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FUTURE ENERGY RESOURCES

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During the last few years there have been quite a number of studies on the energy problem. In respect to the US I would like to mention here the report of the MIT policy study group [1], the study of the Ford Foundation [2], the USAEC Report on the Nation's Energy Future [11], and the study of the National Academy of Engineering [12]. The major thrust of these studies is on the near term aspect of the energy problem, which in fact is fuel supply oriented. With only a few years' delay the near term energy problem will be equally oriented toward the problem of capital investments.

The purpose of this paper is to look into the medium and long range future of the resource problem and the related R&D questions. In order to do this it will be helpful to have a quick look at the fossil resources. This is a big problem in itself. Careful distinctions between ultimate resources, recoverable resources and reserves have to be made. Members of the US Geological Survey such as V.E. McKelvey and D.C. Duncan [10] or M.K. Hubbert [9] have to mentioned here. To have an

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order of magnitude orientation and for the purpose of this presentation I refer only to the data of M.K.Hubbert. Figure 1 reports on his data on a world basis. The resources were divided by the 1970 world annual consumption rate (1/4 Q/year, $1Q \equiv 10^{18}$BTU). There is much fossil fuel, if the total amount, aggregated for the world as a whole, is being considered. The evolution of the world's energy demand is shown in Figure 2. The growth rate of industrialized nations, the development of developing nations and, above all, the population growth will lead to an increase by at least a factor of 5 to 12 in the medium distant future. Figure 3 indicates the time periods for fossil energy resources to last if this increased demand is considered. Even at this highly aggregated level the figures now look uncomfortably low. One has to realize that on a more regional basis the outlook is much more grim. This is true for Europe [4] and even more so for Japan. Furthermore, the major component of the fossil reserves is coal and, as has become more apparent recently, shale oil as well. All this stresses the need for further discoveries of reserves and the improvement of related methods.

Nevertheless, there appears to be an option to go for an all coal or shale oil energy economy in certain well endowed parts of the world. We will touch on this point later.

For the world as a whole it is important to realize that there is more than one option for the practically unlimited supply of primary energy in the long run. In Figure 4 these options are identified. Fission by breeding and fusion by breeding (D-T reaction) have the same order of magnitude of fuel reserves.

Contrary to a widespread belief fusion does not have much vaster resources as long as the lithium supply is the limiting factor.

The supply of solar power is practically unlimited in terms of resources, while the supply coming from hot rocks in the earth crust is not so unlimited though still very large.

I would like to make a strong point by saying that the criterion for making a choice between these options, or a choice for a proper combination of these options, will therefore not be resource oriented. Instead, it will be the constraints for the safe handling of large amounts of energy. In other words it will be the side effects of these options that will lead to an adequate choice. There the interaction of energy with the hydrosphere and the atmosphere has to be considered. Besides conversion losses, all energy after degradation is given as heat to the atmosphere. It is important to realize that it is at least to a great extent the moisture in the atmosphere and its vaporization that functions as the heat sink. Atmosphere and hydrosphere are therefore in the same perspective. The cooling water requirements for waste heat upon conversion are already an ever increasing concern. As the water in the run offs comes from the rain and rainfall is a density, this leads to natural limits for the densities of waste heat dumping. The implications of the energy balance for the atmosphere and the hydrosphere probably establish an upper limit for the adequate handling of energy, or possibly better, for the embedding of the flow of energy from its origin through the hydrosphere and the atmosphere. A certain amount of pollution, radioactive or chemical, always goes along with this embedding of the flow of energy. It is mainly the ecosphere that is affected by embedding. So besides the hydro- and the atmosphere the ecosphere also has to be mentioned in this context. However, the domain that should be called sociosphere must also be considered. Here, the problems of establishing standards, benefit/cost/risks ratios, public acceptance, risk evaluation and reliability control are focused on. It becomes painfully clear that the driving forces for technological developments are no longer engineering or economical considerations, but the very soft aspects I mentioned above.

As already indicated, the problem of embedding the energy flow into the hydro-, the atmo-, the eco- and the sociosphere turns out to be the limiting constraint for making use of the otherwise unlimited resources of non-fossil primary energy. One should therefore consider the hydro-atmo-eco- and sociosphere as a finite resource that will limit the production of energy. Much more must and can be said about it. In view of the very severe time limitations for this presentation I will refer only to recent publications in the July/August issue of the <u>American Scientist</u> [8] and the July issue of <u>Minerva</u> [7].

