CAN THE SUN REPLACE URANIUM?

Alvin M. Weinberg

This report is based on work performed under Contract EY-76-05-0033 between the U.S. Energy Research and Development Administration and Oak Ridge Associated Universities.

ORAU/IEA(M)-77-21
Occasional Paper
July 1977

EHB

DISCLAIMER

CONTENTS

ABSTRACT

Two asymptotic worlds, one based on solar energy, the other based on nuclear energy, are compared. The total energy demand in each case is 2,000 quads. Although the sun can in principle supply this energy, it probably will be very expensive. If the energy were supplied entirely by breeders, the nuclear energy system would pose formidable systems problems — particularly safety and proliferation. It is suggested that in view of these possible difficulties, all options must be kept open.

CAN THE SUN REPLACE URANIUM?*

Fission, in a way, is a fluke. Had man evolved 2 billion years later, when essentially all the uranium-235 had decayed, or had the number of neutrons per fission been less than one, nuclear energy based on uranium reactors would have been all but impossible.** In that event the question I raise, Can the sun replace uranium?, might have been instead, When would we switch from fossil fuel to the sun? What would be the costs — economic, social, and environmental — of a transformation from fossil fuel to the sun?

The almost accidental discovery of fission gave man a long-term energy option besides the sun. As for the other long-term options, fusion and geothermal, I shall assume that fusion will always remain a technological impracticality; and that geothermal will always be a small source of energy — supplying, say, no more than 5 percent of mankind's needs. Both these assumptions can be faulted: fusion may work, and hot dry rocks may yield to the development efforts now going into them. But despite great current enthusiasm, I believe it is prudent to assume that fusion will forever evade us. Furthermore, the geothermal gradient on the continents corresponds to the energy man <u>now</u> uses; it seems unlikely

---

* Presented at the Argonne Universities Association-Argonne National Laboratory Bicentennial Conference, "Accomplishments and Challenges for American Life Sciences", Argonne, Illinois, October 11, 1976.

**Electrical breeders, i.e., accelerators that convert uranium-238 into plutonium, could still have started a nuclear energy system based on breeders even if all uranium-235 had disappeared. This would still require the number of neutrons per fission to be greater than 2.

that in man's ultimate society, geothermal energy will be a really large contributor.

I shall try to visualize and compare an energy future based on the sun with an alternative future based on uranium or thorium breeders. This task is both impossible and timely: impossible since one can hardly say anything about the very distant future; timely because of the nuclear debate that increasingly grips the Western world. A fundamental issue in this debate, as articulated by Amory Lovins and Ralph Nader, is really the role of solar energy. Those who dislike nuclear energy believe an ultimate solar future is inevitable and desirable. Those who support nuclear energy look upon solar as expensive and awkward as compared to nuclear energy.

Underlying these contrasting views of man's ultimate energy system are strongly polarized social views as to centralization and decentralization. For some segments of the neo-Anarchist Left, the rallying cry is decentralization: the perfect society is composed of small groups, each doing its own thing, unencumbered by oppressive power exerted by an insensitive centralized entity, whether that be state, corporation, or union. Centralization is the great enemy; and since central generation of electricity, especially by nuclear reactors, is the epitome of technological centralization, nuclear energy is a prime target of the New Left. Decentralized energy systems, particularly decentralized solar systems, are a prime technological aim of this political current.

