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ENERGY STRATEGIES

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PREFACE

Based on the analytical work of the IIASA Energy Program, this paper is an early effort to synthesize our knowledge on energy demand, energy resources, and constraints for the deployment of new technologically defined energy options.

The long term supply problems are basically interpreted as a consequence of the level of global energy consumption and the exhaustion of either fossil reserves or environmental capacity, on the one hand, and the limited ability of the energy economy to substitute for fossil energy on the other. Thus the global system and the challenge of today's energy engineering are directly interlinked by the dimension of time.

Forthcoming reports on energy strategies will also embrace the geographical dimension. Within the established framework for an adequate timing, they will contribute to the layout of technological options on a regional level. Key consideration will be given to the transfer of resources, the embedding of fuel cycles, and the exchange of production factors with a consequent flow of goods and services between regions, the problem being the closure of regional economic balances. It is only with this information at hand that we can hope to arrive at energy strategies that are both operational on national levels and consistent with the overall global constraints.

ABSTRACT

The amount of fossil energy reserves and resources suggests a transition to an energy supply system that is based on a quasi-infinite fuel supply. Several options exist for this transition such as the nuclear breeder or solar power. Strategies for transitions have to meet a certain demand for energy. A simple but global scenario is given for such energy demand with emphasis on low demand in conjunction with fossil fuels. Consideration is given to the constraints of such fossil energy production and emphasis is put on the CO_2 problem. This allows a rough understanding of the time scale of such transitions. In view of the timing of the transition the various options for quasi-infinite supplies of energy are considered and priorities of a number of physics tasks are conceived.

ENERGY STRATEGIES

INTRODUCTION

Dealing with the energy problem today requires considerations in many directions and a related synthesis--the energy problem is a problem of energy systems [1]. A good starting point for looking at energy systems is the question of fossil-energy resources. Table 1 gives representative numbers for orientation. World resources of oil and natural gas are of the order of 400 billion tons of coal equivalent, those of coal are 20 times larger. A large

Table 1. Fossil energy resources.

	FRG	Western Europe	Middle East	USA	World
Coal & Lignite $[10^9$ t SKE$]^{x)}$	258	422	–	2,459	9.294
Oil & Gas $[10^9$ t SKE$]$	0.43	15	160	50	400 ? Possibly More

$^{x)}$1 t SKE (German coal unit) $\hat{=}$ 2.73 x 10^{10} Watt/sec.

share of the oil resources is in the Middle East. It should be realized, however, that the energy value of existing resources of coal in the Federal Republic of Germany, for instance, is larger than that of the amounts of oil in the Middle East. Similarly, it should be realized that exceedingly large amounts of coal are located in the US, the Soviet Union and, to some extent, also in China.

Table 2 gives the numbers of Table 1 after they have been divided by consumption rates, on the assumption of 10kW-years per year and capita

Table 2. Ratio of reserves and total consumption.[x]

	FRG	Western Europe	USA	World
Coal and Lignite (Years)	385	120	1,105	204
Oil and Gas (Years)	0.9	4.2	22	8.8

[x] 10kW per capita, population of 1974.

(or, simply, 10kW/capita) and the population of 1974 in the areas considered. The final numbers are then in years. At 10kW per capita, the world population of 1974 could live for 204 years by using only coal if all resources were shared equally, the population of the US for 1105 years if all the US coal were consumed in the US, etc. Similarly, one sees that the world could live on oil and natural gas for only 8.8 years and the US for only 22 years. Such a consideration may help us to appreciate more easily the significance of the numbers of Table 1, although there is no physical relevance to the calculated time periods.

Data on fossil-fuel resources represent a complex problem in their own right. Only a very minor part of the total resources has been proved and recoverable; other resources are only probable or considered possible. Recoverability is a function of the costs that can be afforded and costs are, in turn, strongly related to the production technology available and to the environmental and other constraints that are put on such production. These aspects have been fully appreciated only recently. The McKelvey classification of reserves and resources, as given in Table 3, helps to illustrate these differentiations. It is a two-dimensional plot with the abscissa representing the degree of certainty of existence and the ordinate representing the feasibility of economic recovery. It should be noted that the numbers in Table 1 (and also in Table 2) refer to the upper rather than the lower limits of the total resources. They were taken from the World Energy Conference 1974 in Detroit [2]. It is not the purpose of this paper, though, to go into these problems in greater detail. This was done, for example, at a recent conference at the International Institute for Applied Systems Analysis [3]. Instead, we are looking at production costs and prices of energy. Table 4 gives the numbers for 1964 in $/barrel of oil equivalent. The most striking feature is the low production costs for oil in the Middle East. Together with more complex market features, they resulted in low oil prices and helped to conquer a tremendous market share for oil at the expense of coal. In Western Europe, oil now has a share as high as

60% while, at the beginning of the fifties, its share was almost insignificant; then Europe lived mostly on coal. Any other technology such as nuclear had great difficulties in becoming competitive. It was as recent as the years 1964/1966 that nuclear power from light-water reactors achieved a commercial breakthrough.

Table 3. USGS–USBM reserves/resources classification (1974).

<table>
<tr><th colspan="2"></th><th colspan="5">Total Resources</th><th></th></tr>
<tr><th colspan="2"></th><th colspan="3">Identified</th><th colspan="2">Undiscovered</th><th></th></tr>
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<tr><td colspan="2">Economic</td><td colspan="3">Reserves</td><td colspan="2"></td><td rowspan="3">Increasing degree of economic feasibility ↑</td></tr>
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← Increasing degree of geologic assurance ——

Table 4. 1964 production costs and prices of energy in $/barrel.

	Coal Hard Coal FRG	Oil Middle East	Nuclear Heat, LWR	Solar
Production Cost	4.5	0.15	4.0	n.a.
Price for Large Consumers	4.5	2.5	n.a.	n.a.

n.a.: not applicable.

Table 5 illustrates the situation of 1975. Oil from the North Sea is at $2–3/barrel, coal at $10/barrel equivalent, and nuclear energy at $8/ barrel equivalent. Very optimistic estimates for solar power claim figures at $11/barrel. Coal, nuclear and solar appear at almost the same level. The sudden fourfold price increase of oil from OPEC countries has a complex background. Nevertheless, it should be noted that an important aspect of this increase to $11/barrel was the desire to bring energies into focus that could replace oil [4]. The oil supplying countries do realize that, with the present trend, they would be sold out within 40 years or so and so they want to change that.

Table 5. 1974 production costs and prices of energy in $/barrel.

	Coal (Hard Coal, FRG)	Oil (North Sea)	Nuclear (Heat, LWR)	Solar (Tower Concept, Austria)
Production Cost	10	2–3	8	11 (Design Estimate)
Price for Large Consumers	11	16	n.a.	n.a.

The remarkable thing is that at $10/barrel a whole variety of alternatives become actually or potentially feasible. If we call $10/barrel expensive and the oil-production costs of the Middle East of less than $1/barrel cheap, then one may observe that we are amidst a quantum jump that leads us from a state of cheap energy which is resource-constrained to a state of expensive energy which is virtually not resource-constrained.

Indeed there are four to five options for such a virtually not-resource-constrained supply of energy. Table 6 emphasizes this point. All units are given in Q (which equals 10^{18} BTU or 33.5 TW-years). World-energy consumption today is 0.25 Q/year. Coal has 200 Q, nuclear fission on the basis of breeding is on the order of 5×10^6 Q, solar energy is practically infinite, fusion is very similar to the fast breeder, and geothermal (i.e. the dry heat of the earth crust) may have 5000 Q or so. There is technological maturity, however, only for coal at its present scale of use and for nuclear fission power. All other technologies, including those for coal at a truly large scale still have to be developed or are being developed. Such development must be oriented towards side effects or systems effects. They will, in the final analysis, constitute constraints that replace the resource constraints of the state of the energy problem before the quantum jump. In the case of coal, there are pollution and safety problems, together with the social aspects of very hard working conditions. For nuclear fission, it is radioactivity mostly from fission products; for solar, it is severe land requirements; for fusion, it is radioactivity mostly from 14 MeV neutron activation; and in the case of geothermal, the restraints are perhaps pollution and risks of earthquakes. All these effects are side effects when the scale of energy production is within certain limits, but they become a predominant aspect when the scale of energy production becomes truly large [1].

Table 6. Options for 'unlimited energy supply'.

