Energy Vol. 13, No. 1, pp. 73–81, 1988
Printed in Great Britain.

0360-5442/88 $3.00 + 0.00

THE NET-ENERGY YIELD OF NUCLEAR POWER

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(*Received* 23 *December* 1986)

Abstract—Most prior net-energy studies of nuclear-power systems accounted only for the direct consumption of fuels and the indirect consumption of energy embodied in physical materials when making such estimates. Most ignored the energy embodied in labor, government, and financial services. In this study, total economic cost is used as a surrogate to estimate the total input-energy cost of constructing, operating, financing, and disposal of nuclear-power systems. Although the cost and performance data used in this study are from light-water reactor systems experience, it is assumed that fast-neutron reactors may be substituted for light-water reactors when economic conditions dictate. We make the conservative assumption that the cost and performance characteristics of fast-neutron reactors will be similar to those of light-water reactors. We conclude that the operation of a large nuclear-power system, involving a continuing construction program of starting one new 1000-MW system each month for 100 yrs, would yield a relatively small amount of net energy, under optimistic assumptions. Under less-optimistic assumptions the net-energy yield is negligible to negative. The average net-energy yield increases, somewhat, when optimistic assumptions are added to account for the possibility of improved efficiency in an all-electric economy.

INTRODUCTION

Despite relatively low oil prices, it is clear that world fossil-fuel supplies will be ultimately depleted. Hubbert estimated that about 80% of world petroleum supply would be consumed between 1960 and 2030; 80% of natural gas between 1934 and 1999; and 80% of coal between 2000 and 2300.[1] In 1976, Fowler revised and extended this analysis with similar conclusions.[2] The most widely-proposed substitute for fossil fuel has been nuclear-fission power, but there is much uncertainty about its ultimate costs. About 15% of the world's electricity is now generated by nuclear power.[3] France currently generates 65% of its electrical energy from nuclear power (the F.R.G. 31% and the U.S. 16%).[4] Since Three-Mile Island, costs have soared.[5] The recent Soviet accident at the Chernobyl station highlights the large potential costs of plant accidents[6] and diminishes the likelihood for immortality of nuclear systems as envisioned by Weinberg.[7] Even if accidents occur with low probability, accident-prevention measures and restoration of accident-caused environmental damage can significantly raise the economic cost.

This may, however, be the least of the limitations on fission power. We propose to demonstrate that there has been enough experience with this process to show that the net-energy yield of nuclear-fission energy is such that it is at best a reimbodiment of the fossil energies by which it was set in place. Net energy is the energy remaining after the energy costs of production are subtracted (including the energy embodied in capital, labor, government, and financial services) and is a more useful index of the potential benefit of an energy source to society than gross energy.[8–10]

Net energy is sensitive to plant construction, decommissioning, waste disposal, and accident-liability costs. We present both static and dynamic analyses for these costs. Under a wide range of assumptions, we conclude that nuclear power is not a significant source of net energy. In the latter part of the paper, we also discuss the notion of energy quality, which recognizes the unique aspects of electricity.

Our estimates of net-energy yield are probably conservative for two reasons. (1) Rapid technological improvements in net-energy yield usually occur in the early developmental stages of an energy-transformation technology. Given the amount of research and operating experience that has already been accumulated on boiling-water reactor and pressurized-water reactor technology, we have little reason to expect significant future improvements in their net-energy yield. Indeed, requirements to prevent future accidents will cause further cost increases. (2) Cost estimates for fission power have historically been much lower than the eventual real costs and a number of recently completed plants are costing in the high range of our estimates.[11]

ECONOMIC REASONING

The reasoning of standard economists has dominated the world perspective on future energy supply.[12] On the demand side, it is correct to reason that rising energy prices may alter human behavior to seek other alternatives such as conservation or lifestyle change. On the supply side, however, standard economic theory holds that if a good is in short supply, rising prices will trigger entrepreneurial activity to provide an additional supply of the same good or an acceptable substitute. Such reasoning is correct with respect to ordinary goods, but it is our contention that standard economists are in error to view energy as an ordinary good and, therefore, subject to indefinite substitution.