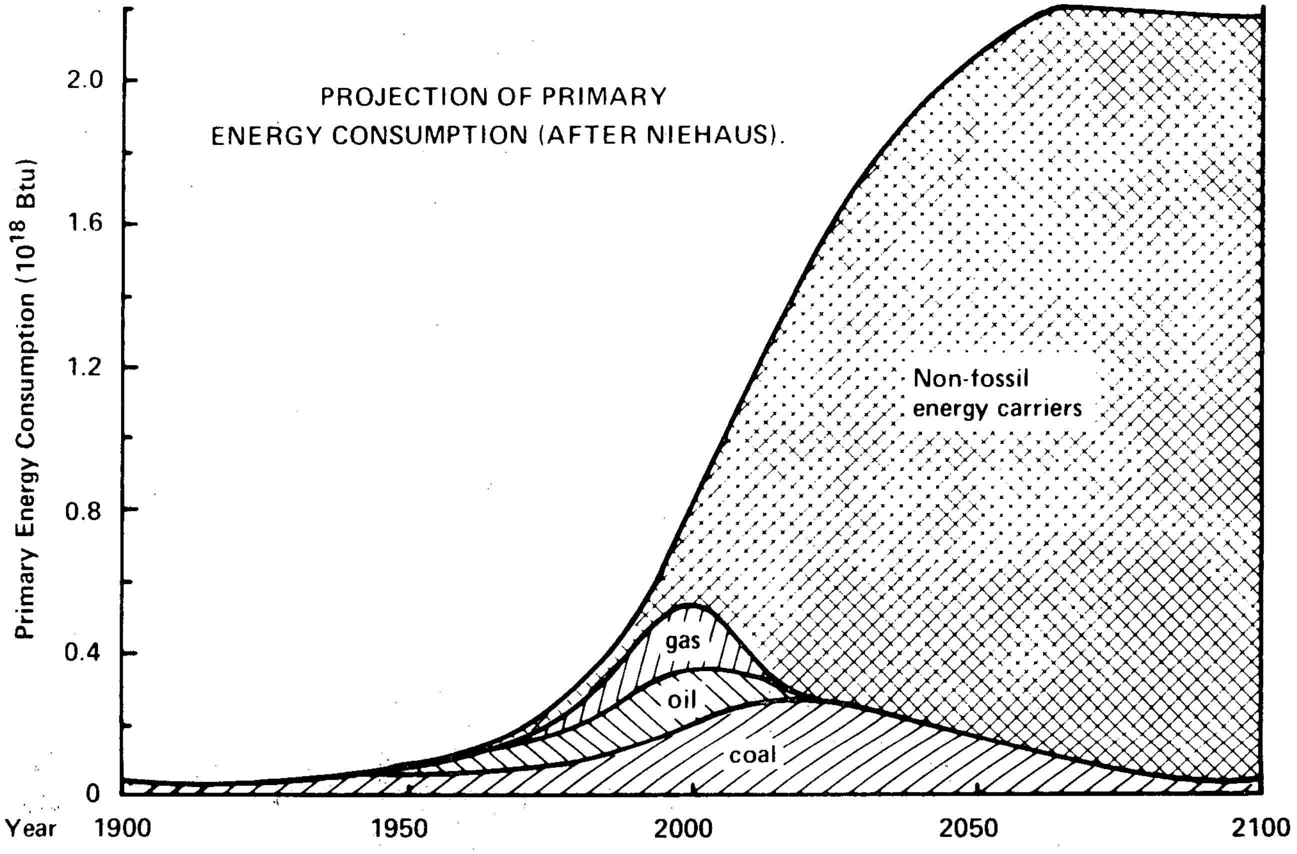
An Asymptotic World

To evaluate these two alternatives, I shall consider an ultimate world in which the great economic discrepancies between poor and rich have been eliminated. R. Heilbroner's "wars of redistribution"[1] will have been avoided, and all people will have reached a living standard comparable to that of Western Europe. I choose such a scenario because it brings out most clearly what may be the essential choice: between a stable world in which all have a relatively large per capita energy but which places great pressure on the environment, and an unstable world in which the average per capita demand is very low (about 50 million Btu per person) but the environmental pressures are much smaller.

I shall assume F. Niehaus' asymptotic world energy demand[2] — 2×10^{18} Btu (or 2,000 quads) — reached in about 100 years, compared to 220 quads today (Figure 1). This corresponds to about 280 million Btu per person for a world of 7.5 billion people or 140 million Btu per person for a world of 15 billion. The latter per capita energy demand corresponds to the current West German demand, and is somewhat less than half the U.S. level.

Our present age of fossil fuel obviously will end rather quickly once this demand is reached. Oil and gas — about 30,000 quads — would last but a few years. The estimated 8×10^{12} tons of coal (assuming all the energy comes from coal) would be used up in about 100 years. Estimates of the total recoverable reserve of shale oil are most uncertain; I shall use the figure of about 100,000 quads given to me by G. Marland