($1Q = 10^{18}$ Btu)	Reserves	Technological Maturity	Side Effects
Coal	200 Q	Mature at Present Scale To be Developed for Large Scale	Unfavorable Working Conditions Land Requirements CO_2 and Other Pollutants
Fission (Breeder)	$\approx 5.10^6$ Q	Sufficient for Power Plants Not yet Sufficient for Large Scale Fuel Cycle	Storage of Fission Products Emission of Radio Nuclides
Solar	∞	To be Developed for Large Scale	Land Requirements Materials Requirements Climatic Disturbance ? Storage and Transportation
Fusion (D - T)	$\approx 10.10^6$ Q	To be Developed	Storage of Activated Material Emission of Radio Nuclides
Geothermal	5.10^3 Q (? ? ?)	To be Developed	Storage of Waste ? Emission of Pollutants ? Earthquakes ?

In the case of nuclear fission power, this is exactly what the nuclear engineering community is experiencing. It is a major task of systems analysis to identify these side effects and to understand the resulting constraints.

What is the present consumption of energy? Figure 1 shows the number of countries and the percentage of the total population as a function of energy consumption. Some 72% live with less than 2kW/capita, a significant number of countries with as little as 0.2kW/capita, while 6% have more than 7kW/capita, the US being at 11kW/capita. Another 22% have energy consumptions between 2 and 7kW/capita, central Europe is at 3–5kW/capita. This situation cannot prevail. What we have to expect and what we have to prepare for instead is a less dramatic consumption scenario, as given in Figure 2. Rightly or wrongly, there will probably always be a distribution of energy consumption, but it must be a smooth one with an increased mean value. In Figure 2 we suggest, for instance, 5kW/capita as mean value. Studies of energy demand in connection with life-style scenarios are important for making such assessments. In fact, at IIASA [5] and elsewhere related studies have been done. From these studies it may be concluded that 5kW/capita is a moderate target. It may well be that the figures eventually turn out to be much higher. If, for instance, desalination of large amounts of sea water turns out to be necessary, the figure could easily double [1]. Similarly, a possible use of very low grade ores could lead to higher figures. But in this paper we wish to take a most cautious approach and would therefore like to account as much as possible for energy conservation. 5kW/capita would imply an almost zero growth situation for Europe and, if applied to the US, a reduction. It is, however, not our purpose to pursue the aspect of energy consumption and conservation in geater detail. Instead, this paper concentrates on energy strategies for meeting such a demand. Obviously, many different strategies can be envisaged. Again we intentionally choose the most cautious approach by assuming that the world should make the greatest possible use of coal, which would be uniformly available throughout the world, i.e. without embargoes in a fully developed free world trade. Such a scenario may not be realistic, but it will help us to understand what a very modest approach to energy strategies would look like. In view of this goal, the explanations given so far could be considered as a zero-order approximation to the problem. Starting from this view, we will try to improve and to elaborate on the next approximation of possible strategies heading for the stated objectives.

THE MOST MODEST APPROACH TO AN ENERGY STRATEGY

Having assumed a mean value of only 5kW/capita for all future times and for all the world, it is then most important to take reasonable estimates for the lowest asymptotic world population level. Such an estimate is given in Figure 3. It makes extended use of the data given by the Secretary General of the UN World Population Conference, Bucharest, August 1974. In 1975, the world population is close to 4 billion people. On the average, there is a gross reproduction rate of 2. The world today is in a state of reduced and still falling mortality, an achievement that has led to the so far experienced

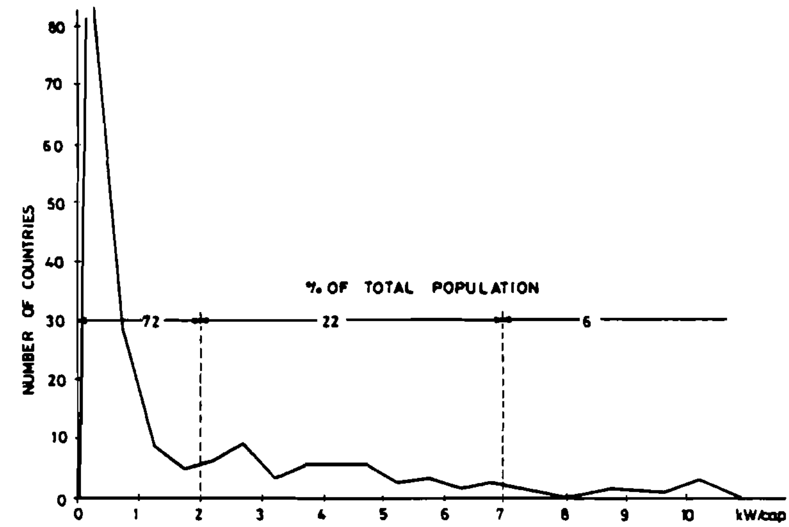


Figure 1. Distribution of per capita energy consumption in 1971 (Source: J.-P. Charpentier, IIASA).

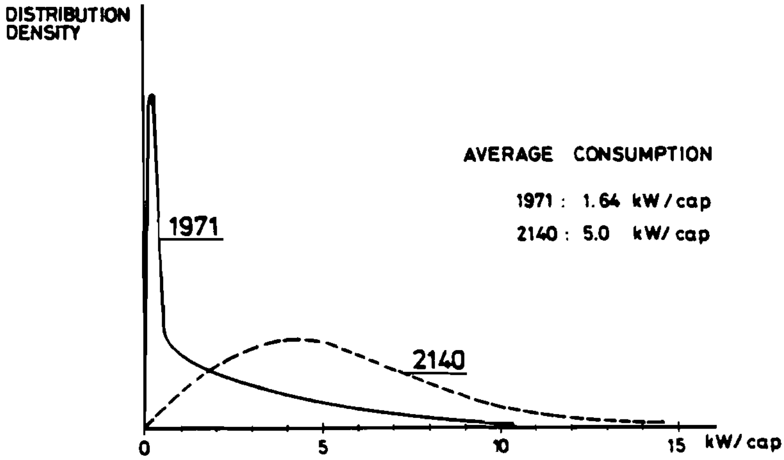


Figure 2. Distribution of per capita energy consumption (Source: J.-P. Charpentier, IIASA).

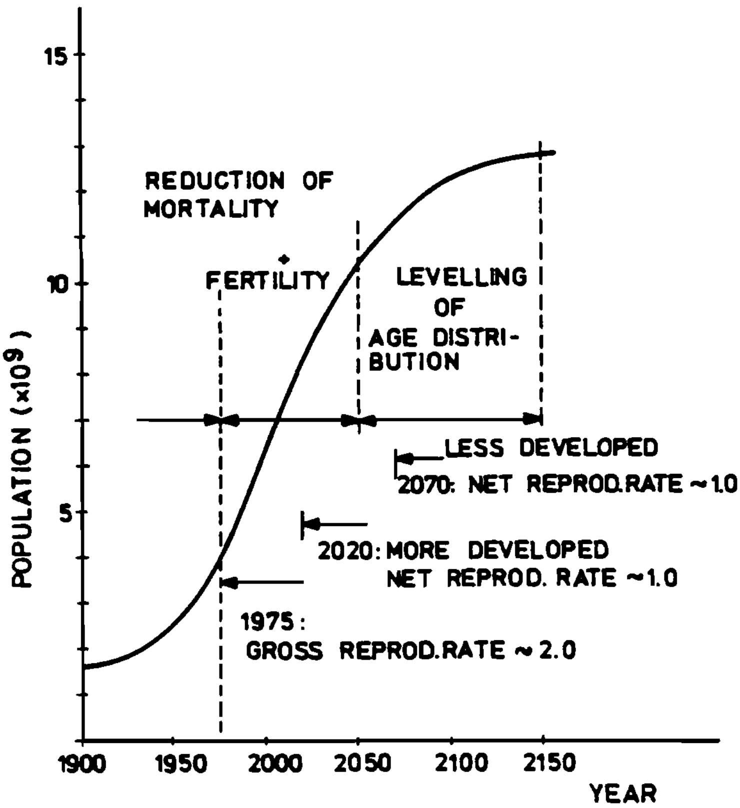


Figure 3. World population growth (Source: UN World Population Conference, Bucharest, August 1974 – Report of the Secretary General).

population increase. For the more developed part of the world, the UN report expects that the trend of reduction of fertility will continue and that for the year 2020 a net reproduction rate of 1 will be reached, while for the countries now belonging to the less developed parts of the world a net reproduction rate of 1 is expected as late as the year 2070. It is stressed that these are optimistic estimates based on an immediate adoption of policies aiming for a low population. During a population increase, the average individual is relatively young as compared with equilibrium conditions. Therefore, for the year 2070 the population growth will continue since those already born will marry and have children. Therefore, only after 2140 or so, can we hope to level off at perhaps 12 billion people.

