Energetics and Systems

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PREFACE

Clearly, energy issues are critical to many aspects of modern society. To those wrestling with environmental problems and those involved with the holistic approaches of general systems research, energy must be approached from a variety of viewpoints, some with immediate pragmatic connotations, some with long-term scientific and philosophical implications.

It is precisely that mix of energy considerations represented in this volume that makes it important to the scholarship of several disciplines and was the motivation of the Editors in sharing it with an expanded audience.

In bringing this material together, the Editors have been most ably assisted by the efforts of Ms. Thelma Goldstein and Ms. Karen Cozine of the staff of the Systems Science Institute and by the advice, suggestions, and prodding of the Editorial staff of Ann Arbor Science Publishers. The authors have also helped greatly in not only supplying the ideas but in putting them into articulate English in a reasonable period of time. We are deeply appreciative of the contributions made by all of these good people.

During April, 1981, there were held in Louisville, Kentucky under the auspices of the Systems Science Institute of the University of Louisville, meetings of the International Society for Ecological Modelling and the Society for General Systems Research, Southeast Region. On Earth Day, April 22, a joint symposium of the two societies was held under the title, *Energetics and Systems*. A number of the foremost researchers in this broad field were involved in that symposium, and the material of this volume is based on those presentations.

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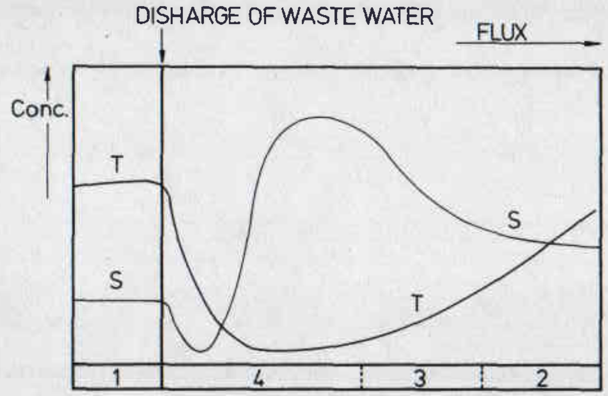

Figure 7. Diversity and population density for higher flora and fauna in a river downstream of influx of high organic load. T indicates number of individuals, while S is the number of species [12].

REFERENCES

1. Morowitz, H. J. *Energy Flow in Biology* (New York: Academic Press, Inc., 1968), p. 179.
2. Jørgensen, S. E., and H. F. Mejer. "Ecological Buffer Capacity," *Ecol. Modelling* 3:39-61 (1977).
3. Jørgensen, S. E., and H. F. Mejer. "Holistic Approach to Ecological Modelling," *Ecol. Modelling* 7:169-189 (1979).
4. Jørgensen, S. E., and H. F. Mejer. "Exergy as Key Function in Ecological Models," in *Energy and Ecological Modeling*, W. J. Mitsch, et al., Eds. (Amsterdam: ISEM and Elsevier Press, 1981), pp. 587-590.
5. Jørgensen, S. E., and H. F. Mejer. "Application of Exergy in Ecological Models," in *Progress in Ecological Engineering and Management by Mathematical Modelling*, D. Dubois, Ed. (Liege, Belgium: CEBEDOC, 1981), pp. 39-47.
6. Mejer, H. F., and S. E. Jørgensen, "Exergy and Ecological Buffer Capacity," in *State of the Art in Ecological Modelling*, S. E. Jørgensen, Ed. (Copenhagen: ISEM, 1979), pp. 829-846.
7. May, R. M. "Patterns in Multi-Species Communities," *Theoretical Ecol. Principles Applications* 8:142-162 (1976).
8. Odum, E. P. *Fundamentals of Ecology*, 3rd ed. (Philadelphia: W. B. Saunders Co., 1976).
9. Pielou, E. C. *Ecological Diversity* (New York: Wiley-Interscience, 1975).
10. Jørgensen, S. E., H. B. Friis, J. Henriksen, L. A. Jørgensen and H. F. Mejer. *Handbook of Environmental Data and Ecological Parameters* (Copenhagen: ISEM, 1979).
11. Jørgensen, S. E. *Lake Management* (Oxford: Pergamon Press, Inc., 1980).
12. Hynes, H. B. N. *The Biology of Polluted Waters* (Liverpool: Liverpool University Press, 1971).

CHAPTER 5

ENERGY DISCOUNTING

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In the modern economy we seem to employ technological strategies to capture, concentrate and release energy to accomplish certain predetermined objectives. Here, these strategies are called processes of energy transformation. Through them, a flow or stock of energy is converted into a form viewed as more useful to the system of which the transformation process is a part. To carry out the transformation of an energy input into a more desirable output (e.g., coal into space heat, mechanical motion, electricity, process heat, etc.), energy flows are required to construct facilities and to operate and maintain the transformation processes. These flows are called processing energies.

In theory, it is possible to trace down and add up all the processing energies required from the entire economy for the creation and operation of a particular transformation process [1].* It is also possible theoretically to construct the most efficient alternative within existing technology to convert these processing energies into the desired output. To the extent that

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*An industrial society also relies on an endowment of available energy when it extracts nonenergy minerals from their naturally occurring concentrations. For the U.S. economy in 1967, this quantity was less than 1.5% of fossil fuel consumption. Consequently, such energy forms are not included here. Also two assumptions were made: (1) that the caloric value of the fossil fuels is equal to total availability; and (2) that nuclear-produced electricity and hydroelectricity can be counted as though they were produced by plants using fossil fuels.

the transformation process under examination can produce more of the desired output than by using the processing energies in the least-energy-cost alternative technology, a surplus of the desired output would be created. Society values any energy transformation process in proportion to the amount of this physical surplus it can produce beyond that needed for self-replication. Moreover, the value of the transforming process to society also depends on whether the ratio of the desired output to the value of the most efficient conversion process is rising, remaining steady or falling over the long run.

Does the transformation process produce a surplus of the desired output? And is this surplus rising or falling with time per unit of input? These questions are the focus of this chapter. The first question establishes the feasibility of using a given transformation process; the second question, the desirability of its use. Together they form a set of necessary conditions for the development of a given energy transformation process.

This view was common among such French physiocrats as Cantillon and Turgot, in the mid-eighteenth century. Single-factor theories of value may not explain rational economic behavior. However, when scarcity problems arise on general inputs that are critical, single-factor analysis may provide useful insights. In a sense, the physically based view of value and scarcity followed here is akin to the views of Ricardo and Malthus, who forecast a diminishing return from land with increasing inputs of capital, labor and technology.