FIGURE 1

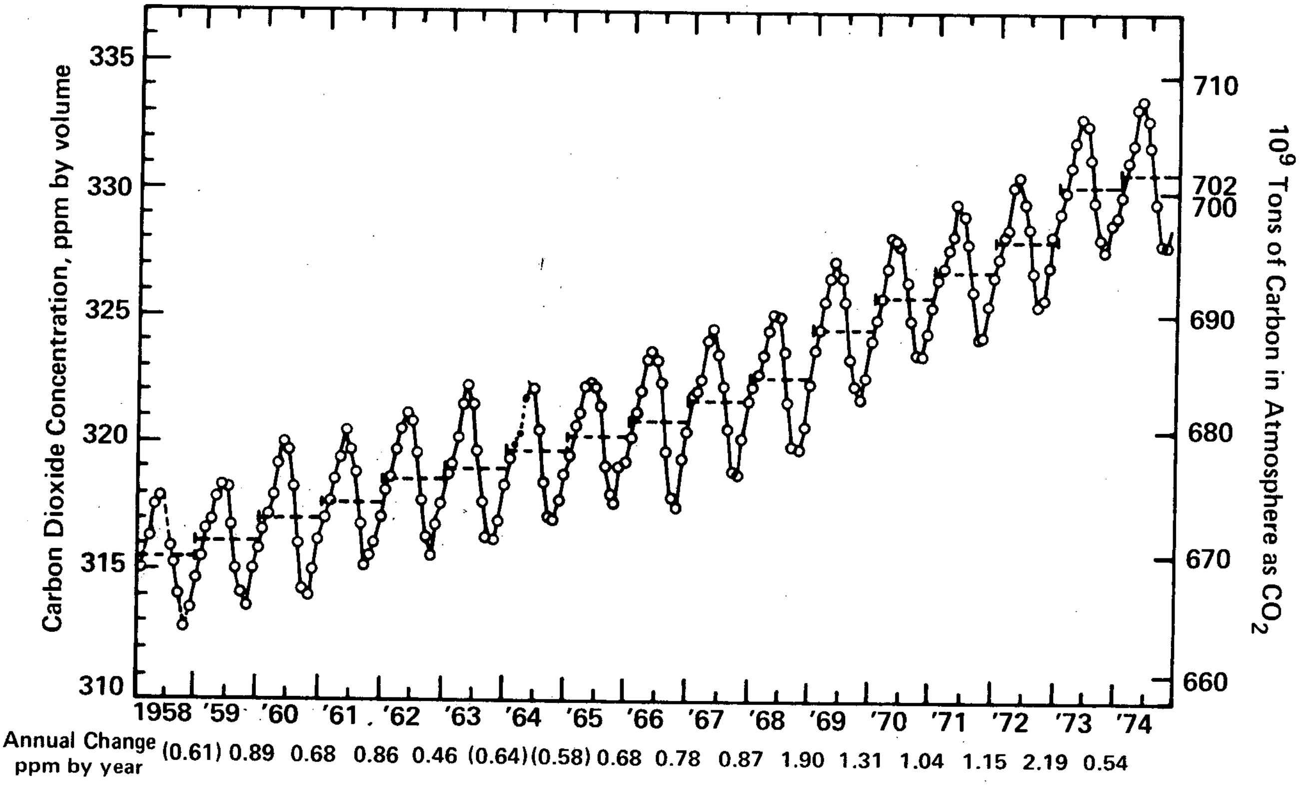

PROJECTION OF PRIMARY
ENERGY CONSUMPTION (AFTER NIEHAUS).
Primary Energy Consumption (10^{18} Btu)
2.0
1.6
1.2
0.8
0.4
0
Year
1900
1950
2000
2050
2100
Non-fossil
energy carriers
gas
oil
coal

of the Institute for Energy Analysis.^{3} This adds another 50 or so years to the time before the fossil fuels are exhausted.

The carbon dioxide added to the atmosphere might end the age of fossil fuel before the fuels are exhausted. About half of the man-made carbon dioxide seems to remain in the atmosphere. Its concentration in the atmosphere is rising at a rate of about 1/2 parts per million (ppm) per year, and is now some 10 percent greater than it was in the pre-industrial era (Figure 2). It has been suggested that if 20 percent of the estimated fossil resource of approximately 300,000 quads is burned, the concentration of carbon dioxide in the atmosphere would double; this might lead to unacceptable heating of the globe. It is conceivable that we shall have to shift to nonfossil energy sources much sooner than one would estimate from the projected depletion of coal resources — say, by the middle of the next century. The issue of the sun and uranium then might become nonacademic within some of our lifetimes.

