g.)	1×10^2 f.)	1×10^4 f.)	3×10^3	3×10^5

a.) US $ values of the late sixtees

b.) assuming a conversion factor of 1 short ton of $U_3O_8 = 7\times10^{11}$ BTU

c.) assuming a conversion factor of 1 short ton of $U_3O_8 = 7\times10^{13}$ BTU (1 short ton = 907 kg)

d.) making reference to note d.) of table 4 in [14]

e.) not necessarily consistent with [14]

f.) assuming a technical extraction factor of 3×10^{-2}

g.) it has been estimated that the extraction of uranium from the sea could be done at 25 $ /pound of U_3O_8 [15]

power, on the basis of present nuclear power plants, does not differ from fossil fuel plants so far as fuel resources are concerned. The picture is qualitatively different for the breeder reactor. Its near-term importance is the fact that increases in prices for uranium ores are practically not felt in the busbar costs of a breeder power station. Prices of beyond 500 $/pound of U_3O_8 can be afforded. Therefore vast amounts of resources become accessible and those resources are better converted to energy by about a factor of 100. Table 7 indicates that the energy resources that are accessible through the nuclear breeder reactor are practically unlimited – and this is the long term importance of the breeder. M.K. Hubbert [13] gives the example for uranium deposits that become meaningfully accessible by the breeder technology: In the U.S., the Chattanooga shale spreads out along the Western border of the Appalachian Mountains. This shale has a uranium-rich stratum, which is 5 m thick and contains 60 g per ton. This is a value far below what is considered interesting under today's circumstances. The energy content of this shale per square meter would be equivalent to that of 2000 metric tons of coal; the energy content of an area of 13 square kilometers would be equivalent to that of the world resources of crude oil ($2\cdot10^{12}$ barrels).

The distribution of thorium on the various parts of the globe is different from that of uranium and this will have regional consequences. For instance India has not much uranium but vast amounts of thorium. India therefore must look for special ways and means for the use of these resources. Altogether however the energy equivalent of the thorium resources only slightly exceeds that of the uranium resources. One is essentially correct if one assumes that these are equal. For further details we refer to McKelvey and Duncan [14]. Energy through the fission of uranium and thorium by the use of the breeder reactor therefore provides the first option for a practically unlimited supply of energy.

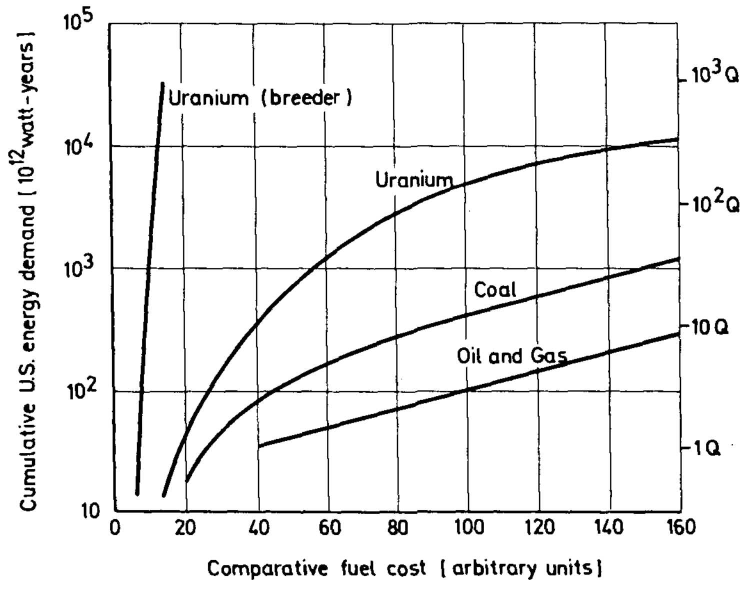
One has to realize that the development of the breeder reactor is far advanced. The most advanced version of the breeder reactor is the liquid metal fast breeder reactor. It has been developed by the USSR, France, the UK and Germany together with Belgium and the Netherlands, the USA and Japan. Large scale developments like that of the fast breeder reactor have to pass three thresholds:

the threshold of scientific feasibility
the threshold of industrial feasibility
the threshold of commercial feasibility.

At present large industrial prototype reactors in the 300 MWe class are being built or put into operation by the USSR, France, the UK and Germany together with Belgium and the Netherlands. In the USA and Japan such construction is expected to come soon. That means that the second threshold, that of industrial feasibility, is being passed now. The commercial feasibility is expected for the middle eighties [17]. Further, the liquid metal cooled fast breeder reactor has back-ups. The helium cooled fast breeder provides such a back-up solution. Certain key problems of this reactor type are being investigated. But also the thermal breeder [18] and especially the molten salt breeder as pursued by Oak Ridge Nat. Lab. in the U.S. backs up the development of the liquid metal fast breeder reactor. The point that must be made here is this: already with the technology of the seventies and the eighties we have with the fast breeder reactor one industrially feasible option for a practically unlimited supply of energy, even if in the not-so-distant future energy consumption of a few Q/year has to be envisaged. Figure 7 summarizes the situation for fossile fuel and nuclear fission reactors [11] and illustrates that one cannot have one single figure for energy resources.

Fig. 7 Comparative Fuel Costs

Source : Ch. Starr [11]



5.c. Lithium and Deuterium Resources

Besides fission there is fusion as another form of nuclear power. It is known that fusion reactors have not yet passed the threshold of scientific feasibility, but it is not unlikely that this will happen in the next ten or fifteen years. Whatever the answer to the scientific and the other feasibilities might be, it is worthwhile to have a look at fuel resources. By far the most probable scheme for fusion is the D-T reaction. This requires lithium as a fuel in addition to deuterium. It turns out that lithium is the limiting factor for the fuel supply. In fact, such a reactor is actually a fusion breeder [19] because lithium is bred into tritium analogous to the breeding of U-238 into Pu-239. If a technical fusion reactor is envisaged, then it has been found that 1 MWd/gram of natural Li (7.4% Li-6 and 92.6% Li-7) can be produced [20]. That is the same amount as for uranium or thorium in fission reactors.

Here again low figures for Li have been reported [14]. This is obviously the case because formerly there was no incentive for adequate prospecting. But the amount of lithium in the oceans alone is indicative: $2.7 \cdot 10^{11}$ metric tonnes, which corresponds to $2.2 \cdot 10^{7}$ Q if all lithium could be extracted. If we again assume a factor of $\sim 3 \cdot 10^{-2}$ for extraction we obtain $\sim 7 \cdot 10^{5}$ Q.

A fusion reactor on the basis of the D-D reaction would be quite another thing as no lithium is required. One should realize however that this is significantly more difficult than a D-T fusion reactor and, as pointed out earlier, even its feasibility remains to be proven. In any event, the deuterium content of the ocean is equivalent to $\sim 10^{10}$ Q, or if again a factor of $3 \cdot 10^{-2}$ for extraction is applied, we end up with the equivalent of $3 \cdot 10^{8}$ Q.

It is obvious that fusion would be a second option for the practically unlimited supply of energy if it eventually can be made a technically feasible scheme.

5.d. Geothermal Sources

The use of geothermal sources for the supply of energy on a large scale is a comparatively new aspect. In the past only in Italy, New Zealand and the U.S. have geothermal power stations been operated. The scale was modest, a few hundred MW at best. The expected lifetime of these stations is of the order of a few decades [13]. It was on this basis that this source had not attracted much attention when the question of large-scale energy sources was debated. More recently, this question has been reexamined. Donald E. White [21] has estimated that the world's ultimate geothermal capacity down to a depth of 10 km is roughly $4 \cdot 10^{20}$ Wsec. Not counting any conversion factors etc. this equals 0.4 Q. It is obvious that this is a negligible amount of energy in the context considered here.

However, there are also other voices. Recently R.W. Dose [22] has stated that by making more rigorous use of the existing geothermal sources in the U.S., sources with a lifetime of more than 1000 years and with 10^{5} MW could possibly be explored. This would correspond to 3 Q in the U.S. and could therefore be crudely compared to the U.S. oil resources. Details for such estimates were not given.

A different order of magnitude comes into the picture when the heat content of the earth's crust is considered. The temperature gradient is of the order of a few tens of degrees C per km depth. If the earth's crust underneath the continents is considered down to a depth of 10 km then the heat content is of the order of $5 \cdot 10^5$ Q. Conversion losses have to be taken into account and only a fraction of the crust underneath the continents can possibly be exploited. A few thousand Q may be in principle available that way. But this is not more than a quick and unsophisticated estimate.

The argument about geothermal power goes further. Besides the continents there is the ocean. The upper 200 m of the ocean is warmer by ten degrees C or so. Again taking all of the surface of the oceans one arrives at a figure of 3000 Q or so. Here the conversion losses will be considerable because the temperature difference is only 10°C and only a fraction of the oceans can possibly be exploited. A few dozen Q may be in principle available that way.

The question whether geothermal energy is exploitable on a large scale is a very open one. No real conclusion can be drawn here. It is not really clear whether geothermal power can be considered an option for large scale energy supply.

5.e. Water and Tidal Power

Water and Tidal power resources of the world are of the order of a few tenths of a Q [13]. Those power sources may be of regional interest but are definitely not an option for the large scale supply of energy.

5.f. Solar Power

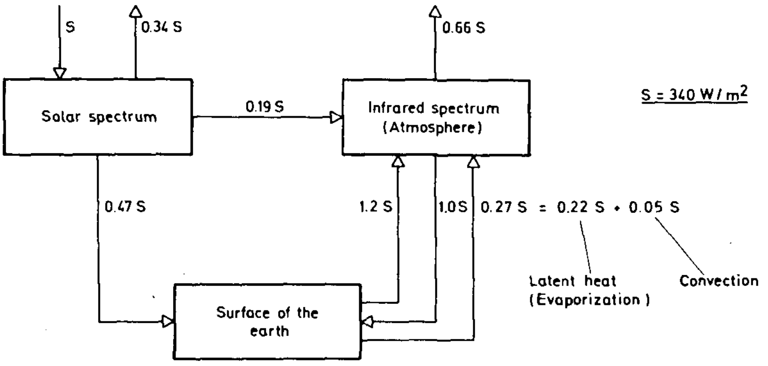
The supply of solar power as such as infinite. It is rather a problem of power density. The solar input above the atmosphere averaged over day and night and all zones of the globe is 340 W/m^2. Roughly 47% reach the surface of the globe, that is 160 W/m^2. The net value of the outgoing infrared radiation is ~ 70 W/m^2. We therefore have

$$160\ \text{W/m}^2 = 70\ \text{W/m}^2 + 90\ \text{W/m}^2$$

visible light = infrared radiation + heat balance.

Figure 8 gives the energy balance in somewhat greater detail. The heat balance is used in turn to drive the water cycle in the atmosphere by evaporization of rain water, to heat the ground and the lower part of the atmosphere and to provide the power for biological processes.