Some economists explicitly hold that capital can be substituted for energy.[13] While this is true for individual activities, we argue that capital is only made available in the overall system by a corresponding depletion of some form of energy and therefore, substitution of an alternate good for energy does not really occur in a broad sense. Energy is an extra-ordinary good having unique qualities for which there is no substitute.

The economic literature is replete with statements which assert, for example, that, when the price of petroleum reaches some higher price, this or that new source of energy will become competitive. For example, when oil was $10/bbl, it was asserted that when it reached $30/bbl, tertiary-oil recovery would be profitable. However, when oil had passed $30/bbl, none had yet been produced from this source because the quoted cost of tertiary recovery in dollars hid the fact that the cost in energy was then 3 barrels of oil to recover each barrel of tertiary oil. Therefore, until a process can be devised in which one barrel expended can lead to substantially more than one, it will never be profitable.[14] Such is the significance of net-energy considerations.

ENERGY ANALYSIS

We argue that most energy forms that are being counted on to substitute for depleting fossil fuels are based on estimates of their expected gross energy, which overlooks the amount of feedback energy needed to make the energy form available. Standard energy analysts[15] count as energy inputs only the direct energy (fuels and electricity) consumed in fabrication and operation of energy systems and the indirect energy embodied in physical materials directly used in the process. These analysts exclude the indirect energy embodied in goods and services consumed by labor, government, and recipients of real (inflation corrected) interest and profits.

It is often argued that the energy cost of labor should not be included in computations of net energy since the workers who earn their living in an energy-transformation activity are achieving the good, i.e., survival, for which mankind exists. While this is somewhat true when the net energy is large, the validity of the argument decreases to zero as the net energy goes to zero. Thereafter, the argument of Voltaire that no society can exist by circularly taking in each other's washing applies. To recognize this effect, labor should be weighted with a factor which is some function of the ratio of the total energetic cost of production (including labor) to the total energy output. Most simply this might be the ratio itself and, if so, it can be shown that the fraction of net energy would properly be calculated by taking the ratio of gross energy minus all costs to gross energy minus internal labor costs.

When the energy costs of labor and government are included in the accounting process, the relationship between constant-dollar value output and the consumption of energy is significant (see p. 1221 of Ref. 9).

It is our position that real monetary cost is a proxy indicator for the approximate amount of energy that is embodied in a particular good or service.† Since no good or service is brought into existence except through a corresponding expenditure of energy and since all recipients of money are institutionally entitled to exchange money for energy-embodied goods and services, it would be logically inconsistent to exclude arbitrarily any economic cost such as labor, interest, and taxes as an energy-input charge (see pp. 51–83 of Ref. 10).

ANALYSIS

Our analysis of nuclear-powered systems asks the following question: Can a large nuclear system provide enough output energy through time to replicate itself, repay its energy bills, and leave a sufficient residue of energy to produce food, clothing, shelter, health care, education, and other needs of society unconnected with the nuclear-power activity itself? We assume the construction of a set of fission-powered electricity-generating plants at the rate of 12 plants per year for a period of 100 yrs. Limits on the uranium supply makes this an impossible scenario for a program of light-water reactors, but this fact is irrelevant to the question. In any case, there is little reason to suppose that their proposed replacement, the fast-neutron reactors, would enjoy cost and performance characteristics that would be substantially more favorable.

Both static and dynamic analyses were done. Static net-energy analysis estimates the output/input ratio of a single energy-transformation entity over its lifecycle, and dynamic net-energy analysis estimates, among other things, average-annual net energy at selected points in time throughout the development of an entire system.

STATIC NET-ENERGY ANALYSIS

The procedure of static analysis involves the following steps. (1) We estimate the real, lifecycle, economic cost of the energy-transformation entity. Based on the argument that electricity is not particularly useful at the busbar but only at the point of end use, we also include electrical transmission and distribution costs and overhead costs as energy-input costs. Although historical data show that, overall, transmission, distribution, and other costs have been approximately 150% of generating-plant costs,[16] a recent report indicates that capital expenditures for transmission, distribution, and other costs have been approximately 45% of generating-plant costs for the period from 1975 to 1986.[17] (2) The lifecycle-output energy of the entity is estimated, based on engineering estimates and historical experience. Most prior energy analyses have been single-plant studies without considering the need for backup generating capacity to meet varying supply and demand situations. In this study it is presumed that the nuclear system would be the sole source of energy and nuclear plants would be needed for both base load, peaking and standby plants. Although some individual, base-load nuclear plants have been reported to have 70 to 90% availability factors, such a statistic ignores the total generating capacity that is needed to keep the overall system in operation. The total system load factor, which takes into consideration the need for backup generating capacity, is used in this study. There has been a general decline in system load factor efficiency of U.S. electric utilities from a high of 57% in 1957 to about 38% in 1985 (see p. 110 of Ref. 10). In this study, we use a range of total-system load factors from 40 to 60%.