One concludes that the aspects of the energy problem change entirely. In the near term future it is the supply of fossil fuel that is operationally the constraint, in the long term future it will be the adequate embedding of the flow of energy that establishes the active constraints. It is obvious that the transition between these two aspects is extremely interesting and challenging for the analyst. Figure 5 therefore identifies three time phases of the energy problem.

In the remainder of my talk I will concentrate on the question of R&D priorities in view of the transition and asymptotic phases of the energy problem.

Having put emphasis on the transition phase the most obvious question is that of timing. A sequence of systems analysis studies is under way at the International Institute for Applied Systems Analysis in Austria and elsewhere to identify possible strategies for such transitions. The first of these studies, completed recently, considers strategies for the transition from fossil to nuclear fuels [6]; a study on the transition from fossil fuels to solar power is under way. Again, in view of the time limitations this is all I can mention here.

Besides looking at the various causal relationships, it is also striking to view markets and societies from a more phenomenological point of view. Some time ago F.C. Fisher and R.H.Pry of General Electric, Schenectady presented a simple substitution model of technological changes [3]. The logistic curve that is shown in Figure 6 fits with astounding precision empirical data for market penetration such as synthetic fiber, plastics, organic insecticides etc. They considered 17 such examples altogether. In the energy group of the International Institute for Applied Systems Analysis, Marchetti applied this model to fuel substitutions in the US market during the last century.

Figure 7 shows the results. The ratio of penetrated to non-penetrated market shares for each primary fuel is plotted. Until 1972 the statistical data fit the curves perfectly; beyond that date curves are extrapolated assuming that these relations hold. During the last century the prevailing fuel was wood. It was substituted by the advent of coal. Please realize that these considerations are phenomenological. It may be interesting to consider the causal forces for this substitution. One may think of limited resources of wood and the greater convenience of coal and others. But this is not explicit in the model. In the early parts of this century oil began to penetrate the market and to replace coal. It has now reached its maximum and is being replaced by gas. It should be noted that the annual rates of penetration are much the same for the ascending and the descending branches of the penetration curves, and also very similar among the various fuels. It should further be noted that coal is replaced in spite of its large resources. The cause for this must be sought in the convenience of uses, that is, the features of the market. Gas will be replaced if another fuel starts to penetrate the market.

Figure 8 now extends the model by allowing for the advent of nuclear fission. As a forecast one can see the rate of the replacement of gas. If there is only nuclear fission, it is this fuel that has to take over the market and its consumption will accordingly increase.

Let us step back for a minute. It seems that the view prevails in many circles that the priorities of R&D that focus on the medium and long range aspects of the energy problem should concentrate on new resources, say, solar or fusion, and that this must have first priority. I do not think so. Also, there is much concern about whether the industrialized societies shall go into the large scale development of nuclear fission power while other energy sources are in the offing. I feel that in either case the problem of timing and penetrating markets is being underestimated.

Let us therefore assume that by the year 2000 the new fuel solfus will begin to penetrate the market, i.e. it meets 1% of the total primary energy demand. It may be any new ingenious kind of fuel. Actually, solfus refers to either solar or fusion. In Figure 9 the market penetration of solfus is taken into account; it expels nuclear. Figure 10 now summarizes the energy consumption for the various fuels that we have considered here in absolute terms, using the Q unit and with the very modest though not unrealistic assumption of 2% annual increase in energy consumption. The point here is that something in the order of 50Q is handled in the case of nuclear fission, even in the case of the arrival of solfus. It should be realized that processing 50Q of nuclear energy by far exceeds the amount of energy that is handled by the oil industry in the US. I would like to point out that these are early results, and also the interpretation of the GE model requires more work. One can of course also play with the figures, but the qualitative features remain.

The analysis made at the International Institute for Applied Systems Analysis to identify strategies for the transition from fossil to nuclear fuels [6] also identifies the incoming of cost benefits during the forthcoming decades. At a 10% discount rate in present worth evaluations practically all of the cost benefits to be expected are in by 2020 or so, which comes before any sizeable market penetration of solfus (Fig.11).

I would therefore like to conclude that R&D on solfus is indeed a requirement, but contrary to a widespread belief I do not think that it should have first priority.

There is one caveat however and that refers to coal. In terms of a pure resources consideration in <u>certain</u> parts of the world, an all-coal society is conceptually possible for a long time to come. This is very much the case for the US and to a much lesser extent for Germany and a few other countries, but it is not clear whether this is feasible in terms of handling these large amounts of coal, nor whether the socio-economic structures and thus the market can be made to accept this. Furthermore, as we progress into the future we have to wait and see whether the large scale uses of coal in the countries with large resources can be implemented, when in the majority of countries there is little or no supply of either coal or oil.