Fig.8 Distribution of Solar Power Input



The determining consideration for the harvesting of solar power on the surface of the globe is then obviously the question to what extent this energy balance may be distorted. This is of course an extremely complex problem of a systems nature and more will be said about it later. A straight-forward estimate for the global average value for harvesting solar power may be 20 W/m^2. It should be noted however that regionally, considerably higher values could be acceptable. This will accordingly be of regional significance. Here in this context we are interested in the question of global large scale energy supply. A value of 20 W/m^2 makes it obvious, as we will see later, that not the supply of power but land use is the determining factor for the collection of solar power on the surface of the globe.

But it is not necessarily so that solar power must be harvested on the surface of the globe, it could be harvested in outer space. A recent proposal of P.E. Glaser elaborates on that [23, 24].

It becomes clear that solar power is in principle an option for the large scale supply of energy.

We can summarize this discussion by concluding that, at least in principle, there are three (four) options for the large scale supply of energy. Large scale means a few Q/year for a thousand years or much more. These options are the following:

1. Energy by nuclear fission
2. Energy by nuclear fusion
3. Solar power
4. Energy from geothermal sources (?)

It should be clearly noted that the one option that is feasible with certainty is energy from fission. Other sources of energy like fossil fuel, water, tidal, etc. do not fit in that category. Their local importance may be nevertheless significant.

6. SYSTEM PROBLEMS

If there is more than one option for eventually having a large scale supply of energy, what is the problem? According to Figure 6 there should be none.

Fission energy is the one option that is already feasible today. More than that, it is being installed now at such a rate that the impact of nuclear energy is beginning to be felt even in the over-all energy picture. By the end of this decade a number of countries expect to have nuclear power produce about 30% of all their electricity. In the U.S. more than 150 GWe are today in operation, under construction or firmly ordered. In the FRG the figure is 13 GWe, in Japan 15 GWe, that for the whole world 254 GWe. But even so it is not pure pleasure to be a promoter for nuclear energy today. There are many objections to nuclear power. The arguments heard are the following:

a) The operation of nuclear power plants implies a certain radiological burden.
b) Nuclear power plants could lead to major radiological burdens in case of a major accident. Especially in focus is the problem of emergency core cooling systems (ECCS).
c) The operation of nuclear power plants necessitates the long-term disposal of radioactive waste.
d) The large scale handling of plutonium in the fuel cycle will unavoidably lead to losses of such plutonium into the biosphere.

e) Fissionable material is potentially dangerous as it can be used for military purposes and the illegal diversion of such material by thefts or groups must be taken into account.
f) Large nuclear power plants release large amounts of waste heat and lead to a distortion of the biosphere by the warming of rivers and lakes.
g) Nuclear power plants require large amounts of land.
h) We do not need the power from nuclear power plants.

A few years ago the objection concentrated on single nuclear power plants. Today the trend is more toward the installation and operation of a large nuclear fuel cycle. How many shipments of irradiated fuel elements are required? What about the superposition of the various releases? And what about plutonium in principle?

To a certain extent the above-mentioned questions are legimate. They were originally contemplated and answered when nuclear energy was in its infancy. Now that nuclear power is maturing the questions come up again for reconsideration. This statement however should not be interpreted as implying that all the objections to nuclear power that are heard are considered legitimate [25].

Let us now take as an example the question of the radiological burden that is due to the operation of nuclear power plants. The Gofman-Tamplin debate in the U.S. is deeply interwoven with that problem. Together with other influences it led to a standard for acceptable radiological burden that is as low as 5 mrem/year (light water reactor).

The central question now is this: What are the alternatives? In a recent publication of the nuclear research centers of Karlsruhe and Jülich in the Federal Republic of Germany a comparison of alternatives was attempted [26]. It was assumed that all the electrical power of the FRG would be produced alternatively by coal, lignite, gas, by pressurized water reactors or by boiling water reactors. It is, of course, a problem to compare a burden

Table 8 Relative Pollutions in case of FRG Using Different Electric Power Sources (1970) after Ref. [26]

	SO_2	Dust	NO_x	Fluorine	Xe	Kr	Total*
Anthracite	0.94	0.45	0.17	0.75	—	—	2.31
Brown coal	1.20	0.86	0.28	1.65	—	—	3.99
Oil	1.16	0.22	0.20	0.06	—	—	1.64
Nat. gas	3.1×10^{-4}	—	0.16	—	—	—	0.16
BWR	—	—	—	—	1×10^{-3}	1×10^{-3}	2×10^{-3}
PWR	—	—	—	—	3×10^{-4}	1.4×10^{-3}	1.7×10^{-3}

* This means only pollution caused by electrical energy production is included

that is due to SO_2 with a burden that is due to radioactivity. To that end the existing standards for each of the relevant pollutants were taken and the values of ambient dose rates (obtained from an admittedly crude meteorological model) were normalized by these standards and the normalized values were then added (see Table 8).

The methodological problems of such a comparison are obvious. For instance, no synergistic effects are taken into account nor is it clear that the various standards were derived by similarly rigorous procedures. We touched earlier on the problem of comparing "apples and oranges". This is one of the key problems of systems analysis.

Even with these reservations in mind it seems fairly obvious that each of the alternatives has a higher pollution load than nuclear energy. So the problem of pollution burdens is much more general. It is not a specific nuclear problem but it became visible and known to the public with the advent of nuclear power. The real problem is the magnitude of energy production. It is in an unprecedented domain of experience and, together with it, concern.

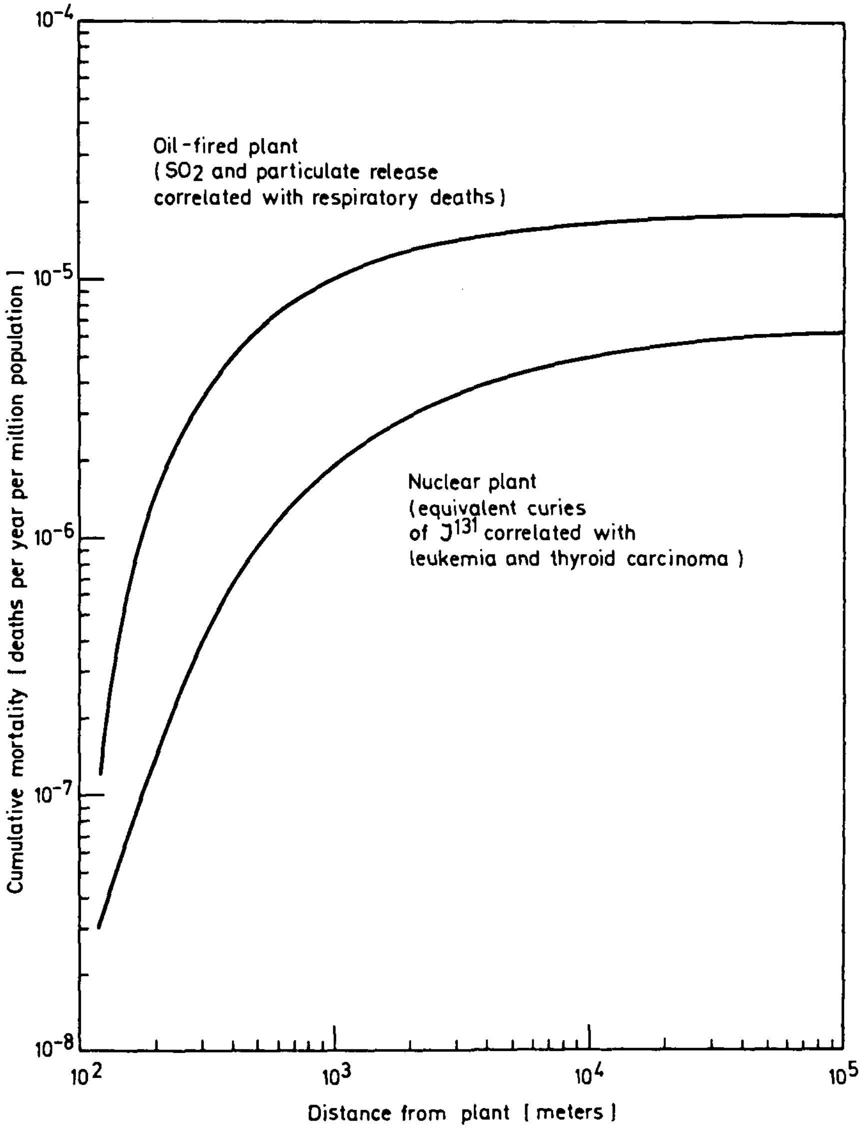
Let us move to the second example. The risk of nuclear accidents is exceedingly small but it exists. In the past such extremely low risks were not explicitly considered but, after having gone through the exercise of nuclear power, other risks are also being evaluated. Recently C. Starr, M.A. Greenfield and D.F. Hausknecht compared the risks of a nuclear power plant to that of an oil fired plant [27]. Figure 9 gives one of the results of this comparison. Again there are methodological questions because qualitatively different things are being compared. The argument here is not so much the details of this comparison. They may change back and forth when the comparison becomes more sophisticated. But the argument is that such a comparison is now imminent. Again, the question of risk is not a special one for nuclear energy, it is a general problem that now comes to the forefront because of the magnitude of energy production.

A further example is the waste during power production. The data given in Table 9 point to that. In the case of fossil fuels ordinary pollution will not be considered. Ideally abatement measures may have taken care of that problem, but the production of CO_2 is an inherent characteristic of that type of energy source and the amounts of CO_2 are so large that it must be released to the atmosphere. At the present rate of world energy production this leads to an increase of 5 ppm by weight/year. An energy production that is 25 times higher leads to correspondingly higher values. The short remark "unrecycled" in Table 9 refers to the fact that atmospheric CO_2 is in a dynamic equilibrium with the CO_2 content of the oceans and the biosphere so the actual values are therefore smaller by a factor that is somewhere near 2. Such values for the increase of CO_2 content have to be weighed against the natural CO_2 content of the atmosphere. In 1950 this was 450 ppm by weight. There is considerable concern that the infrared radiation from the earth back to outer space is reduced by an increased CO_2 content due to the so-called green house effect [28]. At present this effect is definitly small but it is not clear today how large an increase of atmospheric CO_2 could be accepted. Much more work is required here.

But also nuclear power produces waste. Due to the famous factor of $2.5 \cdot 10^6$ (energy output per gram fuel in the case of nuclear power as compared with fossil power) this waste is small in volume and can, contrary to the case of CO_2, be contained. This of course establishes the need to do this reliably and for very long times – this is a large problem. But the right question is not: Do we want to have this problem or not? Rather

Fig. 9 Nuclear vs. Oil Fired Power Plant

(after Ch. Starr et al.)



it is the question: What is more acceptable, to have an impact on the climate (which at present must still be better understood) or to have a long term problem of small volume waste? Again completely different categories have to be compared, a typical systems task that is oriented toward the understanding of interweaving.