By multiplying the population by the average per capita consumption of energy, the global energy consumption can be estimated. We learned from Figure 1 that the present average of per capita energy consumption is at 1.8 kW/capita while we assumed 5 kW/capita for the future equilibrium state. What should we assume for the transition towards our scenario? Let us consider total energy growth rates of 2%, 3% and 4.5% as outlined in Figure 4. A 2% energy growth rate corresponds to the present population growth rate and would leave us at the present average value of 1.8 kW/capita for the next 75 years or so. Only thereafter would we slowly approach the desired value of 5 kW/capita. By contrast, the present growth rate during the past

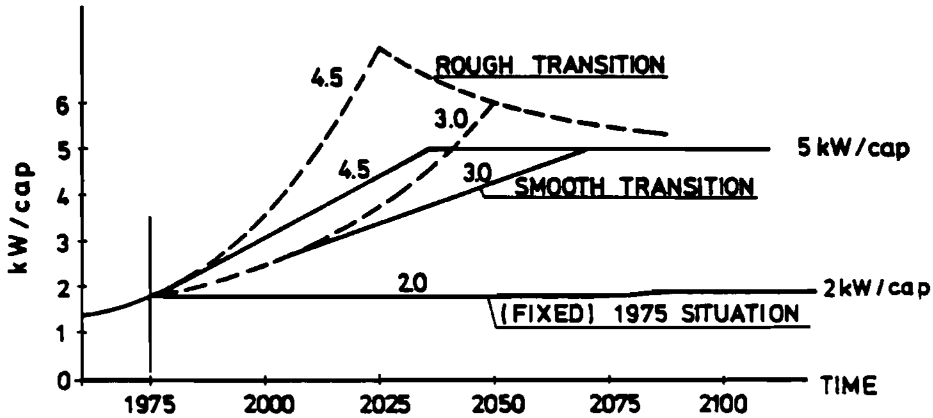


Figure 4. Projected per capita energy consumption (world average) (Data from UN Population Projections, March 1974).

decades was at 4.5%. This value diverges significantly from the population trend. If we continue with 4.5%/capita to around 2010, we would have 5 kW/capita; thereafter, we would have to introduce zero growth abruptly or we would have a swing over. A 3% growth rate that is steadily reduced after the year 2010 leads to a fairly smooth transition, as is indicated in Figure 4 Let us recall that such growth rates are world averages. A 3% energy growth rate would be 1.5 times higher than the present population growth rate. In this paper, we abstain from the temptation to consider distribution problems of such growth rates. Concentrating on the rough transition with an initial growth rate of 4.5% and the smooth transition with an initial growth rate of 3%, the obvious step then is the integration of such energy demand. This is done in Figure 5. In this scenario, 5 kW/capita leads to a global power demand of 64 TW or 2Q/year as compared with current values of 7.6 TW or 0.25 Q/year. For the sake of completeness, the intermediate plateau of 24 TW for a 2% level of energy increase is also indicated. In Figure 6, such a demand is compared with the fossil energy reserves of Table 1. A distinction is made for coal, where the first 20% of the total figure are referred to

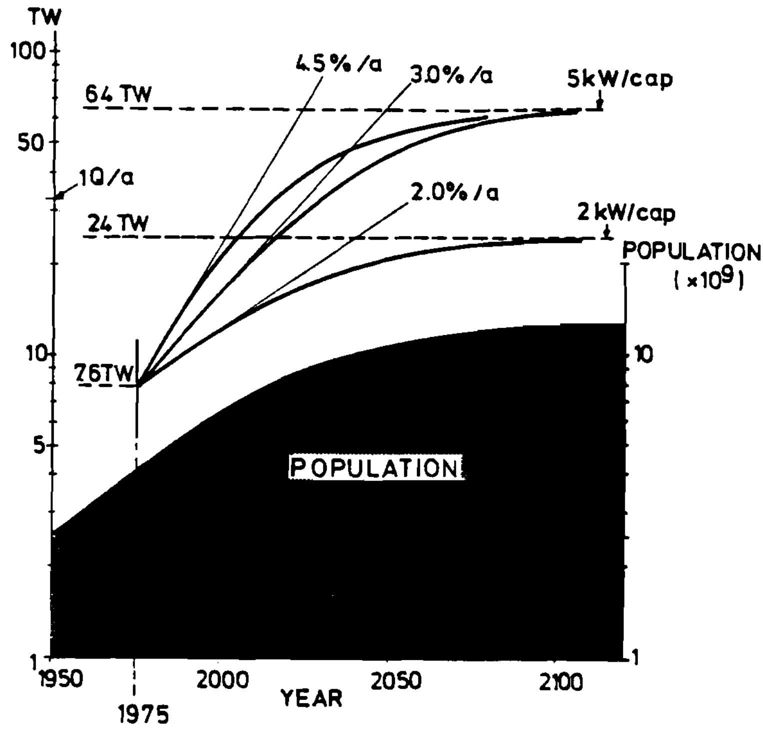


Figure 5. Global energy scenarios.

separately. This is in line with the explanation given with the McKelvey diagram. Not all of the coal resources are accessible. Perhaps equally important is the problem of the recovery factor. Even accessible resources must be harvested economically using a certain technology. This always limits the recoverability and leaves the majority of the resources in the ground: 20% as a world average for the amount of coal that may conceivably be used, therefore, is a high and, in the present context, a conservative figure. It is hard to overestimate the importance and the implications of this point. Figure 6 then indicates that we would be out of oil and coal (combined) by the year 2030 according to the scenario with the rough transition characterized by an initial growth rate of 4.5%. The smooth transition with an initial growth rate of 3% gives us only 8 more years while the unacceptable 2% scenario that leaves the world in the unacceptably low 2kW/capita state for a long time gives as much or as little as 34 additional years. At the

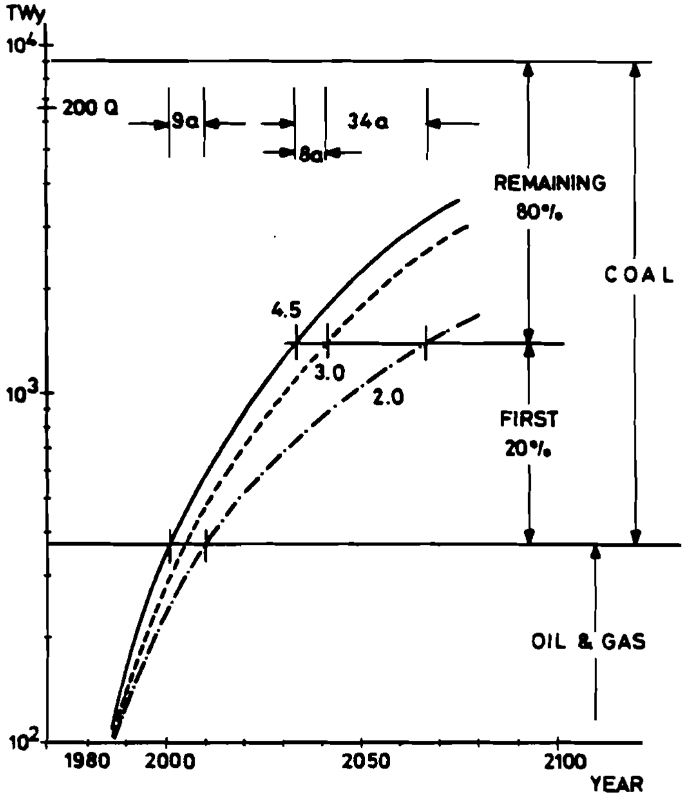


Figure 6. Fossil energy reserves and cumulated energy consumption.

utilization ceiling for oil and gas, the largest time difference (i.e. the 4.5% case compared with the 2% case) is as small as 9 years. This is consistent with similar results for other strategies. Often the benefits of growth-rate reductions and, therefore, of energy conservation are overestimated. What these accomplish is to buy time, which usually is less than one assumes. Further, buying time only makes sense if full use is made of it.