I propose to examine the full implications of dependence on fission and on solar energy in this asymptotic world. In the early days of fission, we generally ignored its very long-term implications. The systems problems that plague fission now that it is widely deployed — safety, public acceptance, wastes, transport of radioactivity — somehow did not seem very important earlier, when it was small and was perhaps not taken seriously. (I remember a colleague on the President's Science Advisory Committee who, in 1960, used to refer to fission as a "solution looking for a problem".) We did not, so to speak, face the full implications of the success of fission energy.

FIGURE 2



ATMOSPHERIC CARBON DIOXIDE CONCENTRATION AT MAUNA LOA OBSERVATORY
(1958-71 data from Keeling et al., 1976; 1972-74 data from Keeling, private communication)

I suggest that we ought not fall into this same trap as we contemplate the sun as the base of our energy system. Can we visualize systems limits if solar energy were our main source of energy — if we really had to face the hypothetical future man might have faced had he evolved 2 billion years later — limits that would be unimportant if solar energy were only a small increment to other energy systems?

Let us then try to delineate in more detail an asymptotic world based on renewable energy sources: geothermal and solar (including hydro, wind, waves, ocean thermal gradients, solar electric, and biomass). To do this properly, we should analyze each end use of energy, and estimate how much energy is used as low temperature heat, high temperature heat, electricity, and mechanical work. This I have not done, and my speculations can be faulted in this respect. Instead, I have lumped together all heat, regardless of temperature, and have done the same for electricity (Table 1). I have taken the present U.S. breakdown of end-use demands and assumed this same pattern for the asymptotic future. This I call Case A: transport is based on liquid fuels derived from biomass, and, at least for a fairly long time, from coal. I consider also Case B, in which transport is based on electricity: battery-driven cars; or electric trains; or conceivably, hydrogen-powered fuel cells of very high efficiency, the hydrogen being generated electrically. In determining how much heat goes into electricity, I have assumed a conversion efficiency of 10,000 Btu per kilowatt-hour (kWh).

TABLE 1

ASYMPTOTIC WORLD ANNUAL ENERGY DEMAND

	1,000 quads/year
Household (22%)	0.44
Commercial (13%)	0.26
Transport (26%)	0.52
Industrial (39%)	0.78
Total heat input	2.00

	Case A (fluid transport)	Case B (electric transport)
Electricity	68×10^{12} kwh	118×10^{12} kwh
Heat not used for electricity	1.32×10^{3} quads	0.8×10^{3} quads

Let us now consider how much heat and electricity man can plausibly derive from each of the renewable resources.

Geothermal

Although the geothermal energy stored in the rocks down to 10 kilometers has been estimated to be as high as several million quads, it is all but impossible at this time to estimate how much can be usefully recovered. However, since we are speaking of an asymptotic future, we can no longer mine the accumulated heat in the rocks; instead, we shall have to depend on the constant geothermal gradient. This amounts to 200 quads for world land areas — about man's total energy demand at present. Since so much of this heat is at very low temperature, and much of it is in parts of the world where no one lives, it seems fair to assume that no more than, say, 10 percent of it can be utilized as electricity at an efficiency of, say, 30 percent. This amounts to no more than 2×10^{12} kWh of geothermal electricity worldwide in the steady state (Table 2). We also assign a total of 10 quads of geothermal energy as heat.

Hydro

The ultimate world capacity for hydro we shall set at 10×10^{12} kWh. This is about 30 times the present total installed hydroelectricity.

TABLE 2

ULTIMATE CONTRIBUTIONS TO ASYMPTOTIC WORLD ANNUAL ENERGY DEMAND FROM HYDRO, GEOTHERMAL, WIND, AND SUN

	Electricity (kWh/year)	Heat (Quads/year)
Hydro	10×10^{12}	–
Geothermal	2×10^{12}	10
Wind	0.8×10^{12}	–
Other (Waves, Tides)	1×10^{12}	–
Total	14×10^{12}	10
Needed from Sun		
Case A (liquid transport)	$\sim 50 \times 10^{12}$	~ 1,300
Case B (electric transport)	$\sim 100 \times 10^{12}$	~ 800

Wind

H. Thirring[4] quotes Putnam for the total ultimate wind energy as 0.8×10^{12} kWh, or about 8 percent of the ultimate hydro capacity. To this, we probably ought to add wind for sailing ships, which might ply the oceans if we really must depend on the sun; this contribution, however, is surely small.