The measure proposed in this chapter is similar to the empirical economic measure used by Barnett and Morse [2], except that they employ cost per unit of extracted resource. The proposal given here is reminiscent of the surprisingly accurate physical-scarcity measure of Hubbert [3] and of the more recent theoretical measures proposed by Fisher [4].

In fact, most modern economists try to determine scarcity according to variations in the total extraction or discovery cost for a unit of resource. The procedure is difficult, however, because it is hard to define the stage of resource development that is most appropriate. For example, Kakela [5] has shown that while lean pelletized taconite (iron) ore is more expensive than natural ore per unit of iron content, iron produced from the taconite is less expensive in the end. This overall improvement in resource efficiency stems from the fact that the taconite pellets allow a uniform and, consequently, rapid decomposition in the blast furnace. Therefore, the best approach is to identify clearly the output of an energy transformation process and to evaluate changes in the total processing inputs per unit of output. Accordingly, the input fuel being converted by the transformation process directly into the output is not included in the present analysis. This input fuel is seen as flowing from the resource base into the economic system, and the processing energies are thought of as having already been committed to use. The processing energies are seen as originating from within the economic system and as carrying with them the option of being used in alternative devices to produce the desired output. They represent an energy "surplus" formed in a previous period and ready for "investment" or present consumption. The question is where this potential energy investment should go to achieve a maximum return, or whether the proposed transformer could provide enough energy to more than reproduce itself using the most energy-efficient existing technology.

In this chapter, a method is proposed and evaluated by which the feasibility and desirability of energy transformation processes can be determined. The degree to which a resource is exploited by a particular transformation process is tempered by its total demand for labor (particularly if labor is scarce), capital and critical materials, as well as the environmental impact created by its use.

To avoid dollar measures of transformation processes, a physical measure is employed, in the spirit of Cantillon, Malthus and Hubbert. The monetary value of energy may not always represent its true value to the society because of subsidies [6], inaccurate pricing techniques and policies, and accounting confusion caused by inflation. For example, new supplies of energy seem to compete on the basis of the marginal dollar cost of energy, while energy conservation measures tend to compete with the average cost, which generally is lower. This phenomenon occurs because utilities are facing a higher marginal cost for fuel than are their customers. Therefore, saving a unit of energy is a more stringent test of cost-effectiveness than is producing a new unit. For system feasibility and desirability, the requisite criterion is one under which a process that saves a unit of energy becomes comparable to processes through which a unit is withdrawn from a stock, or captured from a flow of sunlight or geothermal flows.

It may be interesting, but not instructive, to compare the energy and dollar costs of producing a unit of comparable energy. The United States has not yet experienced much scarcity of any significant natural resource. Therefore, it would not be surprising to find that on the basis of historical data, an energy cost ranking of alternative ways to produce a unit of energy is the same. Later, we shall see that under certain circumstances nothing can be implied about energetic feasibility from financial feasibility: a proposed energy technology may be economically feasible but not energetically feasible. Again, the aim here is to demonstrate an energetic feasibility and desirability criterion that can be applied to proposed energy projects and that gives reasonable results when applied to historic ones.

Finally, since the dollar cost of energy is not yet a major factor affecting optimum production in cost-minimizing industries, optimal solutions for the minimal use of physical energy are appropriate. For example, Pilati [7] has shown that near the minimum dollar-cost solution for the U.S. paper industry (within 1%), the physical-energy cost could vary by a factor of 2.5 for the same production level. In the steel industry [8] we found that increased scrap recycling is energetically, but not economically, feasible. In the construction industry [9], we found an example of a major building where double glazing was energetically, but not economically, feasible. Therefore, the criterion used here must measure energy in physical units.

This chapter probably will be most useful to persons involved in economic planning. The process described may be the most appropriate one for an economy facing the scarcity of a factor that is critical to production. Attempts to estimate the future prices of an increasingly scarce resource proved to be impractical during the 1970s. The strategy proposed here may be the alternative. The main intent, however, is to provide a mechanism that augments the information gained from economic analysis.

An ulterior motive for deriving the above concept is to aid in developing a description of the economy that could be used to describe ecosystem behavior. The long-term goal is to describe economic and ecological systems within a single framework. It is taken as axiomatic that a common currency (e.g., energy) must be used, and that causality exists in both ecological and economic systems.

DEFINITIONS AND ASSUMPTIONS

An energy-transforming system is defined as a process in which an input of a stock or flow of energy is changed into an output of greater utility to the society. "Utility" here has a physical definition: outputs of equal utility have the same thermodynamic availability and the same convenience level, e.g., a stored or flowing energy, a solid or liquid fuel, with or without pollution control. The system receives inputs of a raw or semiprocessed form of an energy stock or flow that it will transform directly into an output of high utility. The system also receives inputs of processing energies from either stocks or flows of energy.

To be complete, this processing must include all the energy needed both directly and indirectly to construct, operate and maintain the energy transformation process. For example, the processing energy must include that needed to preprocess and deliver the fuel to the plant or facility in which the energy transformation takes place. The processing energy must include such quantities as the energy needed to mine the iron ore that provides the steel for the construction and maintenance of the transforming facility or complex.

To obtain appropriate estimates for these energy inputs requires using the results of the energy input-output model developed at the University of Illinois (UI) [10], or the equivalent. The processing units of the UI model are called primary energy, meaning that all uses of, say, electricity have been transformed into all the energy that was removed from the ground to produce the electricity.

However, the processing energies do not include the energy going directly from the energy sectors of the economy to final consumption. Such energy demands as the fuel for work-related travel, exports of coal, and the space heating of government office buildings are not included because of historic, national accounting-base conventions. All such energy together with its processing energy amounted to 46% of total U.S. energy use in 1967 [10].

Costanza [11] recast the accounting procedure to include this significant amount of energy into the appropriate production processes throughout the economy. He also included an estimate of the solar energy consumed through agricultural processes. Such solar energy and labor- and government-related energy costs are not included in the calculations given here partially because most of the extant calculations were completed before Costanza's work was published.

Two sets of circumstances mitigate the effect of this omission, for the purposes of this chapter. First, some of the energy used for personal consumption (the energy cost of labor) and for government may be discretionary. The use of gasoline for pleasure driving and the heating of unused rooms are obvious examples. If such discretionary use does exist, then the energy cost of labor and of government are overestimated by Costanza. Second, it is shown later that even inclusion (approximate) of the labor and energy costs in the feasibility calculation does not reduce the usefulness of the energy calculation.

Baumol and Blackman [12] argue that each input to an energy producing process has an "energy opportunity cost," defined as the energy needed to replace that input when it is withdrawn from elsewhere in the economy. They estimate that the actual energy opportunity cost is small when compared to the theoretical value. Hannon [13] has argued that energy is needed to supply the added consumption arising from spending dollars saved as a result of the more dollar cost-effective investment. Neither this effect nor the energy opportunity cost are incorporated in this chapter.