Let me come to the last point. I do think that a modern and wise deployment of the large energy facilities that the R&D is meant for, and that are to be expected, should keep options open. Options mean fusion, solar, geothermal or even sources that are not anticipated yet. This can, to a large extent, be done if a decoupling of primary and secondary energy takes place [4]. Figure 12 tries to illustrate this. Besides electricity, a synthetic hydrocarbon such as methane or methanol or, even better, hydrogen should be the interface between energy consumption and the provision of energy. Liquids and gases would allow for comparatively easy transportation. This would permit for instance the aggregation of the production of nuclear power in large primary energy parks and would thereby ease the painful problem of siting large power facilities. More important, the infrastructure and the land uses of modern societies would remain uninfluenced by the choice of primary fuels. No longer would primary energy be produced where the consumption is. A supergrid of electrical and pipe-lines would be fed at a few points only. If appropriate, in the more distant future any kind of primary energy, be it nuclear of solfus, can be made to feed the supergrid without drastic adjustment within the infrastructures of modern societies.

It is then along these lines that R&D on solfus is required. If solar power is used on a truly large scale and not only for local space heating, etc., then energy storage becomes a key component of a modern secondary energy system. Hydrogen may be a very good approach to that. Energy storage by electrolytically produced hydrogen could perhaps be gradually used to replace pump storage and could help to introduce a hydrogen economy in a cautious fashion.

Attention should be drawn to the fact that up to now nuclear energy has been more or less exclusively developed for electricity as a secondary fuel. Since February 27, 1974, the AVR reactor of Schulten of the Nuclear Research Center of

Jülich in Germany has operated at 950°C outlet temperature. This allows, among other applications, the consideration of endothermal chemical processes such as the splitting of methane in the presence of water, followed by the transportation of these gases to a chemical reactor for recombination, that is, in effect, the transport of high temperature nuclear process heat over medium distances. I am particularly referring to the EVA&ADAM scheme of methane splitting that is now pursued at Jülich.

Let me come to the conclusion. Priorities for R&D that center on the near term phase of the energy problem have been considered elsewhere in great detail. I can especially agree with the views that have been expressed in the report of the US National Academy of Engineering (see Figure 13). Views on priorities for R&D that center on the medium and long range aspects of the energy problem are given in Figure 14. The data of Figure 12 are given in percentages with the assumption that the R&D budget in question is in the billion dollar range. The first point of emphasis is that the budget for resource oriented R&D should not exceed the 40% level. A major component of that should go into the problems of a responsible, ecologically consistent deployment of a large commercial nuclear fuel cycle. Radioactive waste disposal is only one aspect there. I would like to submit the problem of nuclear parks under this heading. The LMFBR should be similarly strong in the budget, as it is today the only technically feasible source for a practically unlimited supply of energy.

Fusion and solar must be in, solar more than (D-T) fusion from which it differs drastically, as fusion also appears to be plagued by the problems of neutron activation [5]. I feel that this is not sufficiently known.

The second point of emphasis is that R&D on modern secondary fuels should receive the largest share with a view to keeping all conceptually feasible options open and to developing a modern secondary energy system; such a system would decouple the problems of land use, pollution, cooling water, impact on the climate and other system problems from the production of primary energy by providing a supergrid and thereby a concentration of the production of primary energy at a few feeding points.

Synthetic hydrocarbons and hydrogen must be brought in to complement electricity as a secondary fuel, and energy transportation and storage will allow for the decoupling.

The third point of emphasis is the need for R&D that centers around the system problems of embedding the flow of energy into the hydrosphere, the atmosphere, the ecosphere and the sociosphere as outlined above. In other words, R&D is required to tackle the very soft aspects of the energy problem. The 5 % in Figure 12 does not reflect the importance of this type of R&D. It rather reflects the fact that tackling these soft aspects cannot absorb very large amounts of money. Recall that the 100% refers to a budget in the billion dollar range. Systems analysis is one line of R&D, but proper monitoring systems, sociological surveys, exploratory ventures for the hydrosphere and participation in global exercises such as GARP 77 Global Atmospheric Research Program of 1977 [13] should be envisaged.

In presenting these three points of emphasis it must be made clear that the percentage of the various sub-sections should not be taken too literally. These figures are meant to illustrate a qualitative picture; they are not the result of a quantitative analysis.

So let me finish by saying that the environment we are living in and our perception of it are the one ultimately limiting resource. And redeeming the time that is left to us points to the other resource.

FIGURE 1.