We include all real economic costs as a basis for energy-input estimates, including transmission, distribution, and other costs. Interest, profit, and tax costs are captured through a real fixed-charge rate of 10.2834%/yr.‡ We use a range of capital costs from \$1000/kW for the

†Recipients of wages, interest, dividends, taxes, stock dividends, architectural, engineering, attorney and other professional fees, materials purchases, *ad infinitum,* that arise out of nuclear design, engineering, construction, operation, transmission and distribution of nuclear electricity, decommissioning, and waste disposal are all paid in money. The money is exchanged for goods and services. Services are ultimately the indirect purchases of physical goods, i.e., physicians and energy analysts are a part of the service industry who ultimately take their money and buy goods (homes, televisions, heating services, etc.,) that, in an all-nuclear economy would have to be provided by the feedback-electrical energy which would be used in the production of those goods.

‡A real fixed-charge rate of 10.28% is obtained by the equation $\mathrm{FCR} = [C(i, N)/(1-t)] \times 1 - [t/(N \times (C(i, N))] + t_p + r_r + r_i$ where i = real cost of capital (0.038), N = plant life (30 yrs) t = federal/state income tax (0.50, minus 10% investment tax credit, t_p = property tax rate (0.02), r_r = insurance rate (0.0025) and $C(i, N) = i/[1-(1+i)^{-N}]$.

optimistic cases to \$3500/kW for the more pessimistic cases, whereas earlier studies were based on early engineering estimates of cost and performance.† (3) We used three energy/GNP ratios (Btu/(\$1982) in the analyses. A 37 yr mean value of 28,266 Btu/\$1982 was used for the pessimistic scenarios and 21,436 Btu/\$1982 (the 1982 value) for the mid-level scenarios, and 20,000 Btu/\$1982 for the most optimistic scenario. The energy/GNP ratio is multiplied by the corresponding real life-cycle cost to arrive at the energy-input cost of the system (see p. 76 of Ref. 10). (4) Finally, we compare estimated output energy with estimated input energy.

DYNAMIC NET-ENERGY ANALYSIS

In dynamic net-energy analysis we estimate the net-energy balance of an entire energy-transformation system at selected points in time over extended periods. The plant-construction time of a single plant varies from 6 to 9 yrs. We assumed that a new plant is started every month for the 100 yr period and that average-plant life is 30 yrs. It is assumed that decommissioning takes place in a single year and all costs are incurred in a single year. This is an unrealistic and conservative assumption, since waste-disposal costs will be incurred over very long periods of time and real costs of such processes are yet to be determined.

ANALYTICAL MODEL

Table 1 is the static part net-energy model and the results are used in making the dynamic calculations of Table 2. In the exemplary case (Fig. 1, curve 3, year 50), a 1000 MW plant, costing \$2000/kW (\$1982) is assumed, fuel costs are escalated from \$0.01/kWh (\$1982) at 1%/yr to \$0.0165/kWh in year 50, decommissioning and nuclear waste-disposal costs are assumed to be 30% of generating-plant costs.

Table 2 is an exemplary dynamic net-energy model (corresponding to curve 3, year 50) in which we estimate the average amount of net energy that would result from a hypothetical construction, operation, and decommissioning program. It was assumed that twelve new plants are started each year and that it takes 8 yrs (exemplary case of Table 2) to complete each plant. Cell E39 shows the average-annual net energy from year zero to year 50 to be −0.01389 quads.