The flows of replacement capital are incorporated into the analysis done by the Energy Research Group at the University of Illinois, but this is not the case with all of the examples used here. All examples calculate the energy cost of the directly used capital devices, but some neglect the energy cost of the indirect capital consumption. At this time, it is extraordinarily difficult to measure the magnitude of error induced by this omission.

The system might receive a direct input of its own output. This type of input is considered internal to processes of transformation and is reflected in a diminished net output.

The system of energy transformed is shown schematically in Figure 1.

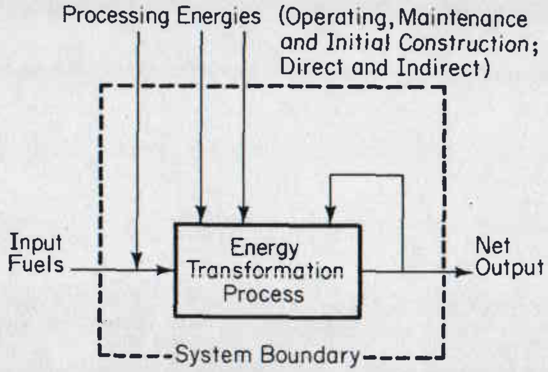

Figure 1. Basic energy system.

METHODOLOGY

The Return on Net Energy Investment

To describe the feasibility criterion, a term, R, is used. "R" is the return on net energy invested: the net output divided by the processing inputs. There are at least three apparently reasonable ways to calculate the ratio. When the ratio is formed for a series of comparable energy transformation processes, each calculation scheme gives a different ranking of the ratios. Therefore, justification must be given for the scheme selected.

One of the alternative methods is similar to the familiar return-on-investment criterion used by many corporations to rank the potential of investment projects using profits. But the view taken in this chapter is that of "society-as-corporation." Therefore, the return should be based on the available surplus, or profit, that society has generated. Under this view, the output of the energy transformation process must be divided by the processing energies required.

The second alternative method involves consideration of the direct use that a transformation process makes of its own output. This direct input (see Figure 1) could be placed in the denominator of the return ratio (as a positive value) or in the numerator (as a negative value). The latter location was chosen here because to group this direct input with the processing energies would be to consider it a surplus about whose use society has a choice. But it is not such a surplus. This direct input is a function of the transformation process used. Thus, this energy is deducted from the gross output of the process, and the net output is divided by the processing energies to form a ratio called the "return on net energy investment."

For an appropriate ratio, compensations must be made in the numerator and denominator for differences in quality and types of end use and time of use. To correct the ratio for quality and utility differences, a symbol for total energy efficiency, α, was used. Alpha represents the most efficient known means of converting primary energy into the exact form needed as an output. To correct for differences in the time at which processing energies are committed for use, a standard continuous-discounting function, $e^{-\lambda t}$, was employed.

In my judgment, the discount rate, λ, is the mechanism by which society implicitly expresses its desire to convert a present surplus energy into an energy transformation process so a greater surplus of energy can be created in the future, rather than consuming the energy now for purposes such as home heating, leisure and certain types of food consumption. While it is usually believed that people discount the total *dollar* value of goods and services, it is not inconceivable that they also discount energy. The apparent dollar discount rate might be viewed as a composite of the discount rates of the various physical inputs to produce each good or service.

The economist J. R. Hicks realized that physical interest rates exist [14]; however, he calculated them based on money interest rates and present and future commodity dollar values. He concluded that since money was the society's standard of value, the money interest rate was a composite of these physical commodity interest rates. His conclusion implies that energy is being used as a standard of value in this chapter. When energy is unambiguously and correctly priced in dollar terms, it is reasonable to expect that energy and financial analyses would yield identical results.

Because of the time element, it is far easier to express the energy uses as a time rate or as power. Figure 2 depicts the highly simplified power diagram of a general energy transformation process.

Figure 2 displays a linearly declining output of a transformation process for constant construction, maintenance and operation processing energies.

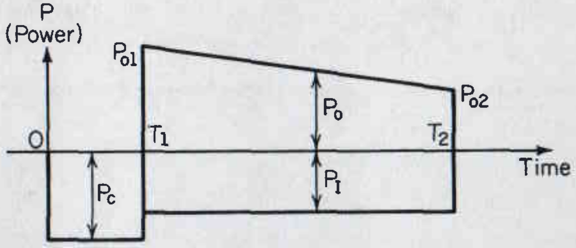

Figure 2. Simplified power curve of a general energy transformation process in undiscounted units.

The declining output represents an increasingly dilute fuel source or a declining energy efficiency for an output device. An example of the latter is the tendency of photovoltaic cells to become inoperable after a time [15]. The remainder of the power curve is simplified because available data on energy transformation processes in most cases are not detailed enough to allow a more elaborate representation.

In Figure 2, P_{o1} and P_{o2} are the initial and final net power outputs at times T_1 (the construction period) and T_2, respectively ($\Delta T = T_2 - T_1$, the lifetime). P_c and P_I represent the primary energy input rates for construction and maintenance and for operation, respectively. m is the slope of the net output rate;

$$m = \frac{P_{o2} - P_{o1}}{T_2 - T_1}$$

The equation for R, the return on net energy investment, based on the diagram in Figure 2, is

$$R = \frac{\alpha \int_{T_1}^{T_2} P_o e^{-\lambda t} dt}{P_c \int_0^{T_1} e^{-\lambda t} dt + P_I \int_{T_1}^{T_2} e^{-\lambda t} dt} \tag{1}$$

Equation 1 is integrated to give

$$R = \frac{\alpha \left[\left(m\Delta T + \frac{m}{\lambda} + P_{o1} \right) e^{-\lambda \Delta T} - P_{o1} - \frac{m}{\lambda} \right]}{P_c(1 - e^{\lambda T_1}) + P_I(e^{-\lambda \Delta T} - 1)} \tag{2}$$

The numerator of Equation 1 may be thought of as the present amount of primary energy saved by the future output of the proposed transformer. The denominator of Equation 1 is the present value of the primary energy needed to effect these savings. Consequently, α must represent the total primary energy conversion efficiency (including the input fuel) of the present technology that most efficiently (energetically) generates energy of the same quality as the proposed transformer. Note that the input fuels to the proposed technology are not counted, but input fuels are counted in the existing technology. This difference arises from the concept of energy in its natural state versus energy in society, poised for present consumption or investment. This distinction also is needed to determine whether the proposed transformer could provide enough output energy to reproduce itself using the most efficient, presently available technology.