WORLD'S SUPPLY OF FOSSIL FUEL

ratio between resources and 1970 world's annual consumption rate

	according to Hubbert: eventually recoverable in years of 1970 supply	%
COAL	770	88
CRUDE OIL	44	5
SHALE OIL	4.5	0.5
NAT GAS	40	4.5
OTHERS	20 (?)	2
TOTAL	878.5	100

FIGURE 2.

WORLD ENERGY DEMAND

(in Q ≡ 10^{18} BTU)

		Q/year
1970	US:	0.07
	WORLD:	0.25

REASONS FOR INCREASING ENERGY DEMAND:

- GROWTH RATE OF INDUSTRIALIZED COUNTRIES
- DEVELOPMENT OF DEVELOPING NATIONS
- POPULATION INCREASE

2000 (?):

LOW: 8.10^9 PEOPLE x 5 KW/ CAPITA = 1.2 Q/year

HIGH: 12.10^9 PEOPLE x 8 KW/CAPITA = 3 Q/year

FACTOR OF INCREASE: BETWEEN 5 AND 12 COMPARED TO 1970

FIGURE 3.

WORLD'S SUPPLY OF FOSSIL FUEL

in years of supply at a rate of:

	according to Hubbert	
	eventually recoverable	years of supply
WORLD TOTAL, 1970	878.5	
TOTAL, 2000 LOW DEMAND	155	
TOTAL, 2000 HIGH DEMAND	73	
TOTAL, 2000 low demand, without coal	21	

FIGURE 4.

FOUR OPTIONS FOR A LONG TERM ENERGY SUPPLY

	SUPPLIES	TECHNOLOGICAL MATURITY	SIDE EFFECTS
FISSION	$\approx 5 \cdot 10^6$ Q	SUFFICIENT FOR REACTORS, NOT YET SUFFICIENT FOR A LARGE SCALE FUEL CYCLE	WASTE DISPOSAL, RELEASE OF RADIOACTIVITY
FUSION (D-T)	$\approx 10 \cdot 10^6$ Q	NOT YET REACHED	DISPOSAL OF ACTIVATED MATERIAL, RELEASE OF RADIOACTIVITY
SOLAR ENERGY	∞	NOT YET REACHED	NEED FOR LARGE AREAS, MATERIALS IMPACT ON CLIMATE?
GEOTHERMAL HEAT AVAILABLE	$\approx 5 \cdot 10^3$ Q (???)	NOT YET REACHED	WASTE DUMPS (?) RELEASE OF POLLUTANTS (?) EARTH QUAKES (?)

FIGURE 5.

THE THREE TIME PHASES OF THE ENERGY PROBLEM

PHASE	CHARACTERISTICS	PERIOD
NEARTERM	ADMINISTRATION OF FUEL SHORTAGES. PREPARATION FOR THE TRANSITION PHASE.	NOW - 1985 (?)
TRANSITION	SUBSTITUTION OF OIL BY COAL, NUCLEAR ELECTRICITY	1985 - 2050
ASYMPTOTIC	BASED ON EITHER: NUCLEAR FISSION, SOLAR, FUSION OR GEOTHERMAL	2000 - forever (?)

FIGURE 6.

PENETRATION OF MARKETS BY NEW TECHNOLOGIES

the logistic curve

$$f = \frac{1}{1 + e^{-\alpha(t-t_o)}} , \qquad \frac{f}{1-f} = e^{+\alpha(t-t_o)}$$