Table 9

Fossil Energy

$$\begin{tikzcd}
C + O_2 \arrow[r] & CO_2 + 97\ \text{Kcal} \arrow[d, Rightarrow] \\
1\text{g C} \arrow[r] & 3.4 \times 10^4\ \text{Wsec}
\end{tikzcd}$$

Nuclear Energy

$$\begin{tikzcd}
\text{Fission of 1 atom U} \arrow[r] \arrow[d, Rightarrow] & 200\,\text{MeV} \\
1\text{g U} \arrow[r] & 1\,\text{MWd} = 8.6 \times 10^{10}\ \text{Wsec} \\
(1\text{g Li} \arrow[r] & 1\,\text{MWd}) \arrow[u]
\end{tikzcd}$$

$$\boxed{\frac{1\text{g U (Li)}}{1\text{g C}} \longrightarrow \frac{8.6 \times 10^{10}\ \text{Wsec}}{3.4 \times 10^4\ \text{Wsec}} = 2.5 \times 10^6}$$

Fossil:

$0.24\ Q/\text{year} \longrightarrow 2.5 \times 10^{20}\ \text{Wsec/year}$

$\Longrightarrow 5\ \text{ppm}\ CO_2/\text{year}$, by weight
(unrecycled)

Nuclear:

$0.24\ Q/\text{year} \longrightarrow 8 \times 10^6\ \text{MW}$

$\Longrightarrow 8 \times 10^6 \cdot f\ \text{Curies/year}$

	10^8 sec	10^{10} sec	10^{11} sec
f =	10^4	10	1

In the case of waste heat disposal it became obvious, even in public debate, that this is a general problem of energy production. It is two-fold: In the conversion of energy there are sometimes very large losses and, further, all useful energy finally ends up as waste heat (except the tiny fraction that goes into binding energies). We will devote a whole section to this problem. There we will see that this was a secondary question but, because of the magnitude of energy production it now becomes a primary question, probably even the limiting one. Once energy is produced from binding energies it remains and does not disappear (except for the tiny fraction that goes back to binding energies). The stream of energy eventually goes to outer space by infrared radiation and this stream of energy must therefore be embedded in such a way that the deterioration of the natural conditions of the globe remains within acceptable limits. It is obvious that investigation of the problem of "acceptability" is an integral part of the system problems.

It is **not** the purpose here to deal with all system problems of all forms of energy production. Nor is it intended to indicate that only fission has system problems. Fusion for instance has system problems too [19]. The same is to be expected for solar power or energy from geothermal sources. Geothermal sources may for instance require consideration of potential earthquakes. The study of system problems is a tremendous task that requires many, many years and much remains to be done in the next years. The point here is rather this: We more and more realize that nuclear power took on a pilot function for all energy production schemes in detecting the fact that **there are** system problems if the mere size of energy production becomes large. The yardsticks for evaluating such sizes must still be better elaborated but it is clear that nature itself and the conditions of the finite globe do implicitly provide these yardsticks. The yardsticks that must be made explicit refer more to the handling of energy, to the embedding of energy and to the problem of acceptability rather than the problem of energy production as such, contrary to the situation of the past.

7. THE TASK OF SYSTEMS ANALYSIS IN THE CASE OF ENERGY SYSTEMS

It is now more easily possible to spell out what the task of systems analysis is in the case of energy systems. It is probable that a proper generalization could lead to an understanding of the nature of system problems beyond that of energy systems. The task has the following subtasks:

a) It is necessary to identify and understand all system problems that are inherent in the various options for large scale energy supply. This will be a continuing task and will probably never be completed as energy systems expand further and further. This task is not a matter of algorithm. It is rather a matter of technological and sociological substance. Scenario writings and life-style descriptions will probably be among the tools for accomplishing this task. It will be in particular important to identify the various interweavings that become important with the increasing size of energy production. This requires to some extent discipline oriented work but only to the extent that is necessary for the identification of the discipline oriented questions. From then on it is the task of the various scientific disciplines to pursue the questions so identified in connection with the systems analysis.

b) In the case of energy systems the predominant system problem seems to be that of embedding, not the production of energy. Such embedding is required in view of the functions of the globe. There must be embedding of energy into:
   - the atmosphere
   - the hydrosphere
   - the ecosphere
   - the sociosphere

c) It is then necessary to identify and evaluate alternatives, options for large scale implementation. There seem to be the following options for large scale energy supply:
   - energy by nuclear fission
   - energy by nuclear fusion
   - solar power
   - energy from geothermal sources.

   While system problems of energy from nuclear fission have been identified to some extent in the past, it will be necessary to do the same for the other options. For the task of comparing the various options it will be necessary to have not only cost/benefit procedures but cost/benefit/risk procedures in a special and a general sense.

d) Finally it will be necessary to minimize the system problems. This leads to severe methodological problems. We mentioned the comparison of apples and oranges several times. More scholarly expressed, it leads to the methodology problem of multiple objectives and decision under uncertainty.

Such systems analysis work has to permanently accompany the technological and sociological evolution of energy systems.

8. EMBEDDING OF ENERGY INTO THE ATMOSPHERE

Much emphasis has been given above to what may be called embedding. It seems to be necessary therefore to give more substance to that. As a first step let us consider the embedding of the stream of energy into the atmosphere. For that it is helpful to consider the distribution of the solar power input as given in Figure 8.

The solar input is 340 watts per square meter of the spherical upper surface of the atmosphere averaged over day and night and all zones of the globe. Roughly 34% of that value is reflected immediately, 19% is absorbed and transformed into heat already in the atmosphere and 47%, that is then 160 W/m^2, reaches the surface of the earth.
Out of this, 20% of 340 W/m^2 makes up the difference between outgoing infrared radiation and the infrared radiation that is back-scattered from the atmosphere to the surface of the earth. Another 22% evaporates water to drive the rain cycle.
By this evaporation the water is lifted to the middle parts of the atmosphere, condensation takes place there, and the condensation heat goes to outer space. 5% is used to heat the lower part of the atmosphere. All heat given to the atmosphere is eventually radiated away to outer space and therefore a balance is maintained between solar power input and heat power output. The temperature of the earth and the atmosphere is such that it permits this balance exactly. We therefore have a yardstick of power densities on the surface of the globe. Table 10 gives a number of such natural power densities in a convenient form. It should be noted that the figure of 55 W/m^2 is not the global average, it refers to wetter parts of the continents.

A few observations must be made:

- the energy balance is a delicate one; it results from a difference between large quantities (in the visible spectrum and in the infrared spectrum). One must therefore carefully evaluate the various influences on the energy exchange mechanisms, for instance the effect of an increased CO_2 concentration in the atmosphere or changes in the various albedos involved.

Table 10 Nature's Power Densities

Heat balance on the surface of earth (Average)	100 W/m^2
Latent heat density of rainfall on the continents	55 W/m^2
Sensible heat density for 1°C of rainfall water on the continents	0.1 W/m^2
Winds, waves, convections and currents (All globe)	0.7 W/m^2
Photosynthesis	0.075 W/m^2

- the recycling of water in the mechanism of vaporization and condensation is intimately coupled to the energy balance.
- the yardstick of these natural mechanisms is given in terms of power density.

For reasons of comparison we now consider man-made power densities. Orientation figures for that are given in Table 11. Today the **global average** of man-made power density

Table 11 Man Made Power Densities

	Consumption	
	Today	Tomorrow
Global average	$\frac{1.5\,KW/cap \cdot 3.3 \times 10^9\,cap}{1.48 \times 10^{14}\,m^2} = 0.033\,W/m^2$	$\frac{20\,KW/cap \cdot 10^{10}\,cap}{1.48 \times 10^{14}\,m^2} = 1.35\,W/m^2$
F. R. Germany	$\frac{4\,KW/cap \cdot 6 \times 10^7\,cap}{2.5 \times 10^{11}\,m^2} = 1\,W/m^2$	$\frac{20\,KW/cap \cdot 6 \times 10^7\,cap}{2.5 \times 10^{11}\,m^2} = 5\,W/m^2$
Industrial area	$\frac{18\,KW/cap \cdot 6 \times 10^6\,cap}{6.5 \times 10^9\,m^2} = 17\,W/m^2$ (Ruhr area)	$\frac{100\,KW/cap \cdot 10^8\,cap}{10^{10}\,m^2} = 1000\,W/m^2$

Production

Large nuclear power parks 30000 MW_e ⟶ 100 000 MW_{th}

$$\frac{7 \times 10^{10}\,W_{th}\,(\text{waste})}{3.5 \times 10^6\,m^2} = 20\,000\,W/m^2$$

is certainly too small to create a problem but the previously considered 20 kW/capita at a level of 10^{10} people gives a completely different picture. A value of 1.35 W/m^2 on the continents compares already with the global average of the power density for wind, waves, convections and currents.

But it is certainly insufficient to consider only global averages. Man's activity is not equally distributed on the globe. Already today, in the case of the Federal Republic of Germany, we have roughly 1 W/m^2. In the more distant future one has to consider highly industrialized areas that give values between 17 W/m^2 and several hundred W/m^2. The question whether such values lead to adverse effects on the atmosphere and climate is essentially open today. It is obvious that one has to approach this problem in steps.

The first impact level of such man-made power densities could be on the pattern of the rain cycle. Already today there are indications that the number of heavy rainfalls over industrialized areas has changed. Industrial areas however do not only produce waste heat but also particulates and pollutants and one has to consider the whole impact. This is complex. If the industrial areas become larger changes of the rain cycle pattern could be more than of just local significance.

A second level impact of man-made power densities would be on climatic patterns over larger areas while only slightly changing certain climatic averages. One has to bear in mind that there may well be instabilities in the atmospheric equilibrium. The question therefore comes up whether there are areas on the globe that are sensitive (or insensitive) to the production of waste heat.

A still more rigorous level of man-made power density impact would be on the global climate as a whole. This would also lead to an increase in the average temperature. One should bear in mind that climatic temperature changes of even 1-2°C are very significant.

These questions are very difficult ones. They lead into the area of methodological and climatological modelling which requires very large computer facilities. Of equal importance are the input data. But an adequate understanding of the physics of the highly nonlinear equations that govern the atmosphere still requires much work. In the past years these problems have attracted more and more attention [28]. Names like Budyko, Smagorinski, Manabe, Washington, Lamb, Fortak, Bryson, Kellogg and others characterize these efforts. For 1977 the world meteorological organization and the international council of scientific unions plan "The First Garp Global Experiment" of a Global Atmosphere Research Programme (GARP) [29]. But also the observational branch of climatic sciences must be employed and promoted. There the CLIMAP program maps the climate of earlier ages and therefore provides the opportunity to test the capability of large climatic computer programs.