The normalization of the output power by the processing powers in Equations 1 and 2 is similar to the power-gain calculation used by electrical engineers for amplifying circuits. The processing powers are similar to the control power used in such circuits. The engineers are interested in how the output changes with respect to changes in the control power.

The discount rate is zero in amplifying circuits, of course. A zero discount rate in Equation 1 produces the standard form of the net energy equation commonly used by energy analysts. Most calculations of energy feasibility [15,16] compare the average annual net output with processing input plus the initial construction energy. The construction energy is divided by the expected lifetime of the system. In this scheme, the sequencing of the energy expenditures has no effect on the ratio of net output into net input.

To show that economic and energetic benefit-cost analysis yields unique and independent results, simplify Equation 2 by assuming very long operating lifetime and a constant output power level. The energy return, R_E, is

$$R_E = \frac{\alpha P_o}{P_c(e^{\lambda T_1} - 1) + P_I} \tag{3}$$

In a similar way, the dollar return, $R_\$$, can be defined as follows:

$$R_\$ = \frac{\alpha P_o p_E}{\frac{P_c}{\epsilon_c}(e^{qT_1} - 1) + \frac{P_I}{\epsilon_I}} \tag{4}$$

where p_E is the average price of primary power in the economy, q is the real financial discount rate, and ϵ_c and ϵ_I are the direct and indirect energy used per unit of produced capital and maintenance-operation, respectively.

The ratio of the returns can be formed:

$$\frac{R_\$}{R_E} = \frac{p_E(e^{\lambda T_1} - 1)P_c + p_E P_I}{\frac{1}{\epsilon_c}(e^{qT_1} - 1)P_c + \frac{1}{\epsilon_I} P_I} \tag{5}$$

Note that since λ and $q \geqslant 0$, then $e^{\lambda T_1} - 1$ and $e^{qT_1} - 1 \geqslant 0$. Note further that $P_E \epsilon_c$ and $p_E \epsilon_I \leqslant 0$, since the direct and indirect dollar cost of energy is not the only dollar cost input to capital or maintenance-operation services.

Then, if $\lambda = q$, $R_\$/R_E \leqslant 1$ from Equation 5. This is the result achieved by Bullard [17]. Thus, if a project is financially feasible, it automatically would be energetically feasible. But if $\lambda > q$, nothing can be determined about energetic feasibility from financial feasibility, as can be seen from the examination of Equation 5. Normally, the real financial interest rate is about 2–3%. In this chapter the energy discount rate is found to be much higher. The energetic analysis appears to yield unique results, which are potentially different from results of a financial analysis.

The Feasibility of Energy Transformation Processes

Energy analysis provides a more unusual situation than is generally found in economic analyses of benefit and cost. In economic accounting the discount rate is treated as known. Projects are ranked on the basis of highest to lowest R. In the case of energy discounting, one must determine first the appropriate λ and then use Equation 2 to rank the resulting values of R. To determine the appropriate λ, R in Equation 2 was set equal to 1. The equation was then applied to all *existing* energy transforming processes and solved for λ in each instance.

The resulting values for λ may be viewed as an "internal" energy discount rate for society. In this view, it is conceivable that some exceptionally efficient processes would have very high rates, analogous to the very high return rates achievable on certain very efficient internal investments of a corporation.

The smallest λ is assumed to be the energy discount rate presently used by society. In the corporate analogy, this minimum value is the market discount rate. This minimum "revealed" λ is used in Equation 2 for all existing and proposed energy transformation processes to produce a ranked list of R's. Under the definitions used with the theory, society would rather consume a unit of energy now than invest in a transformation process with an R of less than 1. Even though such transformation processes may have a positive R, the amount of surplus energy produced beyond the breakeven point is not large enough to justify the use of that process.

An interesting problem arises if we put the analysis on an identical basis with ordinary financial discounting. Then the P_I of Equation 1 would be augmented by the rate at which the energy content of the fuel is processed into the output energy. With certain values of P_o, P_c and ΔT, λ can then become complex or negative, and apparently meaningless.*

Another interesting problem arises that is not pursued here. Equation 2 may be used to determine the maximum R when the size or size-distribution parameters are varied. These parameters are fixed in the examples used in this chapter. The question is, for example, would a few, coal-fired electric plants have a higher return on energy investment than many smaller, cogenerating, coal-gas-electric ones when producing the same end utility?

The value for α must be chosen to represent the most efficient practical way of converting from primary energy to the desired output form. The assumption made is that α applies in Equation 2 when: (1) the output energy is in the form of electricity, $\alpha = 4.0$ [10]; (2) the output is space heating, $\alpha = 1.5$ [18]; or (3) steam is being produced, $\alpha = 1.15$ [19]. An additional assumption is that $\alpha = 1$ in all other processes.

The last value ($\alpha = 1$ in all other processes) is tantamount to assuming that oil, coal, gas, ethanol, wood chips, etc. are of equal utility. The correction is made by calculating the best conversion efficiencies that can be achieved between the input forms and the output form. For the purposes of this chapter, the assumption that $\alpha = 1$ in all transformations producing alternative fuel forms is sufficiently accurate.

The efficiency value for electricity production ($\alpha = 4$) reflects the aggregate efficiency in 1967 of all electric plants using fossil fuels. As such, the value includes oil- and gas-fired plants that did not need significant pollution control devices; many of the coal-fired plants already had precipitators by that time. Therefore, it is assumed here that the value of $\alpha = 4$ is sufficiently representative of the least-energy-cost alternative to all of the options for producing electricity.

In converting the process inputs into the desired type of output, the efficiency $1/\alpha$ includes the energy costs of the capital needed directly and indirectly for the conversion process. This capital energy cost is annualized and then added to the operation and maintenance energy to produce α. Although the effect of time should be considered in the α calculation, that effect is omitted here because of its small contribution to R in Equation 2. Including capital energy effects influences by about 7–8% the energy costs of the average product produced [20]. Here, α includes the capital effects, but in an approximate way ($\lambda = 0$). One can arbitrarily limit the error by an integration of the trial-and-error solution of Equation 2.

The value of α could be reduced to represent the energy lost by placing and maintaining the output in storage (e.g., photovoltaic cell output). Conversely, the amount of fossil fuel backup needed to provide the desired output pattern could be added to P_I. Either way, the return from the net energy investment is reduced.

The Effects of Scarcity on the Desirability of an Energy Transformation Process

The foregoing analysis allows us to determine the feasibility of a particular transformation process at a given state of energy resource availability. The analysis also allows us to rank those transformation processes that produce a certain desired type of output (e.g., electricity), by a descending order of feasibility.