f : FRACTION OF THE MARKET PENETRATED

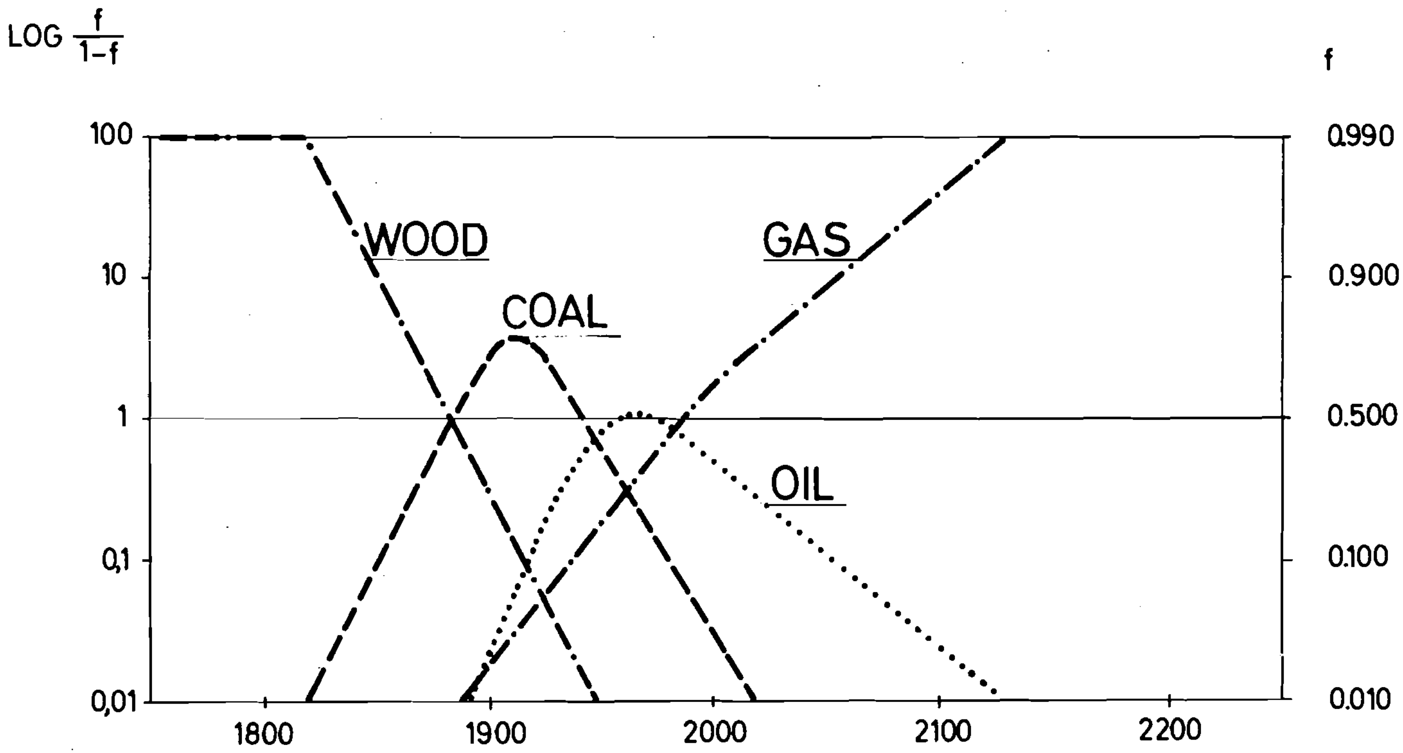
t_o: TIME AT WHICH $f=0.5$

α: CHARACTERISTIC OF TRANSITION

after: F. C. Fisher and R. H. Pry: A Simple Substitution Model of Technological Change

FIGURE 7.

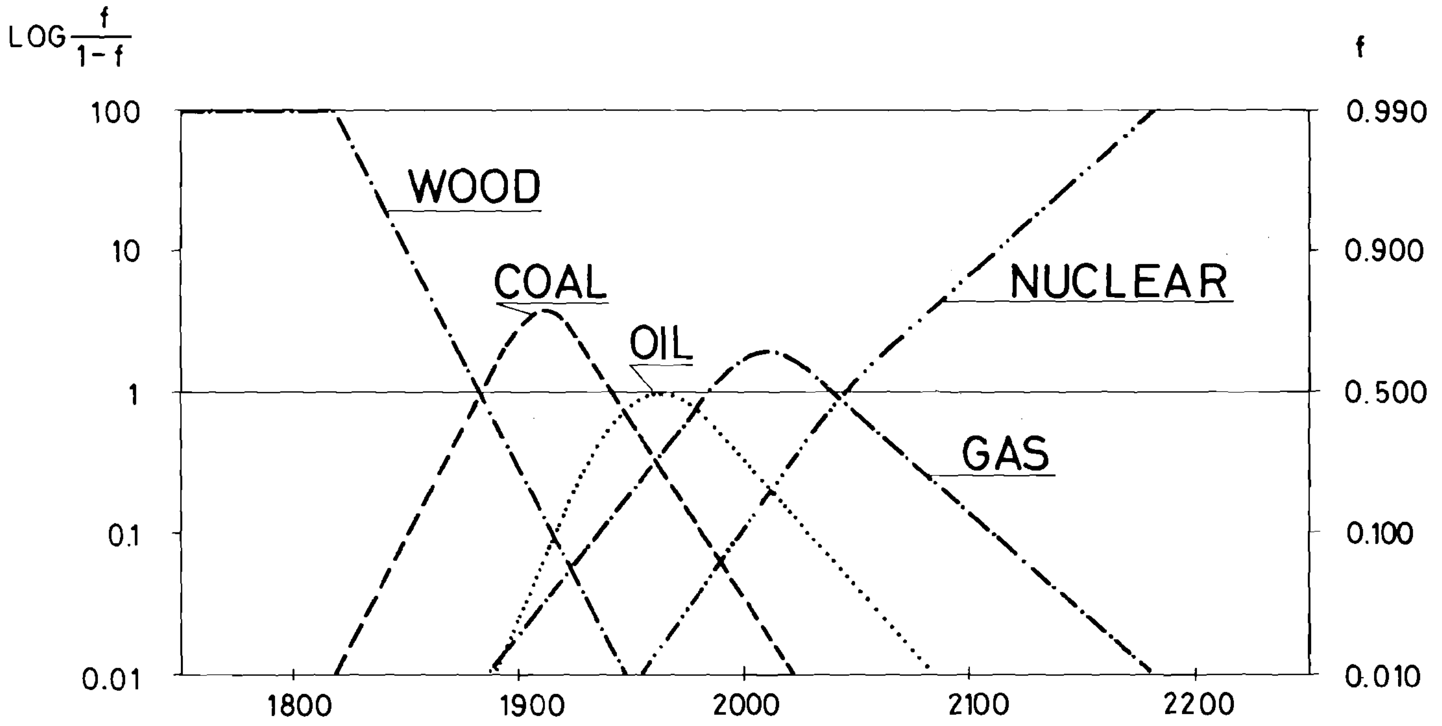
U.S. MARKET PENETRATION OF SUBSEQUENT FUELS