Earlier in this paper reference was made to possible system problems if solar power were to be harvested on a large scale. From Tables 10 and 11 we realize that the required power densities for purposes of civilization in certain industrialized areas will be similar to, or larger than, nature's power densities. The industrially significant employment of solar power therefore involves large areas of the globe, so the changes of albedo and the redistribution of energy lead to the same questions mentioned above in the context of waste heat.

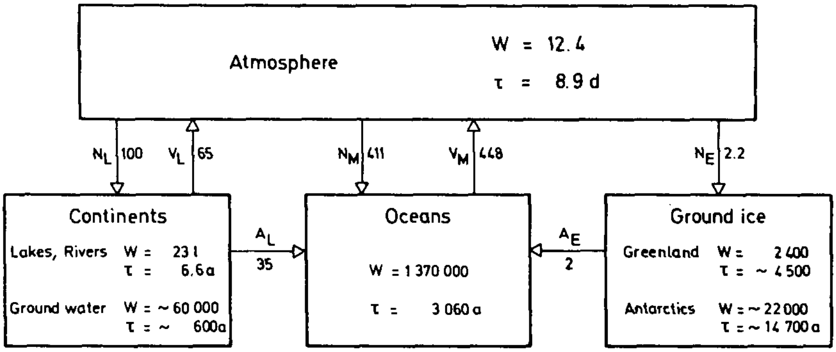
One has to put forward the question whether it will be necessary to bring into phase the relevant research and development work in atmospheric sciences and the energy field.

9. EMBEDDING OF ENERGY INTO THE HYDROSPHERE

Figure 10 provides the necessary background for this topic. The average rainfall on the earth is 101 cm/year, totalling $513 \cdot 10^3$ km^3/year, and the same amount must necessarily evaporate. But the ratio of evaporation and rainfall is not the same in the case of the oceans and the continents. Rain water is transported from the oceans to the continents to feed the run-offs, that is, rivers and creeks; the total run-off being $35 \cdot 10^3$ km^3/year. Table 12 characterizes water consumption. Contrary to a widespread belief irrigation accounts for most of the water consumption today, but by the year

Fig. 10 Water Cycle of the Earth

(after Lvovich 1970)



Water content : W in 10^3 km^3

Transports : F in 10^3 km^3/a

Residence time : $\tau = W/F$

Earth : $V_E = N_E = 513 \times 10^3$ km^3/a
$= 101$ cm/a

Table 12 Water Consumption (after Lvovich 1969) and Water Resources

Water consumption	1965 Consumption	1965 Wastes	1965 Evaporation	2000 Consumption	2000 Wastes	2000 Evaporation
Urban supply	98	56	42 km^3/a	950	760	190 km^3/a
Irrigation	2 300	600	1700 "	4 250	400	3 850 "
Industry	200	160	40 "	3 000	2 400	600 "
Power plants	250	235	15 "	4 500	4 230	230 "
Total	2 848	1051	1797 "	12 700	7 790	4 910 "

Table 13 Representative Values for the Heat Balance in Egypt

(after Flohn 1971)

	Arid	Cultivated land
Global radiation input	280 W/m^2	280 W/m^2
Albedo	25 %	10 %
Black body radiation, net value	32.5 W/m^2	38 W/m^2
Net balance Q	170 W/m^2	205 W/m^2
a) Evaporization	2 cm/a	220 cm/a
b) Vaporization heat	1.7 W/m^2 ≙ 1% of Q	176 W/m^2 ≙ 86% of Q
c) Sensible heat + remainder	99% of Q	14% of Q
Bowen ratio : $\frac{\text{Sensible heat}}{\text{Latent heat}}$	104	0.16

2000 this is expected to change. Lvovich [30] has estimated the consumption in the year 2000 to be roughly 13 000 km^3/year, or roughly 1/3 of all the run-off. It should be noted however that global averages are in most cases not adequate and that the regional picture may differ drastically. In the case of the Ruhr area, already 0.63 km^3/year of industrially used water is lost through vaporization: an equivalent of 14 cm/year or roughly 1/3 of the local run-off. These considerations do not relate yet to energy but give a yardstick for evaluating relevant relationships.

First is desalination. It has been estimated that $32 \cdot 10^6$ km^2 of land could be cultivated. (The total area of the continents is $148 \cdot 10^6$ km^2.) Roughly $20 \cdot 10^6$ km^2 are arid and sufficient amounts of water must be provided. In Table 13 it is indicated that an amount of water equivalent to 200 cm/year of rainfall is required because this would make up the difference between arid areas and cultivated land in areas that were originally arid. 200 cm/year for $20 \cdot 10^6$ km^2 gives 40 000 km^3/year. From Figure 10 it is obvious that such an amount of water can be provided only by desalination. Today this requires roughly 50 kWh/m^3, thus leading to 7 Q/year. This more or less doubles the previously considered energy consumption of 20 kW/capita and 10^{10} people, thus leading to a total of $7 + 6 = 13$ Q/year. These are, of course, only order of magnitude considerations.

It is obvious that land use by cultivating arid areas, water use and energy use go together here.

There are other interactions between energy and water but, in fact, the density of rainfall limits the production of electricity. The difference between rainfall and evaporation, on the average 40 cm/year, feeds the run-offs, which are therefore proportional to rainfall if averaged over sufficiently large areas. One can now examine the amount of waste heat that can be removed by all run-offs for either once-through cooling or wet cooling towers. Table 14 summarizes this. Due to the connection between rainfall and run-off the limits here are also in terms of power densities and this refers inherently to land use. If all the run-offs are heated by 5°C, only 0.25 W/m^2 can be dumped, but this admittedly crude consideration sometimes leads to surprisingly good results. In the Federal Republic of Germany for instance roughly 30 GW of electricity production rely on once-through cooling. This amounts to roughly 60 GW waste heat or 0.24 W/m^2 and this indeed leads to a situation where the heating of rivers and lakes becomes a legitimate concern.

Table 14 Limits for the Production of Electricity due to Waste Heat Disposal

Total water run off $\circ\!\!-\!\!\!-\!\!\!-\!\!\circ$ 40 cm / a

A) All run offs heated by ΔT :

$$\frac{N_{th}}{F} = 0.054 \cdot \Delta T \quad W/m^2$$

(for instance $\Delta T = 2°C \longrightarrow \frac{N_{th}}{F} = 0.1\,W/m^2$)

B) All run offs evaporized (wet cooling towers)

$$\frac{N_{th}}{F} = 40\,W/m^2$$

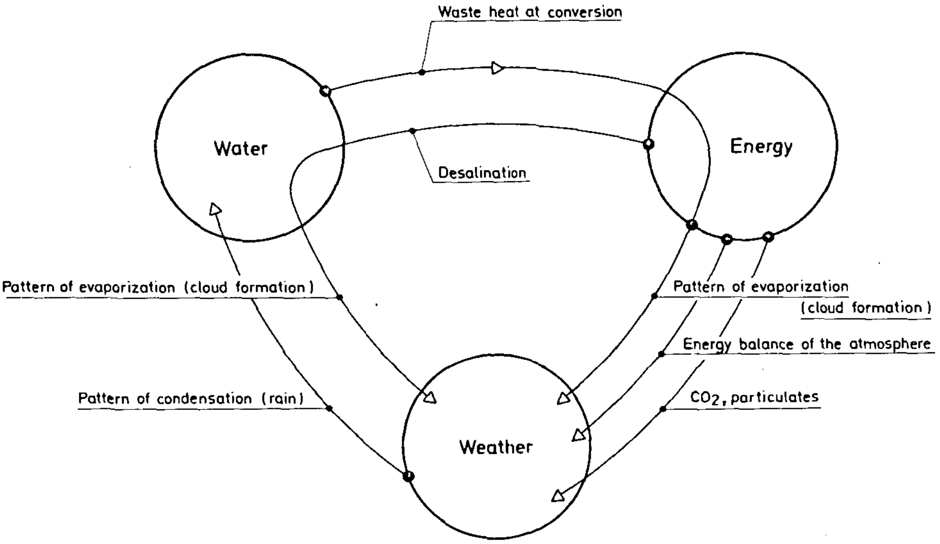
Wet cooling towers help for some time, but one must realize that only a fraction of the run offs can be used for consumption in wet cooling towers. If one then compares the densities with the man-made densities of tomorrow one again realizes there should be a problem and this is indeed the case. More detailed investigations in the Federal Republic of Germany come to the conclusion that wet cooling towers can probably help only for the next fifteen years or so [31].

A third connection between water and energy has been mentioned previously: the feedback of waste heat into the pattern and amount of rainfall.

Figure 11 tries to make these interweavings between water, energy and weather more obvious. It is a Kind of summary of this and the previous section.

Most of what has been said before refers to water on the continents, but there is also a vast reservoir of water in the oceans. Heat dumping there is feasible so far as the heat capacity is concerned but leads to questions of ecology and the dynamics of ocean currents. It might be necessary to identify areas in the oceans that are stable and insensitive to the discharge of large amounts of waste heat. This then would lead to a decoupling of the strong interweaving of water, energy and weather as outlined in Figure 11. Installing (nuclear) power parks by the oceans or on the oceans then leads to the problem of energy transport over greater distances. In order to fully appreciate this problem one should realize that today there is no transport of electrical energy over really large distances. In the case of the Federal Republic of Germany large amounts of electricity are transported not more than 150 km (average) or so. Most of the high voltage lines essentially only stabilize area-oriented distributions of electrical energy. There are a number of technological options for energy transportation on a large scale: ultra high voltage lines, superconductive cables, hydrogen pipe lines and others. In the past more of the large scale technological R + D effort has gone into the problem of energy production, for instance the development of nuclear power. However, under the scope of considering energy use, land use and water use as one comprehensive problem it appears that the technological problem of energy transport may be more important than the development of another energy source.

Fig. 11 Interweaving between Water, Weather and Energy



10. EMBEDDING OF ENERGY INTO THE ECOSPHERE

Embedding the use of energy into the ecosphere leads, among others, to certain environmental problems. Not all of the environmental problems come into the picture this way, of course. A reasonable first step is probably the study of accountability systems. Power plants, urban areas and vehicles are emitters of pollutants and these emissions lead to ambient concentrations. Simple or sophisticated meteorological and hydrological models could establish the relationships between emissions and the ambient concentrations. The design of monitoring systems could help to establish an experimental background for such relations and thus verify the validity of the models. Parallel to that it might be possible to establish relationships between the production of industrial goods and certain emissions, thus leading to the relation: goods – emissions – pollutant concentration. Eventually it will be possible this way to establish an overall accountability for the flow of pollutants. This would inherently provide the possibility of managing pollution. In order to fully appreciate this one should realize that the establishment of the global accountability system for nuclear materials that is now implemented by the International Atomic Energy Agency [32] turns out to be the key to the secure handling of nuclear materials. The universality of the approach also poses certain managerial problems and it is proposed that this aspect of universality be studied. In so doing it should be recognized that systems analysis did play a major role in the design of the present IAEA safeguard system [33].