If net energy efficiency were the only consideration, such a ranking would show the order to be followed in the development of energy transformation

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*For a positive and definite λ, $\alpha P_o > P_I \geqslant 0$ is the necessary condition.

facilities, that is, the relative desirability of each process. However, if each transformation process deemed feasible were to operate on the resource base, its R value eventually would decline even though the facility would continue to produce at constant output capacity.

The decline may occur because (1) λ would be increasing (a change in social objectives, perhaps driven by a reduced concern about scarcity); (2) α would be decreasing (improvements made in the energetic efficiency of the least-energy-cost alternative); or perhaps (3) the amount of processing power per unit of output power would be increasing in a present-value sense (input scarcity). These three factors embody changes in consumer behavior, transforming technology and energy scarcity.

The processes of energy transformation with the highest, most slowly declining R values are the most desirable ones. Among these technologies, those that depend on politically stable supplies of fuels and materials and those that make socially agreeable demands on the labor force, capital market and the environment are the ones that should be developed intensively. Transformation processes with R values that are close to or less than 1 should be dropped from consideration or be the object of further research and development.

Even so, we still do not know how to phase together the ranked technologies for energy transformation to produce the net energy with the greatest present value. To accomplish this phasing, assume that the only reason for the decline in R values is a scarcity of input energy; for example, the coal available to a power plant in a certain region might be found to be in thinner and deeper seams. Assume also that the peak efficiency of scale in energy production had been reached; for example, an incremental increase in the energy efficiency of a large power plant in a certain region would be exactly offset by a decline in the energy efficiency of coal-gathering and electricity transmission. Let the cumulative present value of the output energy be f and the cumulative present value of the capital, operation and maintenance processing powers (energy) be g. (Both f and g are energy measures.) Each transformer has a characteristic relationship, as shown in Figure 3, because of the two assumptions just made.

The three curves in Figure 3 could represent, for instance, the use of oil from Texas, the Middle East and Alaska to move a ton-mile of rail freight with a diesel-electric engine. As is easily proven, the calculation for R is independent of the time lapse from $f = g = 0$ (R depends only on time periods T_1 and ΔT). Therefore, the curves $f = f(g)$ do not depend on the time lapse. Consequently, the curves in Figure 3 can be constructed from the present values of f and g, which are calculated for each energy transformation process independent of its time sequencing.

The derivative df/dg at any point along the curves for any of the three transforming technologies is the return on net energy investment, R. The process labeled I would be the logical place to begin for it has the highest possible initial value of R ($=R_1$) for all three processes. However, when the cumulative energy output reaches point a, it would be appropriate to switch to the second transforming technology (II). At point a, the initial R of the second transforming process would be equal to the current R ($R - R_2$) for the first process. The second process would be employed until its R value declined to point b, where it becomes equal to the highest ($R = R_3$) value for the third process. This pattern would be continued through the range of available transforming technologies until the present-valued R reached 1 (point c).

If the discounting value or the least-cost alternative efficiency should change, Figure 3 would have to be reconstructed. The above procedure still would be followed, but using the newly computed information.

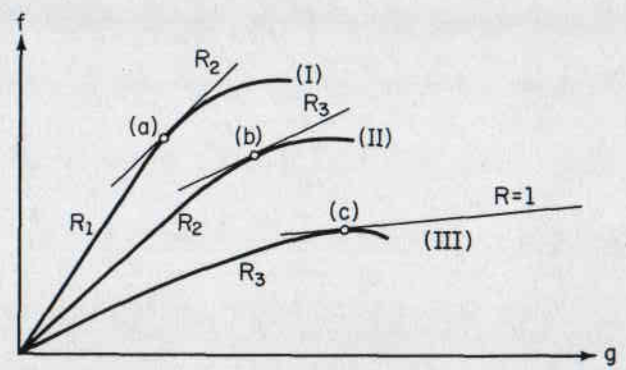

Figure 3. The cumulative present-valued output energy, f, vs the cumulative present-valued processing energy, g, for three energy-transforming technologies.

RESULTS

Data for the feasibility calculation only were found in 44 energy-transforming processes (Table I). Only the solar-powered satellite transformation process showed a decline in output power with constant energy for maintenance and operation. This decline is not an example of the scarcity phenomena already described. Rather, it is typical of an individual satellite unit. Only if the allotted section of the geosynchronous orbit were filled with such units would scarcity begin to lower R values. None of the examples identified in this study showed scarcity responses. Most of the examples were based on the University of Illinois Energy Input-Output model [3], but only one contained an indication of error tolerances [15]. However, the individual authors used different techniques to assign joint energy costs and to credit by-products. Every possible effort was made to place the data in a common framework. Yet, these problems and the assumptions stated earlier make the results in Table I an interesting experiment at best.

No firm policy conclusions should be inferred without further research. For the purposes of demonstrating the potential usefulness of this approach, however, the results were analyzed as though the data were sufficiently accurate.

The examples in Table I were divided according to the output of the process: fuel production, electricity production, space heating and conservation. The first three are segmented into nonrenewable and renewable sources of fuel.

Even though a certain process may have a very high return on the energy investment, the potential for that process may be limited in terms of producing significant additional quantities of useful energy. For example, in the United States, most large and convenient sites for the production of hydroelectricity are already exploited. Yet, because of the negligible operating and maintenance energy, hydropower could have a very high R value. Additional units of such processes should show a rapidly declining R (calculated) as a result of increases in the capital requirements and energy transmission losses per unit of output.

CHOOSING THE DISCOUNT RATE

Equation 2 with R value equal to 1 was applied to each process and solved for λ by trial and error.* The low end of the resulting λ spectrum contains both solar and nuclear processes. The lowest λ value (λ = 13%) is for the high-temperature gas (nuclear) reactor (HTGR). This process, like the light-water (nuclear reactor (λ = 19%)) has a low value for λ because of the large capital outlay required before operation begins. Note that if electricity produced by the light-water reactor process is used for heating, the resulting λ is about 8%.**

Since it is not clear whether society is aware that such a practice occurs (because of the mix of plant types on the same electricity distribution

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*Remember that none of the processes considers the energy content of the fuel that is processed into the final energy output.