CONSTRAINTS

The observation has been made that side effects may constitute constraints that can be as effective as resource constraints, and it was further observed that such systems-constraints become effective when energy is produced on a truly large scale. We would now like to illustrate this for the case of the present modest approach to an energy strategy. Let us take it for granted that effective abatement measures are technically available and will take care of pollution associated with the burning of carbon. Thus, all SO_2, NO_x, fluorides and other coal and oil residuals would be radically retained and thereby taken care of. This is an unrealistic assumption but is in line with the trend of this paper for the most modest approach to an energy strategy. It must be mentioned, though, that in terms of costs this assumption is a severe one rather than a modest one. Even with these unrealistic assumptions there is still the release of CO_2. It is the fuel waste of fossil fuels which is a principal feature of their use. With today's technologies, the CO_2 is released to the atmosphere. Already today there is an increase of CO_2 in the atmosphere amounting to 10–15% that is due to the burning of fossil fuels. The CO_2 content would increase by a factor of 10, which leads to a non-negligible probability that the climate would be severely affected. Sunlight would come in, but infrared radiation does not fully go out at the normal average surface temperature of the earth. To reinstall equilibrium, the surface temperature must increase slightly. The temperature increase at issue is of the order of $1-2^{\circ}$ C, and this could indeed have drastic consequences. It is tempting to go into greater detail here, but this has been done elsewhere and quite often [6]. Over the last two years, this CO_2/climate concern has increased as it has become apparent that the ocean accepts less atmospheric CO_2 than was previously assumed [7]. Let us therefore consider the CO_2 reservoirs and the CO_2 flow, as given in Figure 7. The size of the cubes indicated there is proportional to the CO_2 content of the part of the atmosphere or ocean considered. The deep layer of the ocean contains the overwhelming part of the CO_2: it is the natural place for the final waste disposal of fossil-energy production. The mixed layers of the oceans still contain more than five times the amount of CO_2 that is present in the troposphere, while the stratosphere, in turn, contains five times less than the troposphere. The crucial point is the low transfer rate from the troposphere to the mixed layer of the ocean and, what is far more important, the low transfer rates into the deep sea. The mixed layer, therefore, acts as a buffer that can be loaded and then no longer accepts CO_2 from the troposphere. The troposphere may, therefore, be considered as a kind of balloon that can be filled only once. Only the small transfer rates into the deep layers of the oceans would allow for a continued CO_2 transfer. Figure 7 also indicates the CO_2 transfers into the 'balloon'. By the year 2020, its order of magnitude compares with the CO_2 content of the troposphere. Nordhaus [8] considered cases where 50%, 100% and 200% of the original CO_2 content of the troposphere are introduced as upper limits that are acceptable from a climate impact point of view. At this stage of reasoning, we must clearly point out that these percentages are somewhat arbitrary. Science is not yet in a position to indicate somehow responsibly acceptable levels of CO_2 content in the troposphere. To that extent the reasoning is not stringent. However, there is good reason to be concerned about the impacts of fossil power just as there are reasons to be concerned

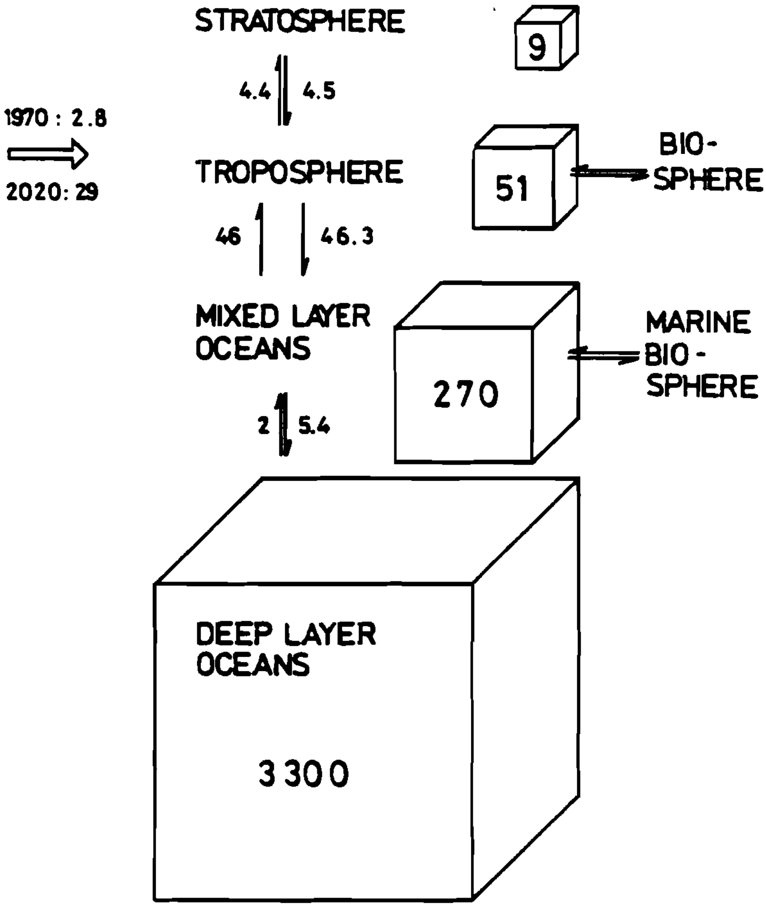


Figure 7. CO_2 reservoirs and CO_2 flow (C contents in 10^9t, C flow in 10^9t per year (1970 values) (Source: Machta).

about the impacts of nuclear fission power. If the same yardstick were applied to fossil power as is applied to nuclear power, one could also ask for a moratorium on fossil power until all open problems are solved. This we definitely do not recommend. Instead, we want to indicate what the side effects and systems problems could look like. Figure 8 shows the permissible fossil power level as a function of time for the various limits considered here. The situation is critical around the year 2050 when the tropospherical 'balloon' is filled, and the traditional fossil-waste disposal site is used up. In the case of 200% CO_2 above the natural background, the maximum power is at 70 TW

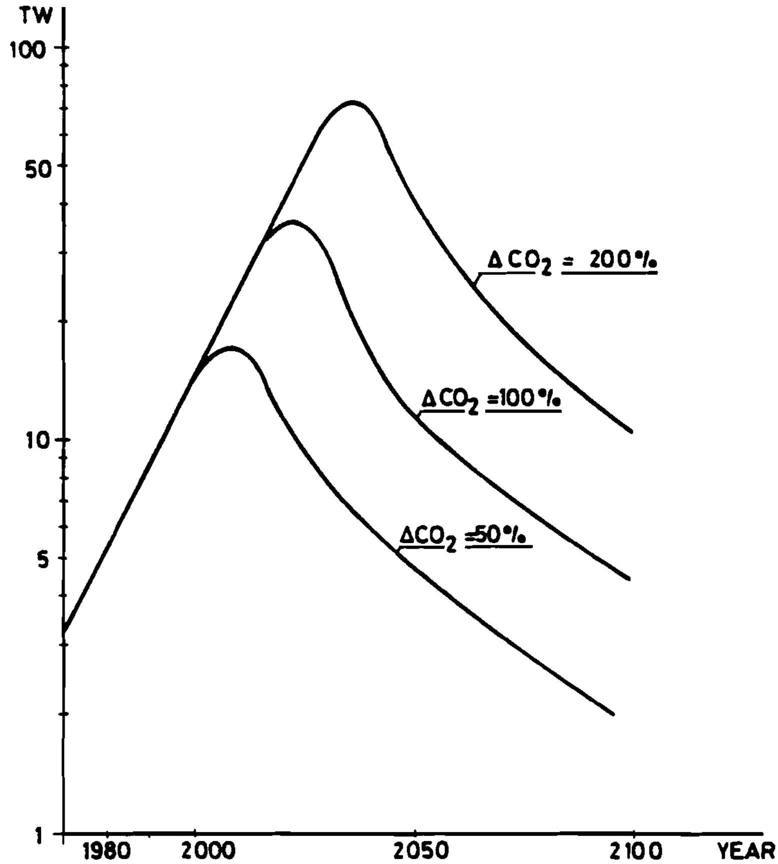


Figure 8. Necessary control of fossil energy consumption, if supplied in the form of coal, to stay below certain CO_2 levels in the troposphere (Source: W.D. Nordhaus).

and the year is 2050. Of course, it is lower and earlier at 50%. Table 7 now shows the integration of the coal consumed. The side effects of the climate impact constrain the permissible coal consumption to something like 1800TWy if a limit of 200% additional CO_2 were set. In the three cases of our scenario in Figure 6, 200% addition of CO_2 occurs between 2041 and 2085. Thereafter, the permissible fossil power level goes down while, by contrast, our considerations call for some further increase. The consequence is obvious: one or more non-fossil energy sources have to enter the scene. We will have a look at the various candidates later on. At this moment, we will instead take up a slightly different line of reasoning.

Table 7. Integrated values of consumed coal until a rapid decrease in CO_2–emission has to be enforced.

Δ CO(%)	50	100	200
Coal Consumed (TWy)	500	950	1800
Achieved in the years between x)	2,005 – 2,015	2,022 – 2,044	2,041 – 2,085

x) If world energy supply is based on coal.