It can be seen that a 50 yr construction program of 12 new plants per year would result in construction starts on 600 new plants, the continuous operation of 360 plants, and the decommissioning of 144 plants over the 50 yr period. If 100 yr were the cycle under study, construction would have commenced on 1200 plants and 756 would have been decommissioned.

RESULTS

Table 3 shows the variables that were used in the calculation of each curve in Fig. 1.

Figure 1 is produced by successive calculations of equation sets of Tables 1 and 2 and shows the results of six 100 yr dynamic net-energy analyses under varying Table 3 assumptions. Figure 1 shows that, even under the most optimistic assumptions, the average annual net-energy yield of 360 continuously operating 1000 MW plants is pitifully small (approximately 3.27 quads averaged over 100 yrs) compared to the current consumption of gross energy of approximately 70 quads. When more restrictive assumptions are made, the net-energy yield is negligible to negative. Similar observations were made by Van Leeweun.[18]

CREDIT FOR ENERGY QUALITY

Technological change may offer new options for society to live high-quality lifestyles with less energy. Some are arguing that this is already occurring, citing recent evidence of increased economic output with smaller amounts of annual energy consumption. We are uncertain as to

†New plants in 1985 cost: \$2130.1/kW, \$2558.4/kW, \$3315/kW, \$1917/kW, \$3281.2/kW, \$2840.2/kW, and \$1992.4/kW. Post-TMI costs are estimated to be \$3531/kW (\$1986) in Elec. World Management Report.

Table 1. Static net-energy model.

(A) LINE	(B) ITEM	(C) VARIABLES	(D) EQUATIONS	(E) RESULTS
1	EXPECTED PLANT LIFE (YRS):	30		
2	GENERATING CAPACITY (KW):	1000000		
3	HOURS IN YEAR	8760		
4	REAL GNP/($1982):	28266		
5	BTU/KWH	3413		
6	GEN. PLANT COST ($1982):	1000	C2*C6	2.0000E+09
7	TRANS, DIST, OTHER ($):		E4*.45	9.0000E+08
8	ELEC. GEN. (kWh):	0.5000	C1*C2*C3*C8	1.3140E+11
9	FIXED CHARGE ($):	0.1028	C1*(E6+E7)*C9	8.9466E+09
10	GEN. PLANT O&M ($):	0.0077	E8*C10	1.0118E+09
11	OTHER PLANT ($):	0.0012	E8*C12	2.1681E+09
12	FUEL CHARGE ($):	0.0165	E8*C12	2.1681E+09
13	DECOMM. & WASTE DISP. ($):	0.3000	E6*C13	6.0000E+08
14	LIFECYCLE SYSTEM COST ($):		SUM(E9..E13)	1.4895E+10
15	TOTAL INPUT ENERGY(BTU):		C4*E14	4.2101E+14
16	OUTPUT ENERGY (BTU):		C5*E8	4.4847E+14
17	OUTPUT/INPUT RATIO:		E16/E15	1.0652
18	LIFECYLE NET ENERGY (BTU):		E16-E15	2.7459E+13
19	DISTRIBUTIVE COST, ($):		E14-E6-E7-E13	1.1395E+10
20	FRONT-END ENERGY (BTU):		C4*(E6+E7)	8.1971E+13
21	DISTRIBUTIVE ENERGY (BTU):		C4*E19	3.2208E+14
22	DECOMM ENERGY: (BTU):		C4*E13	1.6960E+13

WE ESTIMATE THE NET ENERGY FROM ONE PLANT OVER ITS LIFECYCLE. THE VARIABLES IN THIS EXEMPLARY TABLE RELATE TO CURVE 3, YEAR 50. IN REFERENCE TO LINE 7, OTHER PLANT COST INCLUDES TRANSMISSION, DISTRIBUTION, AND OVERHEAD COSTS AND ARE ASSUMED TO BE 45% OF GENERATING PLANT COST. IN THE EQUATIONS, * = MULTIPLY, / = DIVIDE.

whether this is a short-run aberration or whether it will continue to a lower limit. In any event, the transition from a petroleum-dominated society to some other dominant energy form will require a large allocation of resources, just to make the transition. Whether the new society will need more or less energy per unit of GNP output, relatively, is a matter of conjecture. In our study we are assuming a nuclear-powered all-electric economy. Electricity can be considered a high-quality form of energy in its role of performing high-quality tasks such as lighting, electronics, telecommunications, electrometallurgy, electrochemistry, arc welding, electric drive for public transport and for home appliances. Some may argue that, since all output from nuclear plants is in electrical form, some credit should be given for quality aspect of electricity.