after: Marchetti, IIASA.

FIGURE 8.

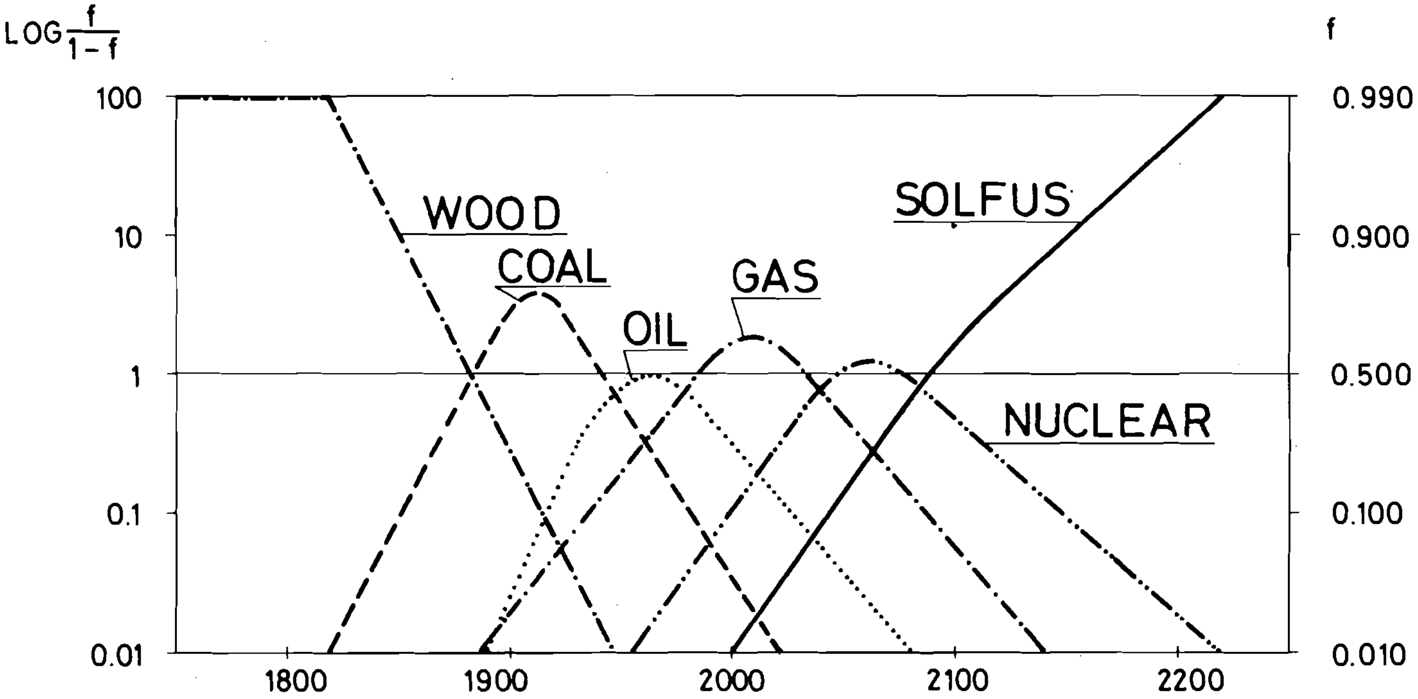
U.S. MARKET PENETRATION OF SUBSEQUENT FUELS



after: Marchetti, IIASA.