Often it is explicitly or implicitly assumed that new inventions, a new product or a completely new technology could grow without limits. Once an innovation has been made, it can be used. This is not so. The bad thing is that it takes time. Marchetti [9] at IIASA has studied world energy-market penetrations, which are shown in Figure 9. The market share F is the percentage

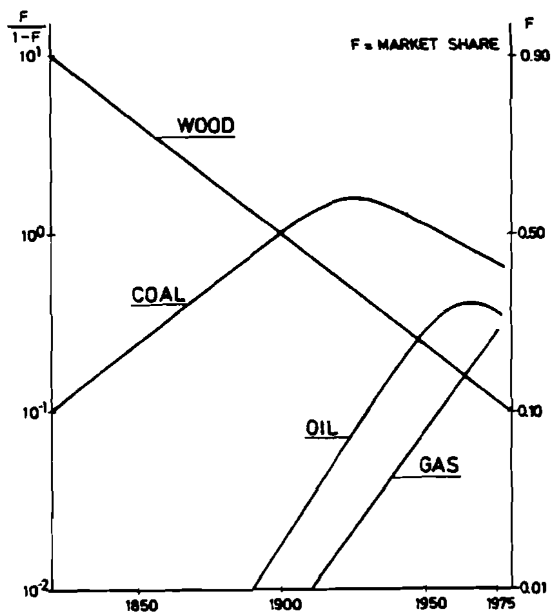
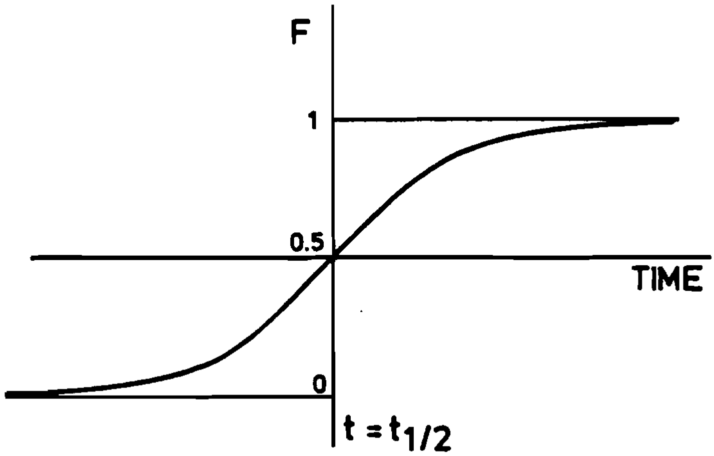


Figure 9. World energy market penetrations (Source: C. Marchetti, IIASA).

of the market held, F/(1-F) is the ratio of percentages of the market held to that not held. Wood dominated the market in 1800. It took 160 years before wood lost 50% of the market. It was conquered by coal which, in turn, was pushed out by oil and gas. It should be noted that the straight line in the diagram represents a logistic curve which is often used in such studies. The mathematics of the logistic curve is given in Figure 10. One may consider this the law of exponential growth in a limited environment, as indicated by its differential equation. At IIASA such considerations are employed for some forecasts [9, 10]. In Table 8, we now give the periods

$$F = \frac{1}{1 + e^{-\alpha(t - t_{1/2})}}$$



$$\frac{1}{F}\frac{dF}{dt} = \alpha(1 - F)$$

F = RELATIVE FRACTION

α = CONSTANT

t = TIME

Figure 10. The logistic curve, growth in a limited environment.

Table 8. Penetration periods. ΔT: period for gaining or losing a market share of 50% (in years).

	Wood	Coal	Oil	Gas
ΔT World	160	170	78	90
ΔT USA	60	66	52/135 x)	95 x)

x) Note: $\frac{1}{135} + \frac{1}{95} = \frac{1}{57}$.

for gaining or losing a market share of 50%. For more recent technologies, such as oil and gas, the world value is at 80–90 years[for the US the figure is lower, namely, 60 years. It certainly is a prudent approach not to assume that new technologies that will be necessary as future complements to and substitutes for fossil power could be introduced faster than technologies were introduced in the US in the past. In principle, faster introductions can be considered but one should be more than cautious in making such an assumption. We cannot elaborate on this here. So we now assume 60 years for the achievement of 50% of a power-production share and turn back to our original reasoning. 50% of a power-production share and turn back to our original reasoning.

We now consider the difference between the energy demands for our global energy scenario and the permissible fossil power level or, in other words, the demand for non-fossil power. It is given in Figure 11. Beyond the year 2030, there is a quick increase and beyond 2100 most of power production would be on a non-fossil basis. The 50% mark, where 50% of the energy demand has to be met by non-fossil power, occurs in 2035. Again, the difference between the two scenarios for 3% and 4.5% initial growth rates is only insignificant. The point now is this: if we subtract 60 years for the introduction period of the new technology, we end up at the year 1975. This looks like a preconceived conclusion. Let me emphasize that this is not so, we were ourselves surprised. Therefore, the time for action on new non-fossil technologies or a technology that bypasses the CO_2 constraints is now, within the limits of the scenario considered.

Let us recall what we did:

1) We considered a scenario with plausible features. Indeed, other scenarios have to be considered as well. While such scenarios do not predict the future, they enhance and clarify the thinking.

2) The present scenario stresses the possible impact of energy conservation and tends to emphasize fossil-fuel power as much as possible.

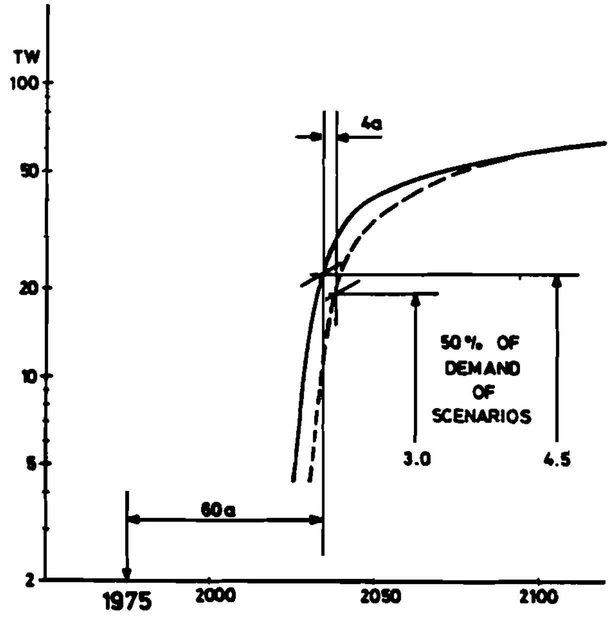


Figure 11. Required non-fossil power production: time for action.

3) It concentrates on the CO_2 issue while arbitrarily and probably unrealistically disregarding the pollution problem that is due to SO_2, NO_x and other ingredients of fossil fuel.

4) Further, it quite realistically stresses the aspect of the dynamics of introducing a new technology on a large and significant scale.

5) The main conclusion is that, even under these restrictive assumptions, a new non-fossil power source must be introduced. The time to do that is now, in the seventies.

6) In reality, the pressure for the introduction of such new technologies is very probably greater than demonstrated here. The reasons are the following:

   - 5 kW/capita is probably too low a figure. New life styles in connection with larger populations may well require desalination, for instance.
   - Uniform distribution of the coal and oil available all over the globe is unlikely. Regionally, the pressure for non-fossil power will be much larger and will set in earlier.
   - Other side effects, not only CO_2, will also come out as constraints.

Let us now at least briefly examine the various candidates for such new technologies from a systems point of view.