Waves and Tides

Wave energy may be a larger ultimate source than we had once believed; nevertheless, it is hard to imagine so dilute a source contributing substantially. Similarly, we would expect tidal power in aggregate to be very small. We rather arbitrarily place the combined contribution of waves and tides at no more than 1×10^{12} kWh.

Sun

The demand for electricity from the sun varies between 50 and 100×10^{12} kWh per year in the two cases; for heat, between 1,300 and 800 quads per year. At present, about 25 percent of our total energy in the United States goes for space and water heating. If the same fraction ultimately went for these purposes throughout the world, this would amount to about 500 quads. Let us further assume that <u>all</u> of this heat is provided directly by the sun; or alternatively, that better methods of insulation reduce the demand so that the entire space and water heating load can be handled directly by the sun. The remaining demand would have to be met either from biomass or solar electricity. Thus our hypothetical world displaced in time by 2 billion years would face the task of drawing between 300 quads and 800 quads from the sun as biomass; and from 50 to 100 x 10^{12} kWh as electrical energy. What are the prospects for achieving these outputs?

The average solar insolation in the Southeast United States is about 560,000 Btu per square foot per year — i.e., 0.2 kW per square meter (m^2) (Table 3). If this is converted to electricity at 18 percent efficiency (a theoretical value for solar cells), we can extract roughly 300 kWh per m^2 per year from the sun. Let us assume the sun's energy is converted into biomass at, say, 0.6 percent conversion efficiency; this corresponds to about 10 tons dry weight per acre per year, 7,500 Btu per pound dry weight, and is five times the global average efficiency of 0.13 percent. On this assumption, the energy obtained by burning biomass is 3.8 x 10^4 kilojoules per m^2 per year — i.e., 10,000 square miles per quad of heat per year. Note that if the biomass is converted to electricity at 30 percent efficiency, we arrive at 3 kWh per m^2 per year, about 100 times less than the efficiency of electrical conversion assumed for photocells.

We now examine limits on biomass and solar electricity in more detail.

TABLE 3

PRODUCTION OF 800 QUADS/YEAR VIA BIOMASS

Average solar insolation (Southeast U.S.)	0.2 kW/m^2
Conversion of solar insolation to electricity, 18% efficiency	300 kWh/m^2/year
Conversion of solar insolation to biomass, 0.6% efficiency	3.8 x 10^4 kJ/m^2/year
Conversion of biomass to electricity, 30% efficiency	3 kWh/m^2/year
Land requirement	22 million square kilometers

Biomass

To get 800 quads per year from biomass would require about 8 million square miles — roughly one-sixth the total land area of the earth. Thus the high biomass scenario seems implausible. Even to supply the 300 quads in Case B (electric transport) requires 3 million square miles — a very formidable demand.

It would seem that biomass simply cannot provide the basis for the abundant energy future I visualize unless the effective photosynthetic yields can be increased much above the 0.6 percent I have assumed, or unless really large-scale farming of the sea (say for kelp) becomes feasible. Several possibilities suggest themselves: from improving crop management so as to harvest year in and year out those plants that in special situations now yield much more than 0.6 percent, to genetic engineering that might increase the effective photosynthetic efficiency, say, fivefold. I have no idea whether photosynthetic efficiency five times higher than the present average is achievable — whether, say, this is more likely than the development of practical controlled thermonuclear fusion. These estimates merely suggest how important such an achievement would be, and suggest possibly vital directions for future genetic research.

Solar Electric Systems

The yearly demand for solar electricity (50×10^{12} kWh to 100×10^{12} kWh) could be met, in principle, by photovoltaic arrays (PV), by power towers (PT), or by ocean thermal energy converters (OTEC). The first two are intermittent, the last is not. If these intermittent systems are small and are backed up by firm power from a grid, they would need little storage; if they stand alone, or if the total demand exceeds what can be met by reliable backup, these systems would need large amounts of storage — say 6 to 12 days. Electrical storage is much more expensive than is heat storage; hence, a priori, we would expect the PV system with full electric storage to be more expensive than the PT, which uses heat storage.