FIGURE 9.

U.S. MARKET PENETRATION OF SUBSEQUENT FUELS



after: Marchetti, IIASA.

FIGURE 10.

TOTAL CONSUMPTION, US (2% growth rate)

(in $Q \equiv 10^{18}$ BTU)

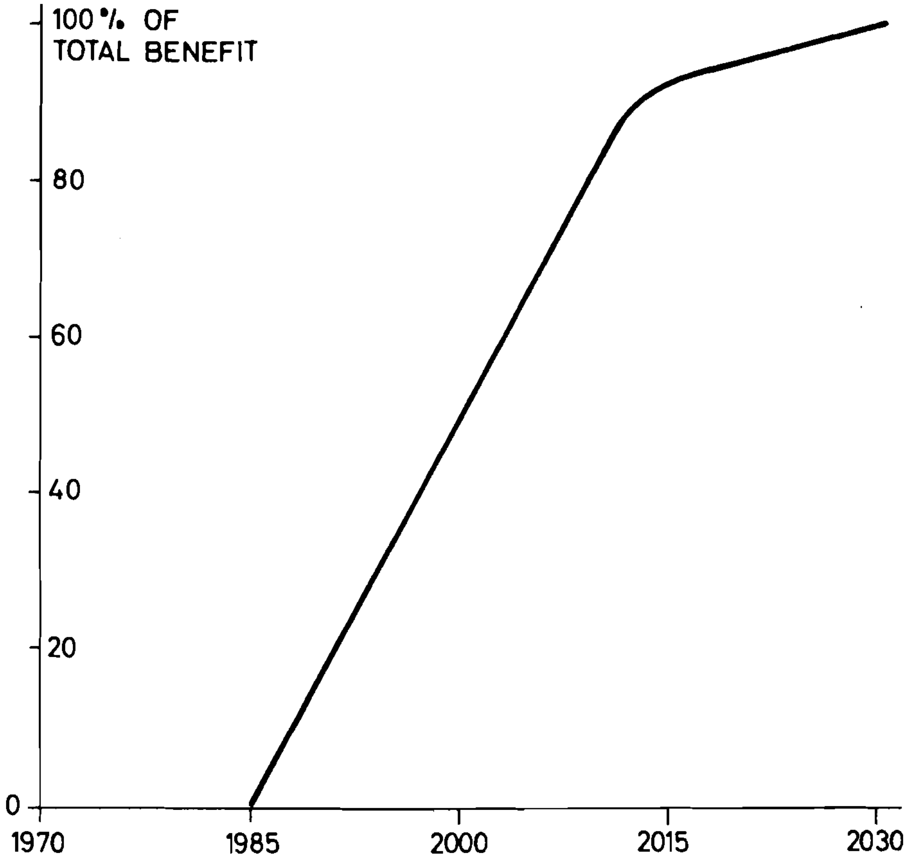
	WOOD, COAL, OIL, GAS	WOOD, COAL, OIL, GAS, NUCLEAR	WOOD, COAL, OIL, GAS, NUCLEAR, SOLFUS
WOOD	0.88	0.88	0.88
COAL	2	2	2
OIL	> 7	3.8	3.6
GAS	> 900	23	14
NUCLEAR		> 900	> 43
SOLFUS			> 900

after: Marchetti, IIASA

FIGURE 11.

CUMULATIVE DISCOUNTED BENEFITS

of thermochemical water splitting by using high temperature nuclear process heat.
(10 % discount rate)



after: Häfele/Manne, IIASA : Strategies For A Transition From Fossil To Nuclear Fuels

FIGURE 12.

MODERN SECONDARY FUELS

- SYNTHETIC HYDROCARBON, MODERN USES OF COAL

- NUCLEAR PROCESS HEAT
- ENDOTHERMAL CHEMICAL PROCESSES, ENERGY TRANSPORTATION BY GASES (R.Schulten: ADAM a. EVA, methane splitting)
- ENERGY TRANSPORTATION
- HYDROG., ELECTROLYSIS, THERMO-CHEMICAL WATER SPLITTING
- ENERGY STORAGE, ELECTROLYSIS

FIGURE 13.