**From Equation 2, we see that lowering α by 63% (4 to 1.5) drops the R value by 63%.

Table I. Calculation of the Return on Net Energy Investment, R (from Equation 2)[a]

Process	Years T_I	Years ΔT	α	P_O	P_I	$P_C \cdot T_I$ (a)	$\lambda\left(\frac{1}{Yr}\right)$ Percent (R = 1)	R (λ = 0.19)	R λ = 0	Comment (Reference)
Fuel Production										
Nonrenewable										
Methanol from natural gas	3	20	1	1	0.42	0.20	76	2.1	2.3	Not used as a fuel [21].
Natural gas	5	30	1	1	0.17	1.32	28	1.7	4.7	Includes delivery [22].
Gasoline	4	25	1	1	0.074	0.63	48	3.9	10.1	Includes delivery [22].
Renewable										
Intensive tree plantation	0.5	15	1	1	0.20	0.091	340	4.6	4.9	Jack pine; chipped, dried [23].
Natural tree plantation	0	15	1	1	0.21	0	–	4.8	4.8	Chipped, dried [24].
Crop plantation (for fuel)										
Corn	0.5	10	1	1	0.35	0.013	660	2.8	2.9	New Mexico, Fert. & Dry [25].
Wheat (dry)	0.5	10	1	1	0.19	0.067	390	4.9	5.1	New Mexico, Fert. & Dry [25].
Wheat (irrigated)	0.5	10	1	1	0.48	0.043	390	2.0	2.1	New Mexico, Fert. & Dry [25].
Sorghum (dry)	0.5	10	1	1	0.25	0.043	455	3.8	3.9	New Mexico, Fert. & Dry [25].
Sorghum (irrigated)	0.5	10	1	1	0.31	0.031	500	3.2	3.2	New Mexico, Fert. & Dry [25].
Alfalfa	0.5	10	1	1	0.37	0.051	394	2.6	2.7	New Mexico, Fert. & Dry [25].
Peanuts	0.5	10	1	1	0.89	0.08	105	1.1	1.1	New Mexico, Fert. & Dry [25].
Methanol (wood)	4	20	1	1	0.34	1.00	32	1.6	2.6	Coal-fired distillation. Low R, does not include Octane Credit [21].
Ethanol (corn)	4	20	1	1	0.75	0.75	21	1.03	1.3	Low R, does not include Octane Credit [26].
Electricity Production and Distribution										
Nonrenewable										
Coal	5	25	4	1	0.09	0.48	75	16.4	36.6	U.S. Average [16]} No scrubbers.
Combined cycle (coal)	4	25	4	1	0.03	0.84	75	14.8	62.9	[16]} No scrubbers.

Table I, continued

Process	Years T_1	Years ΔT	α	P_o	P_I	$P_c \cdot T_1$ (a)	$\lambda \frac{1}{Yr}$ Percent (R = 1)	R (λ = 0.19)	R λ = 0	Comment (Reference)
Eastern surface[b] coal										
No scrubber	5	30	4	1	0.06	1.00	61	10.6	42.9	300-mile coal haul [27].
Limestone scrubber[c]	5	30	4	1	0.34	1.10	57	5.8	10.6	
Western surface[b] coal										
No scrubber	5	30	4	1	0.13	1.11	58	8.3	24.0	1120-mile coal haul; western coal not as intensively scrubbed as eastern coal to meet same emission standards [27].
Limestone scrubber[c]	5	30	4	1	0.36	1.20	56	5.4	10.0	
Coal; w/limestone scrubber[d]	5.5	30	4	1	0.19	0.80	60	8.7	18.5	[29] Less complete analysis than [27].
Coal; fluidized bed (pressurized)[d]	5.5	30	4	1	0.12	0.82	60	10.1	27.1	
Solvent-refined coal	5	25	4	1	0.38	0.72	66	6.6	9.8	[16]
Coal-gas	5	25	4	1	0.23	0.96	61	7.4	14.9	[16]
Shale-gas	5	25	4	1	0.52	0.84	62	5.1	7.2	[16]
Oil-gas	5	25	4	1	0.52	2.04	45	3.4	6.7	[16]
Natural gas	5	25	4	1	0.32	1.08	58	6.0	11.0	[16]
Nuclear										
LWR[e]	6	25	4	1	0.14	11.27	19	1.0	6.8	[16]
HTGR[e]	6	25	4	1	0.11	18.30	13	0.6	4.8	[16]
Geothermal[d]	3.1	30	4	1	0.18	2.28	59	5.2	15.6	Liquid-dominated, high-cost option [30].
Renewable										
Wood (no pollution control)[d]	5	30	4	1	0.802	0.59	67	4.0	4.9	Assumed efficiency = 0.3 [31].
Solar power satellite[d]	5	30	4	1.00 0.44	0.008	9.9	21	1.1	8.5	Output decline [15].
Photovoltaic No storage or backup fuel or transmission costs	0.2	20	4	1	0	12.0	32	1.7	6.7	[32]
Wind	0.4	30	4	1	0	0.15	614	135.0	800.0	Estimated construction time [33].
Power tower	5	30	1.15	1	0	0.54	49	6.7	64	Test facility, steam production only [32].
Space Heating										
Nonrenewable										
Gas furnace	0.25	20	1.5	1	0.15	0.22	38	7.7	9.3	Ref. [34]. Operation energy [10].
Electric										
Nuclear LWR	6	25	1.5	1	0.21	10.53	8	0.4	2.4	
Coal	6	30	1.5	1	0.307	1.00	35	2.3	4.4	Eastern surface mine, conventional scrubber [27].
Renewable–solar										
Flat plate collector	0.5	20	1.5	1	0.56	5.05	17	0.9	1.9	Fossil fuel backup [34].
	0.5	20	1.5	1	0.60	6.89	11	0.7	1.6	Fossil fuel backup [35].
Concentrating collector	0.5	20	1.5	1	0.56	4.31	20	1.0	1.9	Fossil fuel backup [34].
Direct solar gain	0.5	20	1.5	1	0.4	0.93	93	2.5	3.4	Fossil fuel backup [34].
Conservation										
Double-pane windows	0.1	30	1	1	0	0.22	375	24.0	136.0	Chicago [36].
Ceiling insulation (Retrofit-National Program)	7	30	1	1	0	0.49	39	5.1	61.0	Retrofit National Program [37].
Urban car to bus	1	14.8	1	1	0	0.44	118	10.2	34.0	[38]
National Energy Plan I (commercial and residential)	5	20	1	1.0	0	0.12	76	26.4	171.0	Very approximate [39].

[a] *To put this column into average power terms, divide by* T_1.

[b] Surface mine R values only 2% higher than underground R values. A variation in the construction period, T_1 of ±one year gave a variation in R of from ±6% to ±10%, the higher variation being associated with the higher R values.[e]

[c] A Wellman-Lord scrubbing process lowered R by 28% while the limestone scrubbers lowered R by 43%.

[d] The input requirements of these processes were increased by 9% to reflect the losses in transformation and transmission [28]. Data from Reference 16 contained this correction.