SYSTEMS ASPECTS OF NEW TECHNOLOGIES FOR LARGE-SCALE ENERGY PRODUCTION

Before at least briefly reviewing the various possibilities for large-scale energy production, it is necessary to have a look at the final uses of energy. Too often physicists only think of electricity. Figure 12 shows the final energy use in the Federal Republic of Germany as of 1970. This may be

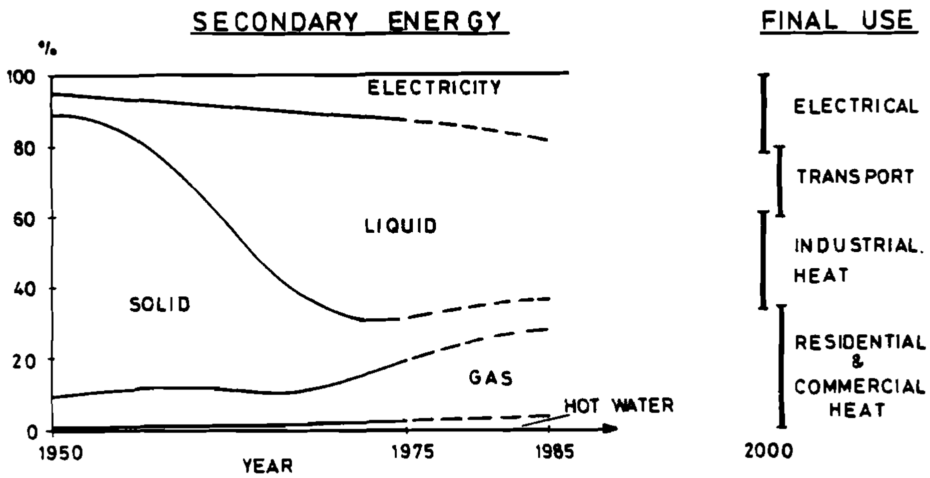


Figure 12. Partitioning and final use of secondary energy (FRG).

considered of some relevance to our purposes. The FRG consumption of energy is at 5 kW/capita and our studies at IIASA indicate that in this range the shares of final energy uses do not differ very much for widely different countries [5]. The largest consumer is the sector on residential and commercial applications, whose largest portion of consumption is low-temperature-level heat. The heat below 200°C for all sectors makes up as much as 47%. By contrast, all electricity consumption together only amounts to about 10% of the final end uses under present circumstances. It should be noted that 10% on the secondary side relates to 25% on the primary energy side. Process heat above 200°C, and this includes automobiles, accounts for about

42%. While it is apparent that the electricity share can be raised, it is nevertheless clear that a new energy source must be in position to produce more than electricity. Let us therefore consider the various forms of secondary energy and their evolution in time. These are shown in Figure 13. One recognizes the trend from solid fuels to liquid fuels and then to gas. Gas and

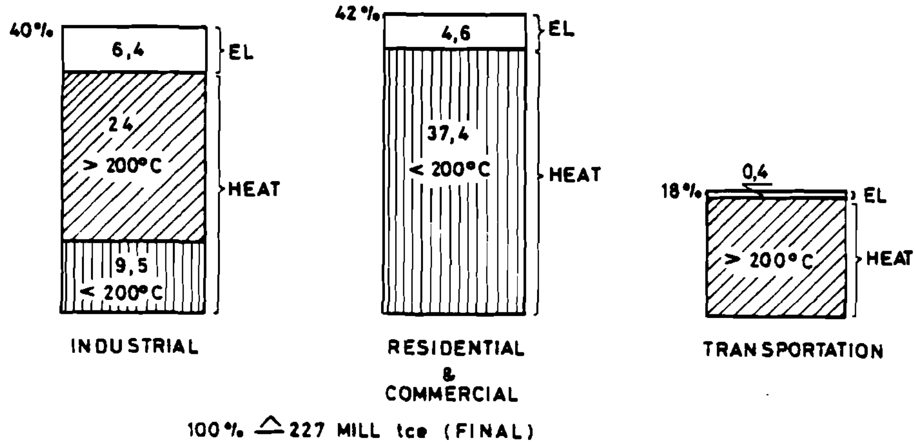


Figure 13. Final energy use in the FRG (1970).

electricity are both expanding in their market share as they are most versatile and easy to handle. Liquid fuels will perhaps be concentrated in the transportation sector. All this requires investigation and explanation in greater detail. The point of importance here is that, besides electricity, a new energy source must be usable for production of a gas as a secondary fuel. The most likely candidate for this is hydrogen made by splitting the water molecule. Burning hydrogen leads to water and is thereby highly acceptable in environmental terms. There is much excitement today about hydrogen for energy applications. The excitement seems to be well founded [11], and this area should certainly receive wide attention. It appears that the difficulties in handling large amounts of hydrogen are not the main obstacle for the introduction of a hydrogen technology. Rather, it is the large-scale production of sufficiently cheap hydrogen. There appear to be two ways of achieving such production. One is low-temperature thermal decomposition (thermolysis). A temperature of 3000°K is required if water molecule splitting is to be achieved on a thermal basis, which on a large scale is not feasible technically. DeBeni [12] and Marchetti developed the idea of dismantling the molecule in stages at more moderate temperatures, which on balance results in a splitting of water. Chemical agents enter the picture and act, on balance, as catalysts (see Figure 14). The goal is to find a process that only involves fluid or gaseous chemical agents which are abundant and environmentally acceptable. The other way is that of electrolysis. However, there has been much objection to it since the overall efficiency of primary energy use is as low as 25%. But let us recall what we said in the beginning: the new energy resources are not or almost not constrained, so that such a low efficiency may well be acceptable if other aspects are favorable. It may well be that a combination of both methods for water splitting turns out to be the best solution. Bowman [13] has proposed such a combination (see Table 9) and Westinghouse is pursuing this now. The thermal heat is applied at moderate temperatures, that are below 1000°C in the first stage, while a remainder is applied

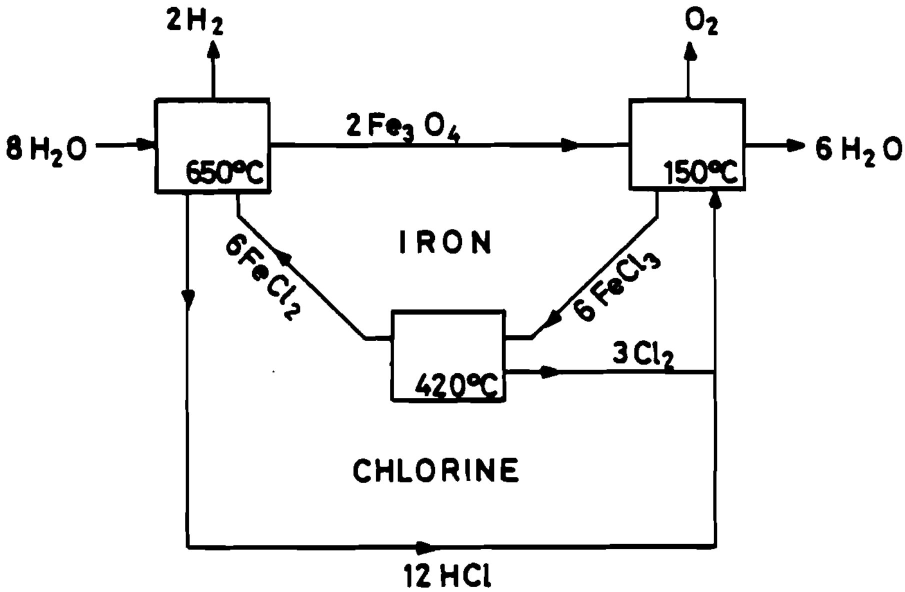


Figure 14. Mark 9 process of thermochemical water splitting.

Table 9. Thermolysis/electrolysis of water.

1.) $H_2SO_4 \xrightarrow{\text{Thermal}} H_2O + SO_2 + \frac{1}{2} O_2$

2.) $2H_2O + SO_2 \xrightarrow[\text{lysis}]{\text{Electro-}} H_2SO_4 + H_2$

After: M.G. Bowman (Los Alamos)

as electricity. This requires new kinds of technical electrolysis. A fallback position in our efforts for the use of a gaseous secondary energy carrier is ammonia, the technology of which is well developed. Equally, the gasification of coal may be considered in this context for shorter or for more extended time periods.

more extended time periods.

The reason why we stressed these aspects is that they are common to almost all conceivable modern, non-fossil energy systems. They may perhaps be more important than the development of new energy sources beyond the ones that are already available.

As far as non-fossil primary energy is concerned, nuclear fission power is the most developed one. It achieved commercial competitiveness in the mid-sixties and is almost entirely geared to electricity production. The present generation of nuclear power stations utilizes only a fraction of the uranium, roughly 1%. The most common reactor type is the Light Water Reactor (LWR); the Heavy Water Reactor of the CANDU type (the Canadian line of reactors) must certainly also be mentioned. The two types of the second nuclear reactor generation are the Fast Breeders and the High Temperature Reactors. Fast Breeders breed fertile material such as U^{238} or Th^{232}, thereby utilizing natural uranium or thorium up to approximately 70 %. The Fast Breeder has achieved a high degree of maturity and is now developed on an almost commerical scale. The French prototype Phenix, for instance, which is at 250 MWe, has been in successful operation since the spring of 1974; the 1200 MWe version of this development line is now going into construction.