A few numbers illustrate the point. If a PV system, possibly with a light condensing system, can be installed for \$10 per square foot (ft^2) without storage (this is 15 times cheaper than the present cost of photovoltaic silicon surfaces), then at our average output of 30 kWh per ft^2 per year, the capital cost of the system is about 33 cents per kWh per year; at 20 percent fixed charges, this comes to about 7 cents per kWh; at 10 percent fixed charge, 3.5 cents per kWh. If the system were supplied with six days' storage and the batteries cost, with one replacement, \$40 per kWh, we would add 66 cents per kWh per year to the capital costs (Table 4). The total cost of firm electricity would come to 20 cents per kWh and 10 cents per kWh at 20 percent and 10 percent fixed charges, respectively. Actually, even these may be underestimates for a full solar system, since we have not taken into account the variation in solar flux between winter and summer. This is about a factor of 2 to 3, depending on the latitude. Thus to provide firm power, winter as well as summer, might require three times the capital investment in

TABLE 4

PRODUCTION OF 100 x 10^{12} kWh/year VIA SOLAR ELECTRICITY

Solar electricity density, 18% efficiency	300 kWh/m^2/year
Cost of PV installed, 6-day storage	\$300/m^2
Capital cost	100 cents/kWh/year
Cost of electricity:	
@ 20% fixed charge	20 cents/kWh
@ 10% fixed charge	10 cents/kWh
Total capital cost	~ \$100 x 10^{12}
Gross world product	~ \$ 75 x 10^{12}

collectors, though not in storage. The storage for the PT system is much cheaper, though it is too early to say whether the PT or PV system itself is the cheaper. Thus if a large PT can be installed complete for as little as \$10 per ft^2, we might achieve solar electricity at 20 percent fixed charges for, say 10 cents per kWh, but this still does not take into account the winter/summer variation. Firm power, winter as well as summer, might cost at least twice as much.

The total land required in the 100 x 10^{12} kWh per year scenario is about 80,000 square miles. The capital outlay, at 100 cents per kWh per year (including storage for the PV system), would be \$100 x 10^{12}. The annual per capita income at that time would be equivalent, say, to the West German average of \$5,000 per person per year. Thus the gross world product (GWP) would come to \$75 x 10^{12} per year. A world electrical system whose capital cost is, say, 1.3 times the GWP may be acceptable, since the present U.S. electrical system, if it were to be duplicated, would cost about \$500 billion, or 40 percent of our gross national product (GNP).

One possibility that has perhaps received insufficient attention is OTEC. We have modified C. Zener's estimate,[5] and find that if the ocean surface temperature were reduced by 1°C from 20°N to 20°S latitude, some 100 x 10^{12} kWh conceivably could be obtained at a cost of perhaps 5 cents per kWh (20 percent fixed charge). However, if OTEC were deployed on so enormous a scale, the amount of water evaporated from the ocean would be reduced significantly, and this might induce serious changes in the climate.

To summarize, it would appear that the high solar electric scenario seems to be very expensive; the high biomass scenario seems to use too much land; the high OTEC scenario seems to imply serious climatic changes. An all-solar future is almost surely a low-energy future, unless man is prepared to pay a much larger share of his total income for energy than he now pays.

An Ultimate Future Based on Breeders

Let us now see what would be involved in providing the electric transport scenario with nuclear energy — i.e., 100 x 10^{12} kWh for direct electricity and transport and 300 quads for all other purposes except space and water heating, which we still assign to the sun. We assume the "all other purposes" will be met by hydrogen generated electrolytically, rather than by biomass as we did in the previous scenario. At 70 percent efficiency of conversion from electricity to hydrogen, 300 quads of hydrogen require 125 x 10^{12} kWh. (This number might in effect be halved if thermochemical splitting of water at 60 percent efficiency could be achieved.) Thus our total breeder system must supply about 225 x 10^{12} kWh of electricity each year (Table 5). We assume in the asymptotic era, each breeder produces 5,000 MW for 7,000 hours, or 35 billion kWh of electricity per year. Thus the asymptotic nuclear world would be powered by about 7,000 enormous breeders, each producing 5,000 MW of electricity at 80 percent capacity factor, and about half of them converting the electricity into hydrogen or other liquid fuel. Is such

TABLE 5

PRODUCTION OF 225 X 10^{12} kWh/year VIA NUCLEAR BREEDER SYSTEM

Direct electricity and transport	100 x 10^{12} kWh/year
Electricity for "all other purposes"	125 x 10^{12} kWh/year
Total electricity	225 x 10^{12} kWh/year