To draw certain conclusions from the results obtained from accountability systems standards are required. The establishment of standards may allow, for instance, the design of certain action levels. Incomplete knowledge in the field of toxicology, decisions under uncertainty, public acceptance, the legislative process and other aspects come into the picture here. The debate on appropriate standards for radiotoxic dose rates that took place in the U.S. and elsewhere in the recent years may be an example of this. The phenomenon of the Gofman-Tamplin affair, the rule making process for "as low as practicable" dose rates, the function of public hearings in the decision-making process and other events of the recent years should be more thoroughly understood from this point of view. Figure 12 briefly illustrates this problem of environmental accountability discussed above.

11. EMBEDDING OF ENERGY INTO THE SOCIOSPHERE: RISK AND RELIABILITY

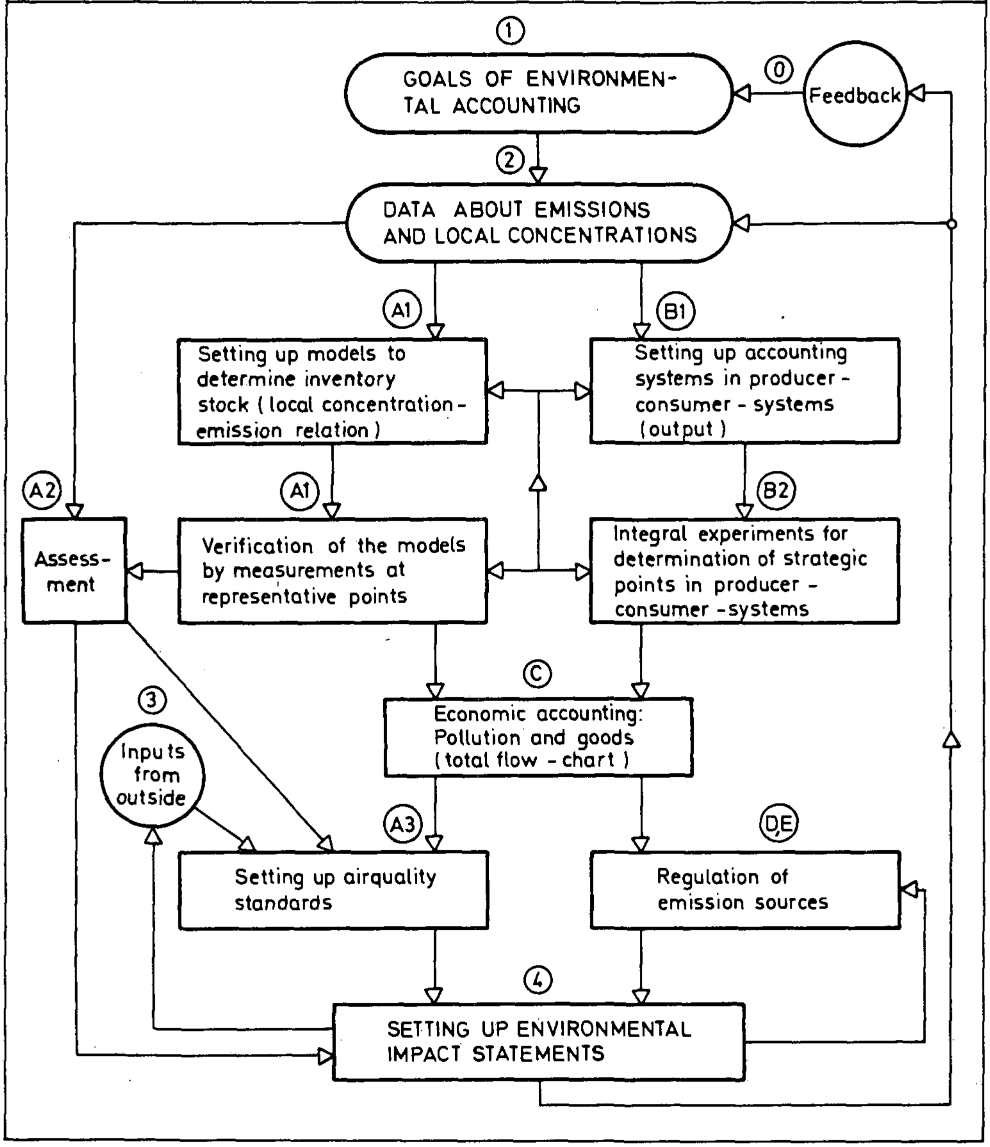
A thorough reflection on the problem of pollution leads also into the domain of reliability control and risk evaluation. Here it is again useful to study Table 9. In addition to embedding energy into the atmosphere one is led to the problem of risk.

Risk has two components: the risk component that is due to the lack of knowledge which, in principle, is obtainable; and the risk component that even in principle cannot be determined [34]. This second component is due to the fact that the strict application of deterministic scientific models requires complete knowledge of initial and boundary conditions even if the laws of nature are fully known. In many cases it is impossible to acquire such complete knowledge, it would require a "Laplacean Demon". Then a risk of the second kind evolves.

The release of CO_2 into the atmosphere together with that of other pollutants establishes a risk of the first kind. In principle it should be possible to understand whether an increased CO_2 content will affect the climate or not, but at present this is not possible.

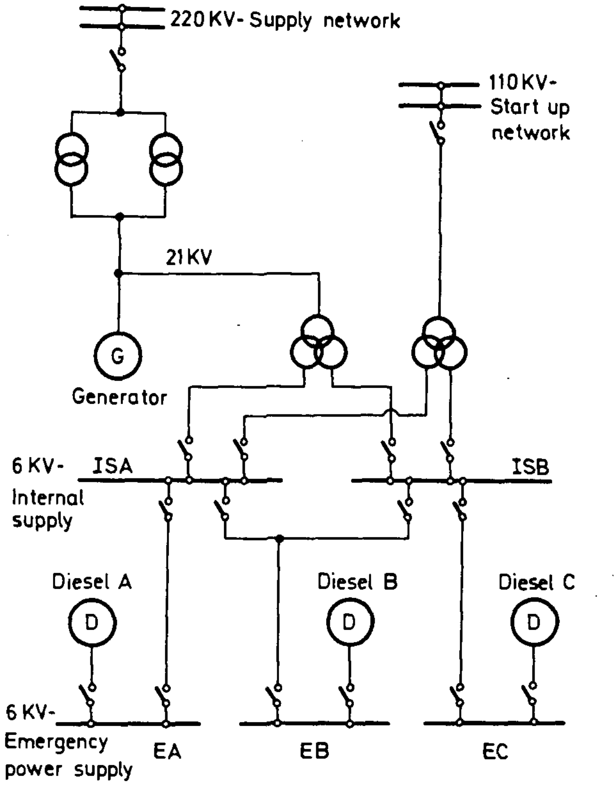
Nuclear energy leads to a risk of the second kind: It is possible to produce energy without touching the environment at all, at least in principle. The reactions in the domain of the atomic nucleus result however in the production of radioactive elements. (This is also true for power from technical fusion reactors that use the D-T process [19]). Due to the factor $2.5 \cdot 10^6$ between nuclear and fossil power the radioactive elements are so small in volume and weight that they can be contained, contrary to the problem of the environmental release of combustion products in the case of fossile power pointed out above. Containment, now, is an example of a technological measure; however, all technological measures can fail and this constitutes the risk.

Fig.12 Environmental Accountability



While the risk of the first kind can be eliminated in principle, the risk of the second kind remains in principle. But the risk of a technological measure can be made smaller than any given small number, the residual risk limit. This leads into the domain of reliability control. Space research, electronics and, more recently, nuclear energy have been the areas where methods of reliability control were developed and applied. The principal tool of reliability control is the establishment of a failure tree. The top of a failure tree represents an undesired accidental event. The use of logical symbols helps to represent the logical structure of the reliability of a given technological device. Figure 13 shows an

Fig. 13 Power Supply System of SNR 300

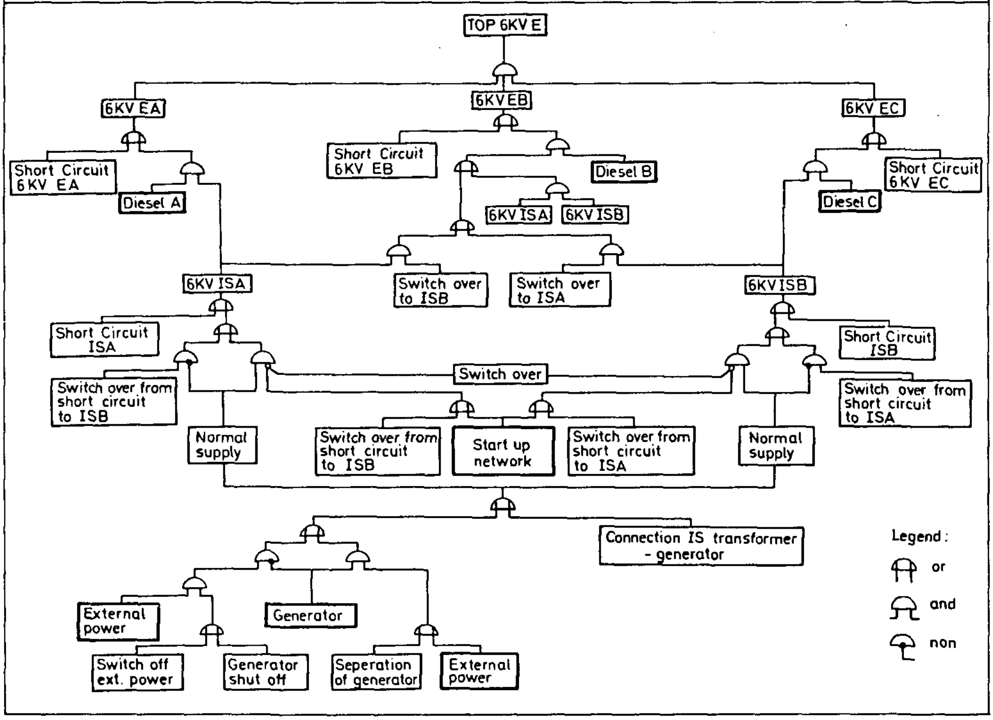


emergency power supply system for the German-Belgian-Dutch fast breeder prototype reactor SNR 300, and Figure 14 shows the failure tree that was used for the evaluation of the supply systems reliability. Having established the failure tree in question, it is then possible to evaluate the failure rate of the technological system by computer simulation using, among others, Monto Carlo techniques.