Table 4 shows how the U.S. used its energy in 1978 by end-use category. We are uncertain as to how this pattern will shift as we deplete the finite supplies of petroleum, natural gas, and coal. For example, space heating of homes and workplaces could be provided by either solar technology or by electric-heat pumps. To allow for the possibility that an information-based, high-technology society might be able to operate its economy in a more efficient way, we made additional calculations to give some credit for the energy-quality aspects of electricity. The results are shown in Fig. 2.

In the Fig. 2 results, we multiplied a portion of the electrical output by a factor of 3, which is the approximate amount of thermal energy that is currently needed to provide 1 Btu of

Table 2. Dynamic net-energy model.

(A) LINE	(B) UNITS	(C) VARIABLES	(D) EQUATIONS	(E) RESULTS
23	CONSTRUCTION TIME (YRS):	8		
24	CYCLE UNDER STUDY (YRS):	50		
25	NO. CONSTR. PER YEAR:	12		
26	NO. DECOMM. IN CYCLE:	144		
27	ANNUAL OUTPUT 1 PLANT:		E16/C1	1.4949E+13
28	ALPHA UNITS:	825	SUM(F1.FN)-SUM(F1..(N-30)	
29	BETA UNITS:	325	(SUM(F1..F9)+(9*(N-9))	
30	TOT. OUTPUT ENERGY (BTU):		C25*E27*C28	1.4799E+17
31	ANN. FRONT-END INPUT (BTU):		(E20/C23)*C25	1.2296E+14
32	TOT. FRONT-END INPUT (BTU):		C29*E31	3.9961E+16
33	ANN. DISTRIB. ENERGY (BTU):		(E21/C1)*C25	1.2883E+14
34	TOT. DISTRIB. ENERGY (BTU):		C28*E33	1.0629E+17
35	DECOMM. ENERGY (BTU):		E22*E26	2.4422E+15
36	TOT. INPUT ENERGY (BTU):		E32+E34+E35	1.4869E+17
37	NET ENERGY (BTU):		E30-E68	-6.9448E+14
38	DYNAMIC O/I RATIO:		E30/E36	0.9953
39	ANN. NET ENERGY (BTU):		E37/C24	-1.3890E+13
40	NUMBER OPERATIONAL PLANTS:		((C24-23)*C25)-E26	360
41	CONSTRUCTION STARTS:		C24*C25	600

TABLE 2 IS A CONTINUATION OF TABLE 1. LINE 39 IS AN ESTIMATE OF AVERAGE-ANNUAL NET ENERGY FROM TIME ZERO TO TIME SHOWN IN CELL C24. IN REFERENCE TO LINES 28 AND 29, ALPHA UNITS REFER TO COSTS AND OUTPUT AFTER PLANTS BEGIN TO GENERATE ELECTRICITY. BETA UNITS REFER TO COSTS INCURRED BEFORE PLANTS BEGIN TO GENERATE ELECTRICITY. IN THE RELEVANT EQUATIONS, N = C24-C23, * = MULTIPLY, AND / = DIVIDE.