Number of reactors	7,000	Cost of electricity:	
		@ 20% fixed charge	5 cents/kWh
Size of reactor	5,000 MW(e)	@ 10% fixed charge	3 cents/kWh
Cost/kW	$1,500	Cost of hydrogen/million kilojoules:	
		@ 20% fixed charge	$20
Capital cost of system	$50 x 10^{12}	@ 10% fixed charge	$10

TABLE 5 (CONTINUED)

PRODUCTION OF 225 X 10^{12} kWh/year VIA NUCLEAR BREEDER SYSTEM (continued)

Number of reactors	7,000
Number of sites	1,500
Number of reactors built/year	~ 150
Uranium required	~ 40,000 tons/year
Pu inventory	175,000 tons
Excess Pu produced per day	10 tons
Accident rate @ .5 x 10^{-4}/reactor/year	0.3/year
High-level wastes produced	~ 6 X 10^4 m^3/year
High-level waste burial land	40 km^2/year

an energy system at all plausible? Let us examine various possible limits to such a system.

Cost

We shall assume the breeder system, together with its hydrogen generating plant, costs 50 percent more than present-day reactors — say \$1,500 per kW. The capital cost of the whole system would come to about \$50 x 10^{12} — about half the cost of the solar electric system with electric transport — yet the nuclear system takes care of essentially all the society's energy (except for space heating), whereas the solar electric system met only the demand for direct electricity and transport.

At \$1,500 per kW, the capital cost is about 21 cents per kWh per year. With fixed charges at 20 percent, and operating and fuel costs of 1 cent per kWh, this leads to electricity at 5 cents per kWh; at 10 percent, to 3 cents per kWh. Hydrogen from the system would cost roughly \$10 to \$20 per million Btu, i.e., five to ten times present costs of fluid fuel. We estimate the yearly world expenditure on all energy in the high scenario to be about \$15 x 10^{12} at 20 percent fixed charge, \$10 x 10^{12} at 10 percent fixed charge — that is, 20 percent and 15 percent of GWP, respectively.

Siting

To site 7,000 reactors, each producing 5,000 MW, is a formidable task. It seems clear that cluster siting will be adopted by then — perhaps five reactors at each site. About 1,500 sites would be needed. If each site occupied 40 square miles, the entire system would require 60,000 square miles. In the United States, assuming an asymptotic population of 300 million and that everything scales according to population, we would need about 50 sites.

Rate of Building

If each reactor lasts 50 years, 150 reactors would be built each year. The total work force on the site, at say, 5,000 per reactor, would be close to 1 million. This number probably would be at least trebled if we count workers at component factories.

Uranium Requirement

Each breeder "burns" about 15 kilograms of uranium per day. To keep the entire system going would require about 40,000 tons of uranium per year. This demand could be met only by "burning the rocks" — i.e., extracting the 12 ppm or so of uranium and thorium from the granitic rocks, or by extracting uranium from seawater.

Plutonium Inventory

Each reactor and supporting chemical plant will contain about 25 tons of plutonium. The total system would contain about 175,000 tons of plutonium. If we assume a breeding ratio of 1.06 for the entire system, we estimate 10 tons of excess plutonium will be produced each day.

Accident Rate

We have no real estimates of accident probabilities for liquid metal fast breeder reactors (LMFBR's). The Rasmussen estimate (one in 20,000 per reactor year with an uncertainty of five either way)[6] would lead to a meltdown every 3 years. This is probably an unacceptable rate; an accident rate at least ten times lower, and possibly 100 times lower may be needed if the system is to be acceptable.

Waste Disposal

Each 5,000 MW LMFBR produces about 75 cubic feet of high-level solidified waste per year, contained in about 50 steel cans. According to present plans, these would occupy about 1.5 acres of burial space. Thus the entire system of 7,000 reactors would require about 15 square miles of burial space per year. After 1,000 years, 15,000 square miles will have been used up; by that time, the radioactivity in the high-level wastes will have decayed sufficiently to allow fresh wastes to be layered over the older wastes. Thus the 15,000 square miles devoted to high-level wastes might be usable for much longer than 1,000 years.