[e] If the construction period were 9 years instead of 6, the resulting λ would be 16% and 12%, respectively.

system), the higher value of λ for the light-water reactor was chosen as the base for all calculations on energy returns. If electricity were not subsidized [6] and were priced marginally rather than on an average [40], only minor amounts of electricity might be used for heat.

The flat-plate solar collectors (λ = 11 and 17%) and the solar-powered satellite (λ = 21%) have low λ values because of the large initial capital investment. The solar-powered satellite also has a declining output over its lifetime because of the slow, irreversible degradation of the photovoltaic cells caused by cosmic radiation. The discounting process makes this decline less important that it would be if λ were zero.

The solar-concentrating collector (λ = 20%) provides only a small improvement over the flat-plate collector. Ethanol from corn (λ = 21%) owes its low λ value to the high operational energy generally employed to fertilize the corn and to distill the alcohol.* Methanol from wood (λ = 32%) is a superior process to ethanol (corn) in overall energy efficiency and has the same λ as earth-based photovoltaic cells. Natural gas production (λ = 28%) is a nonrenewable energy source with a surprisingly low λ value. The relatively high λ values for photovoltaics, windmills and the solar power-tower would be reduced considerably if energy costs for storage were included.

Therefore, the only appropriate solution to Equation 2 with R = 1 was for the light-water nuclear reactor. This is the only technology with a low λ value that is presently used to transform significant quantities of primary energy into desired forms of output (electricity). The discount rate for this technology (λ = 0.19) represents the lowest that society will accept, assuming that such a rate even exists. No other widely used technology has a lower λ value.

How sensitive is this rate to changes in the key variables? We can define a standard elasticity equation as

$$e_{T_1}\lambda = \frac{T_1}{\lambda}\frac{\partial\lambda}{\partial T_1} \tag{6}$$

which is the elasticity of λ with respect to T_1. A small fractional change in T_1 will produce an $e_{T_1\lambda}$ fractional change in λ.

Equation 6 was applied to each of the variables. The results are given in Table II.

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*Suppose that the distillation process involved in making ethanol from corn had been solar heated. How would this energy have been included in Equation 2? First, the heat energy absorbed would have been included in the operating energy. Second, the α would have to have been modified to contain the efficiency of the conversion of that solar radiation absorbed to a similar form of output (possibly dried biomass).

Table II. Elasticities for the Key Variables in Equation 2 (R = 1) Applied to the Light-Water Nuclear Reactor Process (λ = 0.19)

T_1	ΔT	P_o	P_I	P_c
−0.995	−0.001	+0.960	−0.960	−0.431

For example, an increase of 1% in T_1, the construction period, would reduce λ by 0.995%. A 1% increase in the energy rate used in the construction period, P_c, would reduce λ by 0.431%. The lifetime, ΔT, is not an important variable in solving for λ, but T_1, P_o and P_I are important.

The values in Table II reveal the sensitivity of λ to small changes. For a large change, Equation 2 (R = 1) must be solved again for λ by trial and error. When this was done, the λ sensitivity was not great. For example, a change of 10% in each variable produced a maximum change of 2.5%. It is safe to conclude that λ is not very sensitive in the variables T_1, ΔT, α, P_o, P_I or P_c; also, that T_1 is the most important variable with regard to the determination of λ.

The construction period, T_1, is the least accurate of the variables in Table I. T_1 is derived from pure guesswork in some instances, to averages of actual practice recently. In every case, the construction period is that time during which $P_c T_1$ is expended.

Another assumption is that indirect capitalization takes place during T_1. Here is a key problem in this kind of analysis. The time and energy spent on the direct and indirect capitalization must be assigned to the joint products on what amounts to an arbitrary basis. The longest of these assigned periods is T_1. The shorter periods are superimposed in the most practical order possible. This procedure may not represent reality since iron must be made before steel, which is needed for sheet steel. That, in turn, is necessary for power plant fabrication, and so forth. The practical time for these processes may actually exceed T_1. However, the construction period encompasses the bulk of the capital-forming time for any given process of energy transformation. Therefore, it is sufficiently accurate for the purposes here.

An approximation of the R value for the light-water reactor was made using the changes in energy intensities found by Costanza [9] when he included the energy costs of labor and government. The calculated discount rate drops from 19% to about 7%. Even this value is two to three times the real financial discount rate, indicating that information about energetic feasibility cannot be gained from financial information alone (Equation 5).

Finally, we must realize that the R discussed in this chapter is thought of as an aggregate value for the whole society. Regional variations in the discount rate are entirely possible. These variations might arise from differing local views about the certainty of future fuel supplies and their future costs. The concepts set forth in this chapter are so tentative that delving into regional differences in discount rates must wait for appropriate opportunities with suitable data.

THE ENERGY RETURN ON NET ENERGY INVESTMENT

When we compare the R values, what do we find? The liquefied fossil fuels appear to be superior to the liquefied fuels made from vegetables. Gasoline (R = 3.9) is better than methanol (R = 2.1 or 1.6), which is better than ethanol (R = 1.03). Among the renewable fuels, trees are better than field crops such as corn, whether one is making a solid or a liquid fuel, probably because a young- to medium-aged forest can convert more solar radiation into storage per year and per acre than can a cash crop. Trees also require less fertilization and cultivation per unit of energy stored.

Irrigated crops have lower R values than the same crop without irrigation. Here we see the trade-off between the fossil fuels (irrigation) and land (yield). Finally, on the basis of 1 data point (peanuts), it would seem that the grass crops (corn, wheat, sorghum) are better than legumes. The production and distribution of natural gas has a surprisingly low R value because of the extensive investment required in pipelines and the high energy costs associated with pumping operations.

In the production of electricity, fuels and geothermal sources appear to be superior to nuclear and solar-based processes. The exceptions are windmills (no storage costs included) and perhaps wood. Coal-fired power plants without environmental protection equipment are the most feasible processes (e.g., the conventional coal-electric and combined-cycle processes).

In a more detailed view, we compared coal-electric processes in the eastern and western United States, with and without appropriate scrubbers. Scrubbers reduce the effectiveness of coal-electric plants by 50% to 75%. This efficiency reduction is one way to assess the energy cost of air pollution abatement. With scrubbers, eastern coal is slightly more energy-effective than western coal. The energy return is not affected by the type of mine.

The pressurized fluidized-bed coal-electric process,* prescribed because of its low levels of harmful effluent, has an R value that is 16% higher than that of a scrubbed eastern coal-electric plant. To control coal-associated air pollution, the solvent-refined coal and coal-gas processes are approximately as feasible as using either the scrubbers or the fluidized-bed processes. The shale-gas-electric process is better than the (heavy) oil-gas-electric process.