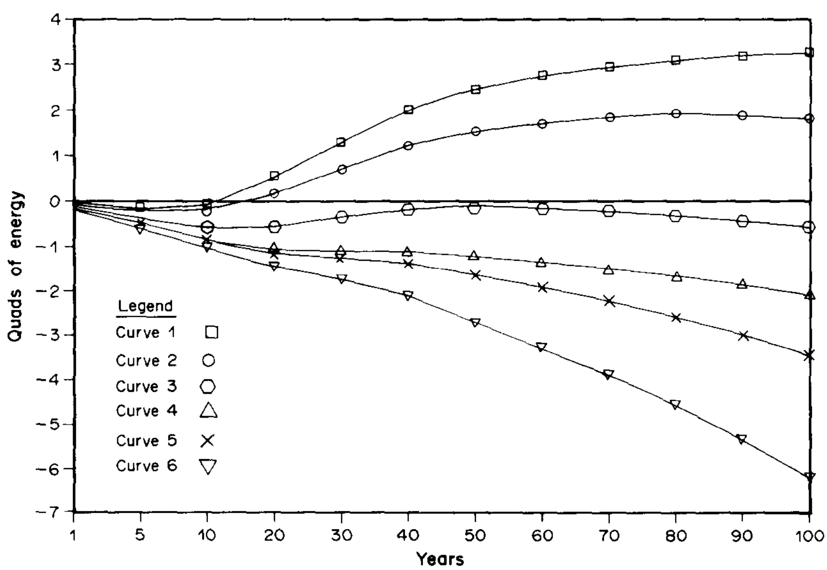

Fig. 1. Net energy from fission systems. A quad of energy = 10^{15} Btu. Curves were generated by successive calculations using equations in Tables 1 and 2. Each part is an estimate of average-annual net energy from time zero to the point of observation. Variables are shown in Table 3 columns A–G.

Table 3. Variables used in the calculation of Figs. 1 and 2.

(A) CURVE	(B) CAPITAL COST $/KWE $1982	(C) DECOMM. WASTE DISP.	(D) ENERGY GNP RATIO BTU/$	(E) SYSTEM LOAD FACTOR	(F) INITIAL FUEL COST $/KWH	(G) CONST. TIME YRS	(H) ENERGY QUALITY CREDIT
1	1000	0.20	20000	0.60	0.0070	6	0.50
2	1500	0.25	21436	0.55	0.0070	7	0.45
3	2000	0.30	21436	0.50	0.0100	8	0.40
4	2500	0.35	28266	0.50	0.0109	9	0.35
5	3000	0.40	28266	0.45	0.0109	9	0.30
6	3500	0.50	28266	0.40	0.0109	10	0.25

COLUMNS A-G USED IN FIG. 1 RESULTS. COLUMNS A-H USED IN FIGURE 2 RESULTS; (C) DECOMMISSIONING & WASTE DISPOSAL AS A % OF GENERATING-PLANT COST; (D) AN AVERAGE OF 21436 BTUS WERE USED TO PRODUCE EACH DOLLAR OF 1982 GNP, 28266 BTU/$1982 IS A 37-YEAR MEAN VALUE, AND 20,000 BTU/$1982 IS AN ARBITRARILY SELECTED LOW VALUE FOR OPTIMISTIC CALCULATIONS; (E) LOAD FACTOR IS FOR THE ENTIRE GENERATING SYSTEM, NOT JUST INDIVIDUAL BASE-LOAD PLANTS; (F) INITIAL FUEL COSTS ARE ESCALTED @0.5%/YR IN CURVES 1, 3, AND 4; 1%/YR IN CURVES 2 & 5, AND 2%/YR IN CURVE 6. (H) SHOWS PER CENT OF OUTPUT THAT IS MULTIPLIED BY 3 FOR FIG. 2 RESULTS.

Table 4. Energy use in 1978.

END USE CATEGORY	GROSS PRIMARY ENERGY (IN QUADS)	PERCENT OF GROSS PRIMARY ENERGY	NET END USE ENERGY (IN QUADS)	PER CENT OF NET END USE ENERGY
THERMAL	28	36%	28	46
ELECTRICAL	24	31%	7	11
TRANSP. FUELS	21	27%	21	34
FEEDSTOCKS	5	6%	5	8
TOTAL	78	100	61	99

APPROXIMATELY 71% OF PRIMARY ENERGY IS LOST TO CONVERSION AND DISTRIBUTION LOSSES. COLUMNS DONOT ADD UP TO 100 DUE TO ROUNDING. SOURCE: DEPARTMENT OF ENERGY (DOE) 1979, "ANNUAL REPORT TO CONGRESS."

electricity. Column H of Table 3 shows the pattern of those allowances. For example, in curve 1, Fig. 2, 50% of the electrical output was multiplied by a factor of 3.