To summarize, although we cannot identify physical limits that make a world of 7,000 large LMFBR's impossible, one would have to concede that the demands on the technology would be formidable. Two issues appear to me to predominate: first, the acceptable accident rate will probably have to be much lower than the Rasmussen report suggests. If one uncontained core meltdown per 100 years is acceptable (and we have no way of knowing what an acceptable rate really is), then the probability of such an accident will have to be reduced to about one in 1 million per reactor per year. This is the design goal for the LMFBR project in the United States. Second, a nuclear world such as we envisage will have long since had to make peace with plutonium. Ten tons of plutonium per day is mind-boggling. It is hard to conceive of the enterprise being conducted except in well-defined, permanent sites, and under the supervision of a special cadre — perhaps a kind of nuclear United Nations.

Thus we can hardly escape the impression that the price nuclear energy demands, if it is indeed to become the dominant energy system, may be an attention to detail, and a dedication of the nuclear cadre that goes much beyond what other technologies have demanded. It is only when one projects to an asymptotic nuclear future such as we have attempted that one recognizes the magnitude of the social problem posed by this particular technology.

Can the Sun Replace Uranium?

Let me return to my original question, Can the sun replace uranium? I hope I have made at least plausible that the sun, if it were to provide as much energy as the breeder, would cost man dearly: in land, in money, possibly in environmental pressure (OTEC, for example). No matter how one looks at it, one cannot escape the impression that the sun is a smaller energy system than is the uranium system.

But when we speak of the uranium system, we are implicitly assuming a properly operating uranium system. Thus the uranium system imposes risks of a quite different kind than does the sun system: social risks that become manifest if parts of the system break down. If the sun system on so vast a scale may cause changes in climate (as in OTEC), or may commandeer land needed to grow food, the uranium system on so vast a scale will surely impose risks — of accident, of diversion, of proliferation.

Surely we are confronted with a powerful dilemma — we have discovered once again that there is no such thing as a free lunch. How is the world likely to resolve the dilemma? Three paths seem possible, and we undoubtedly shall have to follow them all:

- The solar technologies conceivably will improve far beyond what I have assumed. If, for example, the overall practical photosynthetic yield could be increased tenfold and this could be sustained in a large-scale practice, most of the shortcomings of solar energy would be avoided. This is little more than a hope now: I can hardly imagine a more important goal for biologists, agronomists, ecologists, and agricultural scientists.

- The world energy demand may be exaggerated either because population will not grow as I have postulated, or because technology of conservation will become far better than we now believe practical. About population, there is little I can say. About conservation, I mention some attempts that have been made, particularly by Amory Lovins, to construct worlds which live at a high standard at about 90 x 10^6 kilojoules per person per year, rather than the 140 x 10^6 kilojoules per person per year we have assumed. Yet, even this would be insufficient if the population rose to 15 x 10^9: a world requiring 1,400 quads could hardly depend primarily on the sun. Thus we seem to have no alternative but to try to control the population.
- But if we are prudent, we shall have to prepare for the worst though we work for the best: we try to make a 2,000 quad world livable while we work for a 500 quad world. This means to me that we must keep all of our options open. Every one of our energy options, when pushed to the limit I envisage, either is inadequate or imposes risks of a sort we are quite unaccustomed to deal with. Does this not call for a world energy system that is as diverse as possible? Our scenarios were either all nuclear electric or all solar electric, but

this was done largely to make my point, to bring out the relative merits of solar energy and nuclear energy. Is it not the most sensible course to aim for a system that depends on some combination of solar and nuclear? The sun, rather than replacing uranium, would supplement it. Though we cannot say that any combination of energy sources we now see will surely give us both 2,000 quads and acceptable risk, it seems at least plausible that in a combination of all, including conservation, lies man's best hope of creating a world of abundance.

REFERENCES

1. R. L. Heilbroner (1974). An Inquiry into the Human Prospect, W. W. Norton and Company, Inc., New York, New York.

2. F. Niehaus (1976). "A Nonlinear Eight Level Tandem Model to Calculate the Future CO_2 and C-14 Burden to the Atmosphere", Research Memorandum RM-76-35, International Institute for Applied Systems Analysis, Laxenburg, Austria, April.

3. Private communication with G. Marland.

4. H. Thirring (1976). Energy for Man: From Windmills to Nuclear Power, Harper and Row, New York, New York, p. 281.

5. C. Zener (1973). "Solar Sea Power", *Physics Today*, pp. 48-52, January.

6. N. C. Rasmussen, Chairman, U.S. Atomic Energy Commission Task Force. "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants", WASH-1400 (NUREG 75/014), Washington, D.C. [Available from the National Technical Information Service.]