However, a number of methodological problems remain: in most cases there is a lack of input data (the failure rates of the various components of the technological systems), it is difficult to ensure that the considered failure tree is sufficient for the purpose in question, confidence levels must be evaluated, etc. On the other hand it is necessary to have reliability control procedures in most of the coming technological projects because society has to rely on technology to an ever-increasing extent.

Even if the methods of reliability control are fully mastered it will not be possible to make the reliability of a given technological device exactly unity. The limit for the residual risk will always be different from zero, albeit very small. So it will be necessary to

Fig. 14 Fault Tree of the Power Supply System of SNR 300



establish design limits for such residual risks in the same sense as it was necessary to establish standards for the evaluation of accountability systems for pollutants. Such establishment of design limits can only come from the evaluation of existing risks. Risk evaluation as a scientific discipline is only in its beginnings and it is in particular the work of C. Starr and Erdmann at the University of California, Los Angeles, and H. Otway (Los Alamos Scient. Lab., University of California, and IAEA) that must be explicitly mentioned here. In Table 15 a spectrum of existing risks is given. Starr [35] was able to evaluate a number of quasi laws. For instance there seems to be a difference between voluntary risks and involuntary risks, that differ by a factor of 10^3. Further, for voluntary risks there seems to be a relationship between risks and expected benefits. This is illustrated in Figure 15. Figure 16 indicates an approach to rationally answering the question: How safe is safe enough? It is obvious that the general problem of systems analysis, that of quantification, becomes particularly virulent in the case of risk evaluation. More work is obviously necessary in this field. This could result in more established procedures for the assessment of risks.

12. ENERGY SYSTEMS

It should now be possible to give a first order approach on the meaning of the term energy systems.

We have already made it obvious that the simple relationship of Figure 6 is insufficient. As we have seen, in the more distant future the production of large amounts of energy is not

Table 15 Fatal Accidents USA 1967

Type of accident	Total deaths	Probability of death per person per year
Motor vehicle (M.V.)	52.924	2.7×10^{-4}
Falls	20.120	1.0×10^{-4}
Fire and explosion	7.423	3.7×10^{-5}
Firearms	2.896	1.5×10^{-5}
Aircraft	1.799	9.0×10^{-6}
Railway accident (exept M.V.)	997	5.0×10^{-6}
Electric current	376	1.9×10^{-6}
Lightning	88	4.4×10^{-7}
Explosion of pressure vessel	42	2.1×10^{-7}
Streetcar (exept M.V. and train collision)	5	2.5×10^{-8}

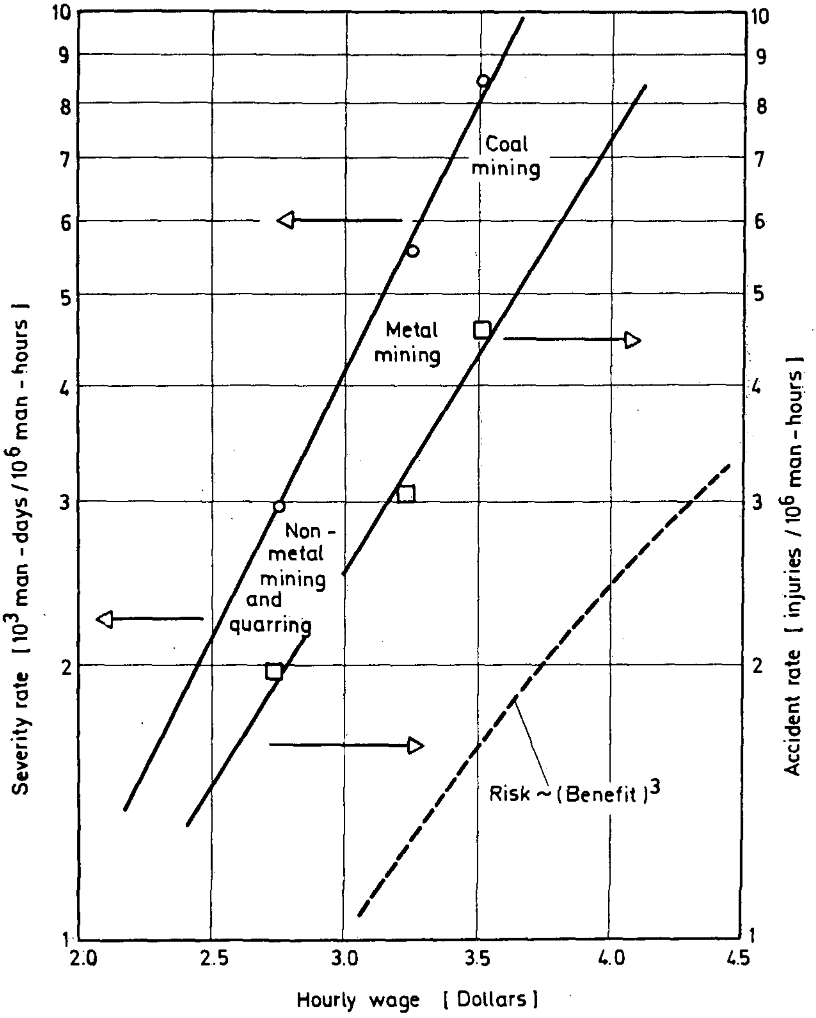
(National Safety Council, Chicago 1970)

a constraint – there is sufficient energy. But there are probably other severe constraints. One such constraint is the amount of cooling water if power plants are to be built on the continents. As we have seen, it is the power density that is limited. The acceptable heat load to the atmosphere is also a limit that is given in terms of density. In the case of pollution load this is true for a long time to come, although there may eventually be absolute limits. The case of CO_2 could be a tentative example of this. Having focused attention on the term density one realizes that risk limits may also be expressed as a density. The discussion on reactor siting indicates this. For instance an airport, a chemical factory and two nuclear power plants all in one place might be considered too much of a risk aggregation. A distribution of risk would be required.

Figure 17 is an attempt to illustrate what the term energy systems could mean. In dashed lines we have the traditional understanding of Figure 6 where the circles indicate constraints. Each constraint also refers to acceptability and therefore to the sociological part of the constraints. Within these constraints energy can be produced. An optimization process should now lead to an adjustment of densities for risk, power and

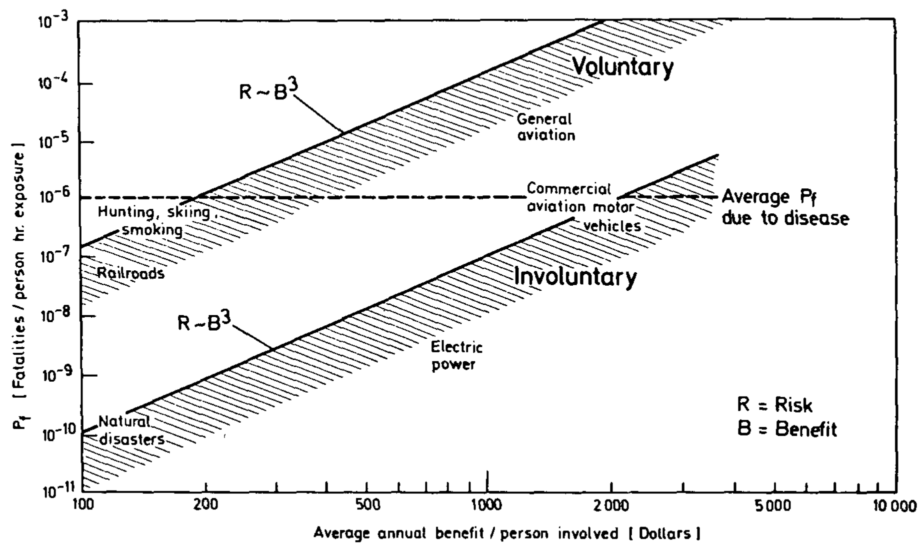
Fig. 15 Mining Accident Rates vs. Incentive

(Ch. Starr, Benefit - Cost Studies in Socio - Technical Systems, April 1971)



pollution. The means that allow this are technological development, the distribution of all relevant installations and the transportation of energy and water over larger distances. A generalized objective function, as discussed in section 3, would be employed in such an optimization. Econometry thereby becomes a more general discipline than previously. It is obvious that other factors have to be taken into account on the level of an long range policy approach. For example communication, data processing, general transport requirements and other factors come equally into the picture. But the

Fig.16 Risk vs. Benefit
Voluntary and Involuntary Exposure
(Ch. Starr, Benefit-Cost Studies in Socio-Technical Systems, April 1971)



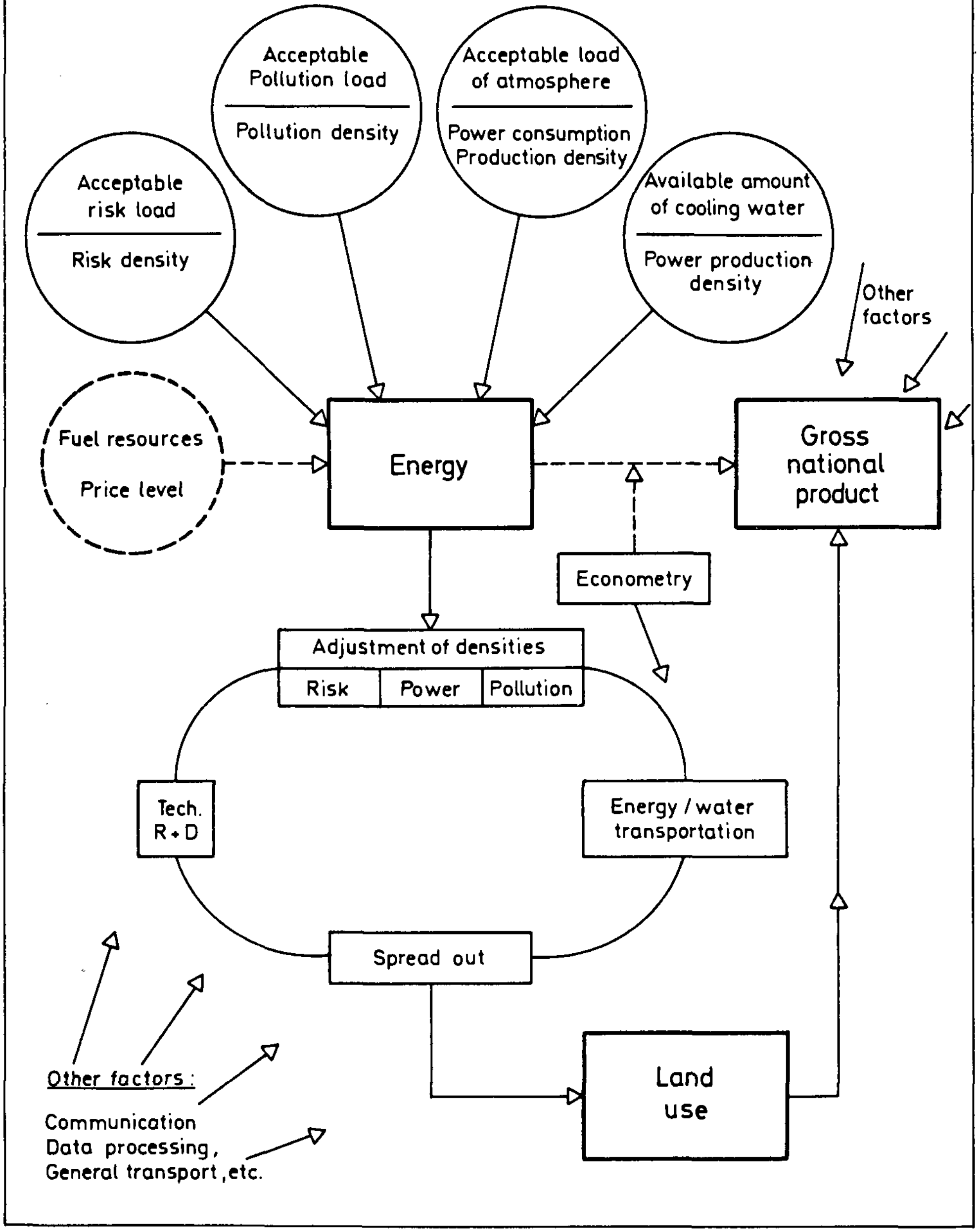
scope is now broad enough to describe the impact as far as energy is concerned and to provide for a proper integration of energy systems into a suprasystem. The result of such an optimization is a scheme for land use. Only through the use of land can energy result in a gross national product. Land use then is one of the major interweavings between energy systems and other large systems of the infrastructure of modern civilization.