CONCLUDING COMMENTS

Most prior net-energy analyses of nuclear-power systems were for single, base-load plants, whereas our study is of an entire generation, transmission and distribution system, to include backup systems to meet the varying demand conditions of a complex industrial society. At the same time, most prior studies only accounted for the energy associated with the direct consumption of fuels and the indirect energy embodied in physical materials. The energy that is embodied in the goods and services consumed by labor, government and financial services was not included in prior studies. It is our position that there is an inextricable link between the real financial cost of economic activity and the amount of energy needed to carry out such activity.

The results of our study (Figs. 1 and 2) show that, when all system costs are considered, including design, construction, operation, maintenance, all fuel-related costs, decommissioning, waste disposal, transmission, distribution, management, overhead, government oversite are included, the amount of net energy available from nuclear power is negligible to negative, depending on the assumptions that are made about future cost and efficiency. If more

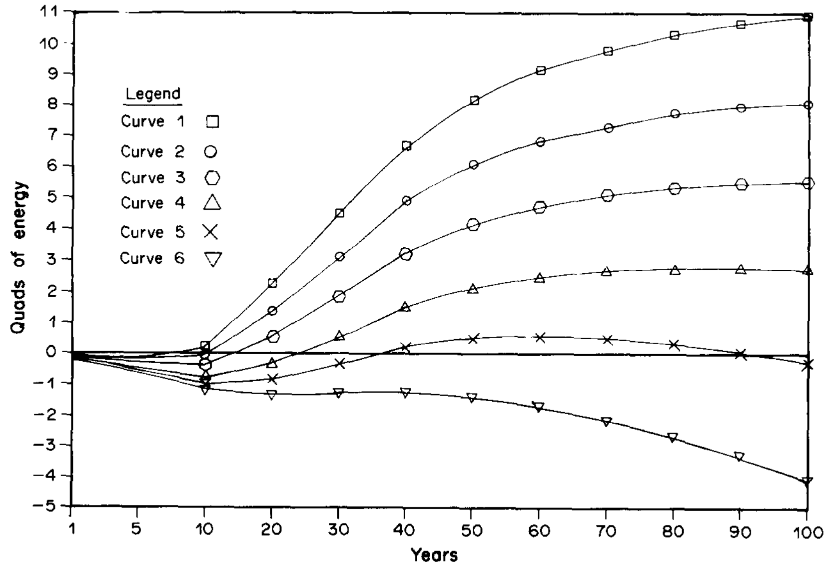

Fig. 2. Net energy from fission systems with energy-quality credits. Curves were generated by successive calculations using the equations in Tables 1 and 2. Each point is an estimate of average-annual net energy from time zero to point of observation. A percent of electrical output was multiplied by a factor of 3 as noted in column H of Table 3. Variables are shown in Table 3 columns A–H.

optimistic assumptions are made with respect to the energy-quality aspects of an all-electric economy (Fig. 2), the net energy improves somewhat. Even then, however, the amount of available net energy is small, relative to our current rate of energy consumption. The net energy to be expected from future energy-transformation entities is related to their economic cost and technical efficiency. Among other things, technical efficiency involves reliability, safety, and longevity. The Chernobyl, Three-Mile Island and Windscale disasters indicate that current nuclear-powered technologies cannot be considered as fool proof or expert proof as once imagined. The cost of increasing their reliability will lower the net-energy benefits accordingly. Net energy can be increased only by lowering economic cost or increasing efficiencies. Our results show that the improvements must be substantial, in order for nuclear power to be a significant source of net energy.

Another major factor affecting the energy cost of significant energy-transformation systems is the cost of beneficiation of other earth materials (e.g., minerals and metals). Others have called attention to the difficulty which will be faced in extracting leaner ores since it is apparent that we have already used up the relatively rich sources.[19] Unless major technological breakthroughs are forthcoming, the gleaning of these leaner resources will require additional feedback energy to get the necessary materials for the sustenance of a continuing nuclear program as discussed in this paper.

A recent study also found that wind-powered electrical generating systems are not producers of net energy, i.e., even under fairly optimistic assumptions, they would not be able to replicate themselves out of their output energy and leave a residual for society to use for other purposes (see pp. 137–158 of Ref. 10).

We have grave doubts about the future energy-supply picture beyond the easily-handled fossil fuels. It appears that fission technology is likely to be an insignificant contributor to society's net-energy resources and may even be a net-energy sink under our pessimistic assumptions.

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