High Temperature Reactors produce high temperatures. In 1974, at Jülich, FRG, the AVR reactor was in routine operation at 950°C. Their large-scale development is as favorable as that of Fast Breeders. In looking at scenarios for the more distant future as they are considered in this paper, and in realizing their slow or even no growth features, it becomes natural to think of a combination of both, Fast Breeders and High Temperature Reactors. One may consider this combination with the idea that the breeding gain of the breeder reactors would be used to provide the net fuel requirements of High Temperature Reactors. Such net requirements of, say U^{233} exist as this reactor type does not breed. If the Fast Breeder had, for instance, a radial blanket containing thorium, this fuel-cycle coupling would be possible. It is then natural to have the Fast Breeder produce electricity and the High Temperature Reactor produce a gaseous secondary energy carrier, say hydrogen. This is outlined in Figure 15. Such schemes and, in particular, the problem of timely transitions from today's features of energy supply to such asymptotic reactor scenarios have been studied recently by Häfele and Manne [14].

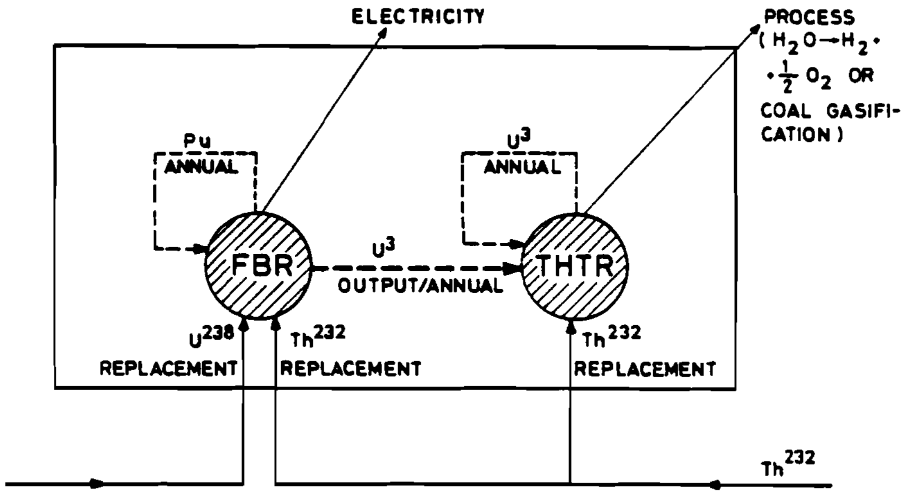


Figure 15. Asymptotic integrated reactor system.

These authors used a medium size linear programming model for the allocation of power from various sources such as coal, oil, and gas to the LWR, Fast Breeder and High Temperature Reactors. Such reactor strategies are therefore different from those that were studied in the sixties, when the sequencing of various reactor types within the scope of electricity production was studied [15].

The next candidate for a new type of energy production is coal. This may be surprising in view of what was said before. Indeed, in the long-range future, coal may not be usable in view of the CO_2 constraints on the atmosphere. But the CO_2 does not necessarily have to go to the atmosphere.

Marchetti's idea (IIASA) to avoid such atmospheric releases is this: consider large energy parks in the open sea that are located in ocean streams which by-pass the mixed layer and end directly in the deep sea. There is such a place around Gibraltar. Below the sea surface is a stream that comes from the Atlantic and enters the Mediterranean while, at greater depths, a counter system with a higher salt concentration flows from the Mediterranean, enters the Atlantic and quickly falls into the deep sea. If coal were burned in such an energy park, the CO_2 could be directly released to the lower ocean stream and the CO_2 constraint could accordingly be eliminated. Of course, pipeline connections for such CO_2 dumping could also be considered. It should be realized that a debate is forthcoming that will deal with the question to what an extent nuclear power should be produced in energy parks [16]. We now see that there may be broader reasons to follow such a concept. In such energy parks, coal and/or nuclear power could be converted into a gaseous secondary energy form which could then be transported and stored. One now also has a much better vision of the importance of modern forms of secondary energy. It is obvious that such a scheme still requires much analysis, but new thinking is essential. While such advanced schemes for burning coal may not yet be necessary for tomorrow, modern forms of mining coal may be required much sooner. High recovery factors, together with acceptable working conditions at production rates ten times as high as today, may well force us into radically new technologies. The liquefaction of coal *in situ* by ammonia or methanol [17] or other solvents may indicate the kind of breakthroughs that are required for greatly augmented coal utilization.

Another candidate for new technologies is solar power. In Table 10, the insolation is given for three places: Vienna (Austria), Paris (France), and Phoenix (Arizona). The insolation at Vienna is about 3 kWh/m^2 day. This figure is typical for our latitudes. At Phoenix in the US, only a factor of two is gained and the insolation is at 6 kWh/m^2 day. However, these figures are yearly averages, the real difference between regions like the Southwest of the US and Austria lies in the difference between the maximum and the minimum values. For Phoenix the ratio is as low as 2 while for Vienna it is close to 7. A truly large scale use of solar power does require large-scale energy

Table 10. Sunlight in some cities (kWh/m^2–day) (Löf et al., 1966).

City	January	April	July	October	Annual
Vienna (Austria)	0.8	3.9	5.3	1.9	2.96
Phoenix (U.S.A.)	3.5	7.5	7.6	5.3	6.05
Paris (France)	0.9	3.9	5.3	1.9	3.04

storage to bridge the summer/winter cycle. We consider hydrogen to be an excellent candidate for this. The conversion efficiency of solar power to electricity is between 10% and 20%. If 1000MWe, today's usual size for a modern power station, is to be produced on the basis of solar power, large land requirements have to be met, as shown in Table 11. At 10% and 3 kWh/m^2 day, we need 80 km^2; at 20% and 5 kWh/m^2 day, 24 km^2. Such large requirements may be difficult to meet in regions like Europe. The impact on ecology, the

Table 11. Land demand for solar energy (km^2 for 1 GWe) (average power).

System Efficiency	Insolation[x)]		
	3	4	5
0.1	80	60	48
0.2	40	30	24

[x)] kWh/m^2–day.

settlement pattern and consequently the whole infrastructure of a country have to be carefully studied. Similarly, the implied changes to the albedo and their conceivable impact on the climate have to be investigated too. Again, one can visualize constraints for the use of this power source that is unconstrained in terms of fuel resources. All this looks much better in regions like North Africa. But this invokes energy transportation on a truly large scale. Again, a secondary gaseous energy carrier may be a good solution. It should be noted how vastly different schemes for the use of solar power can be. This is indicated in Table 12. On the 3-10 kW level, the solar house is

Table 12. Four alternatives of solar energy.

- Solar House ~ 3 – 10kW
- Tower Concept ~ 100MWe
- Photovoltaic, Many Small Sites
- Ocean Thermal Gradient
  10 GWe ?

a fairly near-term opportunity with warm water as its prime output. The tower concept opens the 100MWe domain: a tower of perhaps 200m hight is located in the center of an area of $3km^2$ that is covered with mirrors which heat a boiler on top of the tower. Photovoltaic cells inherently allow us to make use of land that is available only in bits and pieces, a hectare here and half a hectare there. They also allow for cloudiness but they tend to be expensive. There is a fourth mode of solar power that should be borne in mind: the ocean thermal gradient in the mixed layer. It requires the large-scale application of low temperature Carnot cycles using freon or ammonia as a secondary working fluid. As vast areas are available on the sea, this may be a possibility. We should bear in mind, however, the constraints that may become visible with large-scale implementation. The effects upon the ecology of these areas may be a related question, for instance. Not very much will be said about nuclear fusion. It is more similar to nuclear fission than one thinks [18]. As long as the D-T reaction is employed, the resource situation of lithium is very similar to that of uranium, and the energy is then offered in terms of 14MeV neutrons. This always leads to neutron activation. The hope is to find a structural material that largely avoids such activation. It is a personal view that we may expect a factor of 30-100 improvement in the curies per watt thermal that have to be handled in a fusion reactor, as compared with a fission reactor. This difference is quantitatively significant but does not alter the situation qualitatively as compared to fission. Nor can we say much about geothermal here, the dry heat of the earth crust, as the hot water and steam sources all over the globe make up only for 60GW or so. There is a thermal gradient of about $35^{o}C/km$ in the earth that allows for energy harvesting which is similar to that described above for the ocean. Yet the heat conductivity of the earth is small. What one has to expect is a tight lattice heat-exchanger arrangement over wide areas and in great depths. At IIASA, we will look into such schemes only in 1976. We will not discuss this here any further.