13. MORE REMARKS ON THE LONG RANGE PHASE OF THE ENERGY PROBLEM

Earlier in this paper the observation was made that a smooth transition through the medium range phase into the long range phase of the energy problem should be achieved. For that it is necessary to have a conceptual understanding of asymptotic solutions of the energy problem. After the remarks on embedding it is now more easily possible to elaborate a little bit further on one example for an asymptotic solution of the energy problem.

We have seen that the concept of having large nuclear parks could lead to a certain decoupling of the interweaving between water, energy and the weather. To that extent it might be necessary to identify certain areas in the oceans that are particularly insensitive to the release of large amounts of waste heat in terms of meteorology as well as in terms of ecology. Large meteorological and ecological modelling is probably required for this. Such nuclear parks should be large enough to incorporate the whole nuclear fuel cycle. This means that a minimum size of 30 GW thermal or so is required. A concentration of the nuclear fuel cycle would eliminate a number of concerns about nuclear power. For instance all the plutonium would remain in one place and the operators could be highly trained and highly effective due to the concentration of facilities. An upper

Fig. 17 Energy - Land Use - Gross National Product



limit for such nuclear parks is probably given by considerations of energy supply security. As we have seen earlier, the production of electricity is only one aspect. It is not necessarily true that an all-electric economy is an optimal solution. We therefore envisage the production of hydrogen in high temperature reactors. Conversion efficiencies of 75% could be expected. In a more or less stable future economy the breeding gain of large fast breeder reactors must not necessarily be obtained as plutonium. U-233 could also be produced and could be used in the operation of high temperature gas cooled reactors. The transportation of electricity and hydrogen should not be too large a problem. We mentioned earlier new technological aspects of this. Hydrogen could be pumped into the pipeline systems which had been used in the medium-range energy phase when gaseous hydrocarbons were the secondary fuel. A smooth transition could then take place.

Electricity and hydrogen are both very clean secondary fuels and hydrogen is also feasible for all forms of transportation and industrial use. Only very minor pollution impacts are to be expected.

Much work is required to study in detail all aspects, and in particular the system problems, of a scheme for the asymptotic solution of the energy problem. The remarks made here only give an example of what could be an asymptotic solution. Other options have to be studied too. For instance the Peter Glaser scheme to harvest solar power in outer space [23] should be pursued and its systems problems better understood.

This paper is not meant to represent a completed part of that task. It is intended only to help understand the scope of the energy systems problem.

REFERENCES

[1] M.K. Hubbert: The Energy Resources on the Earth, Scientific American, September 1971.

[2] See for instance, Herbert S. Rickey: "Coal: Prospects and Problems", Proceedings, National Energy Forum, Sept. 23-24, 1971, sponsored by: The National Division of the US National Committee of the World Energy Conference.

[3] See for instance: "Quandary", R-1084-NSF/CSRA, R-1115-RF/CSA, R-1116-NSF/CSA, September 1972, RAND, Santa Monica, Calif.

[4] Walter J. Levy: Oil Power, Foreign Affairs, July 1971, Vol. 49, No. 4.

[5] Walter J. Levy: An Atlantic-Japanese Energy Policy, Europe - America Conference, Amsterdam-Holland, March 27, 1973.

[6] Stephen D. Bechtel Jr.: "Energy for the Future: New Directions and Challenges", Annual Meeting of the American Gas Association, Cincinatti, Ohio, October 16, 1972.
See also: Nuclear News, a Publication of the American Nuclear Society, July 73, Vol.16, No.9.

[7] H.C. Hottel and J.B. Howard: New Energy Technology, Some Facts and Assessments, Chapter 3, MIT Press, Cambridge, Mass., and London, England, 1971.

[8] P.F. Schweizer, C.G. Love and J. Hunter Chiles III: A Regional Energy Model for Examining New Policy and Technology Changes, oral presentation at the MIT conf. on: Energy, Demand, Conservation and Institutional Problems, Febr. 1973, Massachusetts Inst. of Techn., Cambridge, Mass./USA.

[9] Alan S. Manne: On Linking Energetics to Dynamics, Part 3 of the Study: Multi Level Planning, Case Studies in Mexico, Stanford University.

[10] A.M. Weinberg and P. Hammond: Proceedings Fourth Int. Conf. on "Peaceful Uses of Atomic Energy", Geneva, Sept. 1971.

[11] C. Starr: Energy and Power, Scientific American, Vol. 225, No. 3, Sept. 1971, p. 37.

[12] Earl Cook: Private Communication, Paper for the Congressional Research Service, Library of Congress of the United States, to be published.

[13] M.K. Hubbert: Energy Resources for Power Production, Proceedings IAEA Symp. on Environmental Aspects of Nuclear Power Stations, New York, August 1970, IAEA-SM-146/1.

[14] V.E. McKelvey and D.C. Duncan: United States and World Resources of Energy, Mineral Resource Development Ser., No. 26, II (1969) 9.

[15] R.V. Davies et al.: Extraction of Uranium from Sea Water, Nature 203, 1110 (1964).

[16] See for instance: Ergänzendes Material zum Bericht: "Kernbrennstoffbedarf und Kosten verschiedener Reaktortypen in Deutschland", KFK 466, September 1966, Gesellschaft für Kernforschungszentrum Karlsruhe, Germany.

[17] The last international fast breeder conference took place at Karlsruhe, Germany, October 9-13, 1972. Their proceedings give a good insight in the development of fast reactors: Engineering of Fast Reactors for Safe and Reliable Operation. Karlsruhe, Gesellschaft für Kernforschung.

[18] A.M. Perry and A.M. Weinberg: Thermal Breeder Reactors, Annual Review of Nuclear Science, Vol.22, 1972.

[19] W. Häfele and C. Starr: A Perspective on the Fusion and the Fission Breeders, Kernforschungszentrum Karlsruhe and University of California, Los Angeles, 1973, to be published.

[20] J.D. Lee: Tritium Breeding and Energy Generation in Liquid Lithium Blankets, Proceedings BNES Conf. on Nuclear Fusion Reactors, Culham, Sep. 1969, BNES 1970.

[21] D.E. White: U.S. Geolog. Surv. Circ. 519, Wash. (1965).

[22] R.W. Rex: Geothermal Energy, the neglected energy option, Science and Public Affairs, Bulletin of the Atomic Scientists, October 1971, Volume XXVII, No. 8.

[23] P.E. Glaser: Power from the Sun: its Future Science, Vol.162, 1968.

[24] P.E. Glaser: Power without Pollution, Journal of Microwave Power, Vol.5, No.4, Dec. 1970.

[25] W. Häfele: See for instance: 150 Jahrfeier, München, 1972.

[26] H. Büker, P. Jansen, W. Sassin, W. Schikarski: Kernenergie und Umwelt, Table 21, page 47, Kernforschungszentrum Karlsruhe, KFK-1366, or Kernforschungsanlage Jülich, Jül-929-HT-WT, March 1973.

[27] C. Starr, M.A. Greenfield and D.F. Hausknecht: A comparison of public health risks: nuclear versus oil-fired power plants, Nuclear News, a Publication of the American Nuclear Society, October 1972, Vol.15, No.10.

[28] See for instance: William H. Matthews, William W. Kellogg, and G.D. Robinson: Man's Impact on the Climate, the MIT Press, Cambridge, Massachussets and London, England, 1971;

[29] The first GARP global experiment, objectives and plans, GARP publication series, No.11, March 1973, World Meteorological Organisation and International Council of Scientific Unions.

[30] M.I. Lvovitch: World Water Balance (General report), Publications de l'Association Internationale d'Hydrologie Scientifique 93 (1969).

[31] See [26], page 15 ff.

[32] International Atomic Energy Agency, The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, IAEA, Vienna, Inf./Circ/153, 1971.

[33] W. Häfele: Systems Analysis in Safeguards of Nuclear Material, Proceedings Fourth Int. Conf. on "Peaceful Uses of Atomic Energy", Geneva, Sept. 1971, UN, New York, IAEA, Vienna, Vol.9, p.303, 1972.

[34] W. Häfele, Ergebnis und Sinn des SEFOR Experimentes in: Einheit und Vielheit, Festschrift für Carl Friedrich von Weizsäcker zum 60. Geburtstag, Vandenhoek and Ruprecht, Göllingen-Zürich, 1973.

[35] C. Starr: Benefit-Cost Studies in Socio-Technical Systems, Colloquium on Benefit-Risk, Relationships for Decision Making, Washington D.C., April 26, 1971.