R and D PRIORITIES

for the near and medium near phase

SEE REPORT OF THE US NATIONAL ACADEMY OF ENGINEERING

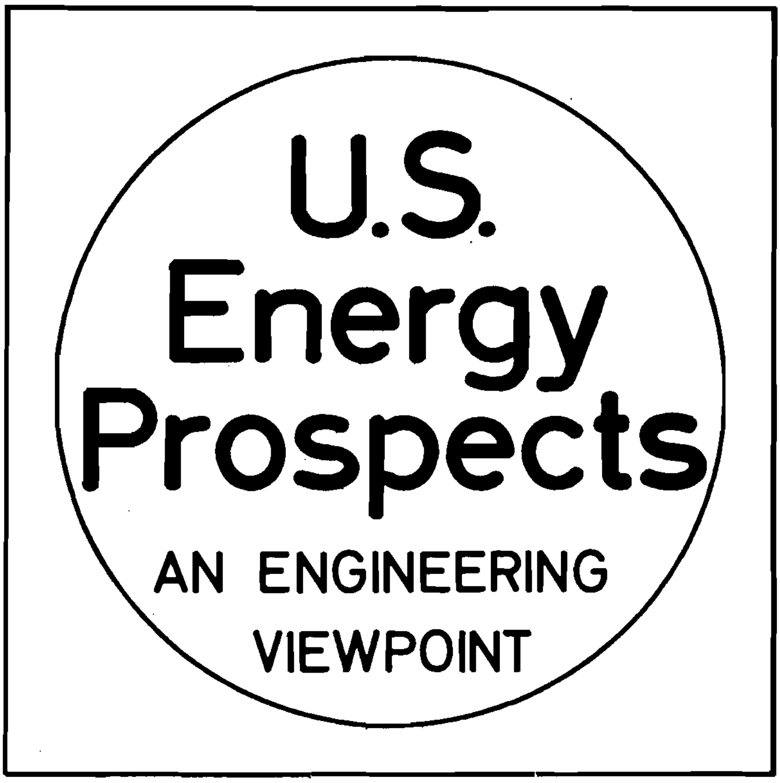


FIGURE 14.

R & D PRIORITIES

for the medium & long range phase
(R & D total funds in the few billion dollar range=100%)

A) RESOURCE ORIENTED R & D: 40%	
● DEPLOYMENT OF AN ECOLOGICAL CONSISTENT NUCLEAR FUEL CYCLE	13%
● L M F B R	15%
● FUSION	4%
● SOLAR	6%
● OTHERS	2%

B) MODERN SECONDARY FUELS:+ 55%	
● SYNTHETIC HYDROCARBONS, MODERN USES OF COAL OR OIL SHALES	10%
● HIGH TEMPERATURE NUCLEAR PROCESS HEAT	12%
● ENERGY TRANSPORTATION	10%
● ENERGY STORAGE	10%
● HYDROGEN, ELECTROLYSIS	13%

C) SYSTEMS ANALYSIS: 5%	
● ECO, HYDRO, ATMO, SOCIOSPHERE	

+with the assumption not to opt for an all coal economy

References

[1] "Energy Self-Sufficiency: An Economic Evaluation," M.I.T., Technology Review, 76 (May 1974), 23-58.

[2] "Exploring Energy Choices," Energy Policy Project of the Ford Foundation, Washington, D.C., 1974.

[3] Fisher, F.C. and R.H. Pry. "A Simple Substitution Model of Technological Change," General Electric, Research and Development Center, Schenectady, N.Y., Report No. 70-C-215, June 1970.

[4] Häfele, W. "Energy Choices that Europe Faces: A European View of Energy," Science, 184 (19 April 1974), 360-367.

[5] Häfele, W. and C. Starr. "A Perspective on the Fusion and Fission Breeders," Journal of the British Nuclear Energy Society, 13 (1974) 2, 131-139.

[6] Häfele, W. and A.S. Manne. "Strategies for a Transition from Fossil to Nuclear Fuels," International Institute for Applied Systems Analysis, Laxenburg, Austria, Research Report RR-74-7, June 1974.

[7] Häfele, W. "Hypotheticality and the New Challenges, The Pathfinder Role of Nuclear Energy," Minerva, 10 (1974) 3, 303-322.

[8] Häfele, W. "A Systems Approach to Energy," American Scientist, 62 (July-August 1974), 438-447.

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

[10] McKelvey, V.E. and D.C. Duncan. "United States and World Resources of Energy," Proceedings, 3rd Symposium on the Development of Petroleum Resources in Asia and the Far East, UN-ECAFE, Mineral Resources Development Series, No. 26, Vol. 2, 1967.

[11] "The Nation's Energy Future," A Report to the President of the U.S. by the Chairman of the USAEC, WASH-1281, December 1973.

[12] "U.S. Energy Prospects, an Engineering Viewpoint," National Academy of Engineering, Washington, D.C., 1974.

[13] World Meteorological Organization and International Council of Scientific Unions. "The First GARP Global Experiment, Objectives and Plans," GARP Publication Series, No. 11, 1973.