After this crude review of the various TW technology candidates, one further remark must be made: none of these can be expected to have a conversion efficiency as high as that for the use of oil today. By conversion efficiency, we mean the ratio of useful energy required by the final energy consumer to the amount of primary energy which is necessary to produce that useful energy. This holds for the production of hydrogen, gasification of coal, fusion power when converted into hydrogen, ocean and earth thermal gradients, etc. Let us favorably assume a 50% additional loss upon conversion. This then leads to an increase from 5kW/capita to maybe 10kW/capita and, accordingly, to the power production scenario of Figure 16. The shaded area indicates both the required increase and the domain for improvements by technology and physics that could lead to less drastic increases above 5kW/capita.

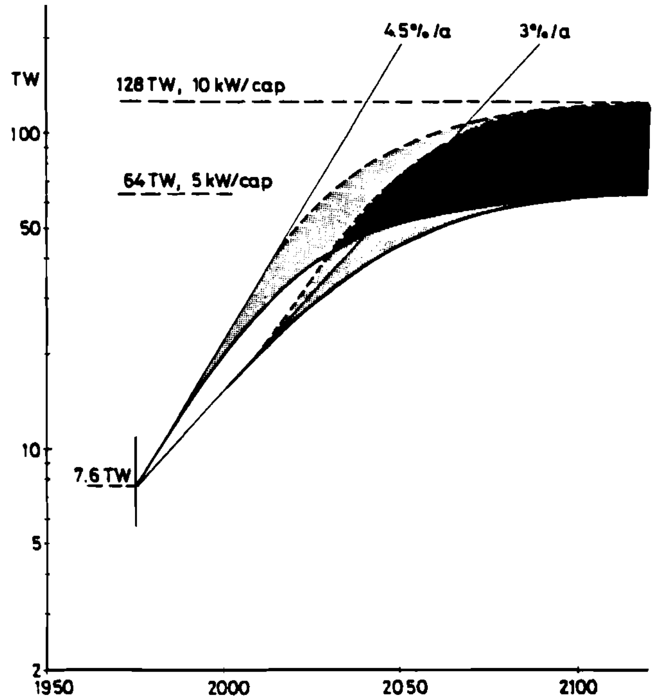


Figure 16. Required additional power production for non-fossil (10kW/cap).

TIME FOR ACTION, PHYSICS TASKS

We saw that in our decade we must take actions that are designed not only for the commercial short-range-future--though they continue to be important, of course--but that also take into account the long-range future. This challenge is new. It comes from the fact that the world is getting smaller and the population larger.

It is then very important to reflect on the sequence of decisions to be faced, one after the other. It seems convenient to plot such a sequence of decisions in the form of a decision tree. At IIASA, we are doing this more and more extensively. As our own thinking is constantly evolving, we cannot claim to have arrived at a fairly broad and conclusive decision tree. Nevertheless, we have elaborated such a decision tree that covers a partial aspect of the problems. It is shown in Figure 17. The decision tree is embedded in the time power plane and is meant to evolve into these dimensions accordingly.

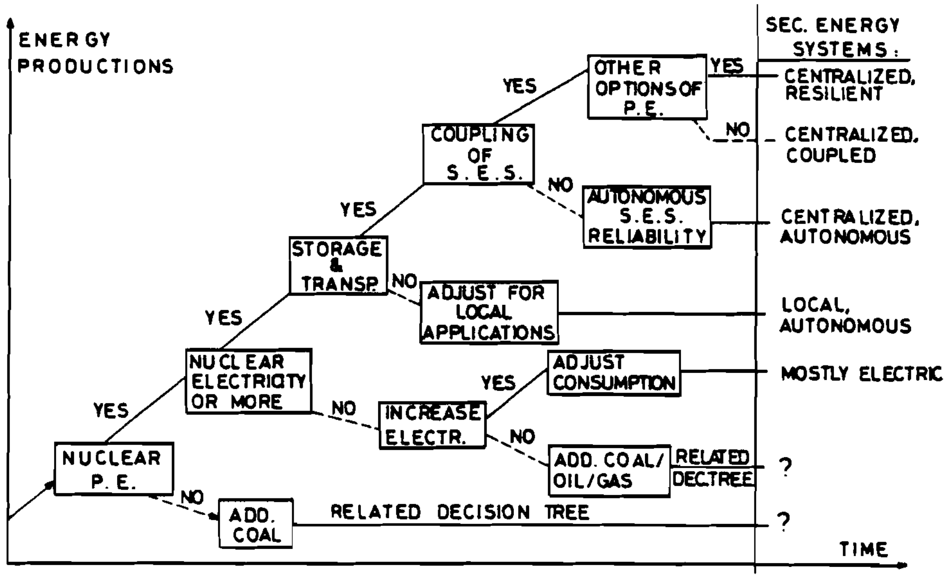


Figure 17. A decision tree for advanced energy systems.

The first question is the following: nuclear power, yes or no? If no, then other alternatives come in. Similar decision trees have then to be considered for each such alternative. If yes, then the next question is: nuclear power for the production of electricity or more? If not, then the next step is to face the question: is one satisfied with the present share of electricity or not? If yes, nuclear electricity may have a share as high as 25% of the primary energy demand. If not, consumption has to be adjusted to additional uses of electricity and the share may rise to as much as 40 or 50%--but then there is a limit. If more than nuclear electricity is desired, the next question concerns the full scale infrastructure for storage and transportation of a gaseous fuel. If the answer is negative, only local and sufficiently large-scale applications of nuclear-process heat can be envisaged. This may be not more than 7-10% [16]. If it is positive, the next question to be answered is: coupling of the secondary energy systems or not? If not, then two autonomous secondary energy systems will evolve, electricity and gas, both of which have to be sufficiently reliable and self-sufficient. If yes, the reliability will increase or become cheaper and it will be possible to store electricity in that way. Such coupling has several advantages. It will be more easily possible to accept other primary energy sources, in particular solar power which somehow goes better with hydrogen than with electricity. But also shipments of secondary fuels from energy parks could more naturally be accepted. If such other options come in, we have a diverse, redundant and thereby resilient energy system. If not, we may face the problems of centralization.

We do not claim that all these so envisaged decisions have to be faced at once. But one's thinking should be organized in this or a similar fashion. This could mean that, in early decisions, lower in the tree, one could look for ways that keep future options open. Here some decisions on energy parks that are forthcoming may be crucial.

What, then, are the physics tasks for the TW domain? How could we physicists best contribute in view of such energy strategies? Table 13 lists a few of these tasks. No claim for completeness is made. Storage and transportation will in almost any event be a key to modern TW technologies and

Table 13. Physics tasks for the TW domain.

o	Storage of Energy	
o	Transportation of Energy	
o	Coal Liquefaction in Situ/Coal Gasification	
o	Physics of the Atmosphere	Climate Control
o	Dynamics of the Ocean	
o	Hydrogen/Electrolysis/Thermolysis	
o	*Cheap* Solar Power Receivers	
o	Fusion	

should therefore be studied. The most obvious candidate here is storage and transportation of a gas. But storage and transportation by means of superconductivity, for instance, may be equally important as it is still within the domain of electricity. Fuel cells and electrolysis in the GW and TW domain are related to this topic, too. The liquefaction of coal *in situ* by liquid solvents, as mentioned earlier, may be crucial for the tenfold larger harvesting of coal when compared with what is done today. Coal gasification is probably a must if coal is to recapture a share of the market under near- and medium-term aspects. It invites a tie between coal and nuclear power, in particular. Perhaps the most urgent topic of all is climate control, as not too much is known in this field. A new theoretical approach to the equations of gas dynamics should be sought. More personally, we feel that the most recent topological methods for looking into the climate without weather calculations appear very promising. But also more physics and related physics data are required, particularly in the field of ocean dynamics. Similarly, our understanding of the physics of the stratosphere must improve. Do we have to expect constraints from that angle or not? Within ten years or so, we should be in a position to give at least a vague answer to the decision makers. Most certainly, hydrogen with all its implications has to be developed. Modern electrolysis in the GW range and beyond, with efficiencies of 80% and more, and temperature ranges between 500°C and 1000°C, must be looked into, as must thermolysis. It should be emphasized that so far our list has not included new power sources. A general trend today is to over-emphasize the importance of the production of energy. But, the adequate handling and embedding of the stream of energy into the atmosphere, the hydrosphere, the ecosphere, and the sociosphere are equally or, under present circumstances, even more important. Even so, physicists must continue to look for devices for harvesting solar power, the salient point of which is that it must be cheap. Work on fusion must continue at the present or an increased rate. There are more tasks, we cannot list them all.

Studying energy strategies reveals big challenges. The time for action is now. We physicists must act, too. But prudently.

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