Commercial Power Reactors in Operation

Name	Location	Type	Net output MW(e)	Criticality date	Note
ARGENTINA					
Atucha	Atucha (North of Buenos Aires)	PHWR	319.00	Jan 1974	
CANADA					
NPD (nuclear power demonstration)	Rolphton (Ont.)	PHWR	22.50	Apr 1962	* 2
Douglas point	Tiverton (Ont.)	PHWR	208.00	Nov 1966	
Gentilly	Point-aux-roches (Quebec)	HWLWR	250.00	Nov 1970	
Pickering-1	Pickering (Ont.)	PHWR	508.00	Feb 1971	
Pickering-2	Pickering (Ont.)	PHWR	508.00	Sep 1971	
Pickering-3	Pickering (Ont.)	PHWR	508.00	Apr 1972	
Pickering-4	Pickering (Ont.)	PHWR	508.00	May 1974	
CZECHOSLOVAKIA					
A-1	Jaslovske Bohunice	HWGCR	110.00	1972	
FRANCE					
G-2, G-3	Marcoule	GCR	2 X 39.00	Jul 1958 Jun 1959	
Chinon-2 (EDF-2)	Avoine	GCR	200.00	Aug 1964	
Chinon-3 (EDF-3)	Avoine	GCR	480.00	Mar 1966	
Ardennes (Chooz)	Chooz	PWR	270.00	Oct 1966	* 3
El-4 (Monts d'Arrée)	Brennilis	HWGCR	70.00	Dec 1966	
Saint Laurent des eaux-1 (EDF-4)	Saint Laurent des eaux, Loir-et-Cher	GCR	480.00	Jan 1969	
Saint Laurent des eaux-2	Saint Laurent des eaux, Loir-et-Cher	GCR	516.00	Jun 1971	
Bugey-1 (EDF-5)	Bugey near Lyon	GCR	545.00	Apr 1972	
Phénix	Marcoule	FBR	250.00	Aug 1974	
GERMANY, DEM. REP.					
Rheinsberg					
Kilw Nord					

Name	Location	Type	Net output MW(e)	Criticality date	Note
GERMANY, FED. REP.					
MZFR (Mehrzweck-forschungsreaktor)	Karlsruhe	PHWR	52.00	Sep 1965	
KRB Gundremmingen	Gundremmingen	BWR	250.00	Aug 1966	
KWL Lingen	Lingen	BWR	256.00	Feb 1968	* 4
KWO Obrigheim	Obrigheim	PWR	328.00	Sep 1968	
KWW Wuergassen	Wuergassen, Kreis Hoexter	BWR	640.00	Oct 1971	
KKS Stade	Stade near Hamburg	PWR	630.00	Jan 1972	
KKN Niederaichbach	Niederaichbach	HWGCR	100.00	Dec 1972	
INDIA					
Tarapur-1	Tarapur	BWR	190.00	Feb 1969	
Tarapur-2	Tarapur	BWR	190.00	Feb 1969	
Rajasthan-1	Rana Pratap Sagar	PHWR	200.00	Aug 1972	
ITALY					
Latina	Borgo Sabotino - Latina	GCR	200.00	Dec 1962	
Garigliano	Sessa Aurunca - Caserta	BWR	150.00	Jun 1963	
Trino Vercellese (Enrico Fermi)	Trino Vercellese	PWR	247.00	Jun 1964	
JAPAN					
Tokai (Japco-1)	Tokai	GCR	157.00	May 1965	
Tsuruga (Japco-2)	Tsuruga	BWR	340.00	Oct 1969	
Fukushima-1 (Tokyo-1)	Fukushima	BWR	439.00	Jul 1970	
Mihama-1 (Kansai-1)	Mihama	PWR	320.00	Jul 1970	
Mihama-2 (Kansai-2)	Mihama	PWR	470.00	Apr 1972	
Shimane-1 (Chugoku-1)	Kashima	BWR	439.00	May 1973	
NETHERLANDS					
Dodewaard	Dodewaard	BWR	54.00	Jun 1968	
Borssele (Provinciale Zeeuwse Energie-Mij.)	Borssele, near Vlissingen	PWR	477.00	Mar 1973	
PAKISTAN					
Kanupp (Karachi nuclear power plant)	Paradise point near Karachi	PHWR	125.00	Aug 1971	

Name	Location	Type	Net output MW(e)	Criticality date	Note
SPAIN					
Jose Cabrera (Zorita-1)	Zorita de los Canes	PWR	153.00	Jun 1968	
Santa Maria de Garona	Santa Maria de Garona (Burgos)	BWR	440.00	Jan 1971	
Vandellos	Vandellos (Tarragona)	GCR	480.00	Feb 1972	* 5
SWEDEN					
Oskarshamn-1	Simpevarp, Oskarshamn	BWR	440.00	Dec 1970	
SWITZERLAND					
Beznau-1	Beznau (Aargau)	PWR	350.00	Jun 1969	
Muehleberg	Muehleberg, near Bern	BWR	306.00	Mar 1971	
Beznau-2	Beznau (Aargau)	PWR	350.00	Oct 1971	
USSR					
Siberian	Troitsk	LWGR	6 X 100.00	Sep 1958 Dec 1962	
Beloyarsk-1	Sverdlovsk region (Beloyarsk)	LWGR	94.00	Sep 1963	
Novovoronezh-1	Novo Voronezh	PWR	265.00	Oct 1963	
VK-50 (Ulyanovsk)	Melekess	BWR	50.00	Oct 1965	
Beloyarsk-2	Sverdlovsk region (Beloyarsk)	LWGR	200.00	Oct 1967	
Novovoronezh-2	Novo Voronezh	PWR	365.00	Dec 1969	
Novovoronezh-3	Novo Voronezh	PWR	440.00	1971	
BN-350	Shevchenko	FBR	150,00	Nov 1972	* 6
Novovoronezh-4	Novo Voronezh	PWR	440.00	Dec 1972	
Kola-1	Murmansk	PWR	420.00	1973	
UNITED KINGDOM					
Calder	Calder Hall	GCR	4 X 50.00	May 1956 Dec 1958	
Chapelcross	Chapelcross	GCR	4 X 50.00	Nov 1958 Dec 1959	
Berkeley	Berkeley	GCR	2 X 143.00	Aug 1961 Feb 1962	
Bradwell	Bradwell on sea (Essex)	GCR	2 X 125.00	Aug 1961 Apr 1962	

Name	Location	Type	Net output MW(e)	Criticality date	Note
UNITED KINGDOM (continued)					
WAGR (Windscale advanced gas-cooled reactor)	Windscale	AGR	32.00	Aug 1962	
Hunterston-A	Hunterston (West Kilbride)	GCR	2 X 160.00	Sep 1963 Mar 1964	
Hinkley point-A	Hinkley point	GCR	2 X 250.00	May 1964 Oct 1964	
Trawsfynydd	Trawsfynydd	GCR	2 X 250.00	Aug 1964 Dec 1964	
Dungeness-A	Dungeness, Kent	GCR	245.00	Jun 1965 Sep 1965	
Sizewell-A	Sizewell	GCR	2 X 210.00	Jun 1965 Dec 1965	
Oldbury-A	Oldbury on Severn	GCR	2 X 300.00	Jun 1967 Sep 1967	
SGHWR (Steam generating heavy water reactor)	Winfrith	HWLWR	92.00	Oct 1967	
Wylfa	Wylfa Head, N.W., Wales	GCR	2 X 420.00	Nov 1969 Sep 1970	
USA					
Shippingport-1	Shippingport (Pa.)	PWR	90.00	Dec 1957	
Dresden-1	Morris (Ill.)	BWR	200.00	Oct 1959	
Yankee	Rowe (Mass.)	PWR	175.00	Aug 1960	
Indian Point-1	Buchanan (N.Y.)	PWR	265.00	Aug 1962	* 7
Big Rock Point	Big Rock Point (Mich.)	BWR	70.30	Sep 1962	
Humboldt Bay-3	Eureka (Calif.)	BWR	68.50	Feb 1963	
N Reactor (NPR)	Richland (Wash.)	LWGR	800.00	Dec 1963	
Peach Bottom-1	Peach bottom (Pa.)	HTGR	40.00	Mar 1966	
San Onofre-1	San Clemente (Calif.)	PWR	430.00	Jun 1967	
Haddam Neck (Connecticut Yankee)	Haddam Neck (Conn.)	PWR	575.00	Jul 1967	
LACBWR (La Crosse boiling water reactor)	Genoa (Wisc.)	BWR	50.00	Jul 1967	
Oyster Creek-1	Toms River (N.J.)	BWR	650.00	May 1969	
Nine Mile Point-1	Scriba (N.Y.)	BWR	625.00	Sep 1969	

Name	Location	Type	Net output MW(e)	Criticality date	Note
USA (continued)					
Robert Emmett Ginna-1	Ontario (N.Y.)	PWR	490.00	Nov 1969	
Dresden-2	Morris (Ill.)	BWR	800.00	Jan 1970	
HB Robinson-2	Hartsville (S.C.)	PWR	700.00	Sep 1970	
Millstone-1	Waterford (Conn.)	BWR	625.00	Oct 1970	
Point Beach-1	Two Creeks (Wisc.)	PWR	497.00	Nov 1970	
Monticello	Monticello (Minn.)	BWR	545.00	Dec 1970	
Dresden-3	Morris (Ill.)	BWR	800.00	Jan 1971	
Palisades-1	South Haven (Mich.)	PWR	700.00	May 1971	
Quad Cities-1	Cordova (Ill.)	BWR	800.00	Oct 1971	
Vermont Yankee	Vernon (VT.)	BWR	513.90	Mar 1972	
Quad Cities-2	Cordova (Ill.)	BWR	809.00	Apr 1972	
Point Beach-2	Two Creeks (Wisc.)	PWR	497.00	May 1972	
Pilgrim	Plymouth (Mass.)	BWR	655.00	Jun 1972	
Surry-1	Gravel Neck (VA.)	PWR	788.00	Jul 1972	
Maine Yankee	Wiscasset (ME.)	PWR	790.00	Oct 1972	
Turkey Point-3	Turkey Point (Fla.)	PWR	693.00	Oct 1972	
Browns Ferry-1	Decatur (Ala.)	BWR	1065.00	Aug 1973	
FT. Calhoun-1	Fort Calhoun (Neb.)	PWR	457.00	Aug 1973	
Indian Point-2	Buchanan (N.Y.)	PWR	873.00	May 1973	
Oconee-1	Seneca (S.C.)	PWR	841.00	Apr 1973	
Oconee-2	Seneca (S.C.)	PWR	886.00	Nov 1973	
Peach Bottom-2	Peach Bottom (Pa.)	BWR	1065.00	Sep 1973	
Prairie Island-1	Red Wing (Minn.)	PWR	530.00	Dec 1973	
Surry-2	Gravel Neck (Va.)	PWR	788.00	Mar 1973	
Turkey Point-4	Biscayne Bay (Fla.)	PWR	693.00	Jun 1973	
Zion-1	Zion (Ill.)	PWR	1050.00	Jun 1973	

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* 2 Converted from PHWR to BHWR in 1968 and back to PHWR in 1971.

* 3 Electricity produced is shared equally between Belgium and France.

* 4 Power output includes 82 MW(e) from fossil superheat.

* 5 Electricity produced is shared between Spain and France.

* 6 Initial rate 350 MW(e) electrical output, now 150 MW(e) for desalted water production (1.20E + 08 liters/day).

* 7 Reactor equipped with oil-fired superheater.