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*This process and its companion in Table I were not analyzed in as much detail as the others [15,16,29]. They appear only to give the relative energy efficiencies.

The natural gas-electric process, normally thought of as attractive because pollution control is achieved without a major investment, has a similar energy return to the scrubbed-coal electric or the fluidized-bed coal processes under the analysis presented here. The geothermal-electric process, which is free of air pollution, is classed as nonrenewable because the resource rock is actually mined of its heat content. This process has a high R value, comparable to the coal-gas-electric process and the solvent-refined and scrubbed-coal processes.

Of the renewable electric processes, the photovoltaic, wind and power-tower do not store energy. Consequently, they cannot be compared to the other process in Table I. The wind machine is a superior energy converter compared to the photocell or the concentrated solar-heated boiler (power-tower). The wood-electric and the solar satellite processes are comparable because, theoretically, the electrical energy is available on demand from either process. The wood-based process appears to be superior, although reliable data for either process are not available.

The last comparison points up one of the most important technological questions of our time. Can man devise a renewable energy source to meet an arbitrary demand cycle that is superior in energy efficiency to the natural processes of capturing, storing and releasing high-quality energy? The data in Table II indicate that we have not yet managed to duplicate the efficiencies of natural energy. However, the wood-electric process does not include pollution control effects and, therefore, is not strictly comparable to a solar satellite as an energy source.

None of the solar space heating options compare well with the gas-furnace heating system. The direct-gain, or passive solar space heating, process works with flat-plate or concentrating solar collectors and is approximately equivalent to the scrubbed-electric heating process. All space heating processes investigated had a greater net energy return than the light-water nuclear reactor.

Note that the solar processes described use gas heaters to provide heat when solar radiation is not available. By this procedure, one of the energy costs of convenience (demands for energy that differ from the natural solar cycle) can be estimated.

The conservation projects appear to be feasible in terms of overall energy efficiency. They compare well with fossil-based processes in which pollution control strategies are used. The conservation processes are somewhat difficult to fit into the simplified graph in Figure 1 because they are national programs with effects that are being felt before the construction programs are finished. This was true of the ceiling insulation program and of National Energy Plan **I**.

The phenomenon of the extended process points up an interesting and complex problem. Both conservation and supply-construction programs theoretically can proceed at rates that will not produce a net energy output. In general, the data in Table I are achieved only when building rates slow toward a replacement level. Clearly, a proper energy analysis would be applied to the entire program from initiation until a steady-state condition is reached–with the energy costs and benefits being placed in present-value terms. However, as stated earlier, if a single, typical proposal is feasible, the collection is feasible.

Also note the effect on R values of different λ values. When $\lambda = 0$, for example, Equation 1 reduces to the form commonly used by energy analysts. The ranking of the R values in Table I is changed substantially when $\lambda = 0$, mainly because some processes have a long construction period with heavy capital commitments in relation to others.

If the λ value does represent the society's time value of energy, then it should rise during periods when energy is perceived as being plentiful and should decline during periods of energy scarcity. From the values in Table I, we find that a wood-burning society has a value for λ of 67; in a coal-burning society, λ ranges from 75 down to 55 with pollution control; and in the nuclear age, we have a λ value of 19. The minimum λ generally seems to have declined in the United States over the past 100–125 years. From the consumer's viewpoint, this phenomenon would indicate a gradually increasing scarcity of available energy. Eventually, as fossil and nuclear fuels are depleted, the minimum λ will decline until it reaches the level for the steady-state, agrarian society, probably zero. No surplus energy would be needed to replace the depreciating structure and provide for all aspects of the renewal cycle of society and family life. These needs would be considered part of the maintenance energy demand.

Also recall the classic argument of Page [41]. He said that owing to the unavoidable decline in the availability of resource stocks because of use by the present generation, the only way to be totally fair to future generations is to leave them the tools and knowledge to derive as much benefit as we could have originally using the known resources that remain. To accomplish this goal, no better procedure seems conceivable than the one given here.

SUMMARY

The present value, net energy feasibility of 44 energy-transforming processes was calculated and compared on a purely energy-efficient basis. The method allows a quantitative comparison of all forms of supply and end use processes–whether they are from renewable or nonrenewable sources of energy; whether they are fuel, electricity, space heating or transport end use; or whether the energy gain results from a substitution that frees energy for use elsewhere. Processes using fossil fuels generally are superior to most of the solar and nuclear ones. With certain noted exceptions, the conservation processes studied are comparable to fossil fuel processes.

The data are of limited validity and do not allow any firm policy conclusions to be suggested. Even so, I believe, a useful method of energy analysis has been created and demonstrated. The availability of suitable data with the requisite validity would permit the analytical procedure to be applied broadly in the process of formulating and implementing energy policy.

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REFERENCES

1. Joyce, J. "Exergy," Technical Memo 120, Energy Research Group, University of Illinois, Urbana, IL (January 1979).
2. Barnett, H., and C. Morse. *Scarcity and Growth, The Economies of Natural Resource Availability* (Baltimore, MD: Johns Hopkins University Press, 1963).
3. Hubbert, M. "Degree of Advancement of Petroleum Exploration in the U.S.," *Am. Assoc. Pet. Geol. Bull.* 51(11): 2207-2227 (1967).
4. Fisher, A. "Measures of Natural Resource Scarcity," in *Scarcity and Growth Reconsidered,* K. Smith, Ed. (Baltimore, MD: Johns Hopkins University Press, 1979).
5. Kakela, P. "Iron Ore: Energy, Labor and Capital Changes with Technology," *Science* 202(4373): 1151-1157 (1978).
6. Bezdek, R., and B. Cone. "Federal Incentives for Energy Development," *Energy* 5:389-406 (1980).
7. Pilati, D., Brookhaven National Laboratory, Upton, NY. Personal communication (April 15, 1980).
8. Hannon, B., and J. Brodrick. "Energy Conservation in the U.S. Steel Industry," Energy Research Group, University of Illinois, Urbana, IL (April 1981).
9. Hannon, B., R. Stein, B. Segal and D. Serber. "Energy and Labor in the Construction Sector," *Science* 202:837-847 (1978).

10. Bullard, C. W., P. S. Penner and D. A. Pilati. "Net Energy Analysis Handbook for Combining Process and Input-Output Analysis," *Resources and Energy* 1:267-313 (1978).
11. Costanza, R. "Energy Costs of Goods and Services in 1967 Including Solar Energy Inputs and Labor and Government Service Feedbacks," ERG Doc. 262, Energy Research Group, University of Illinois, Urbana, IL (September 1978).
12. Baumol, W., and S. Blackman. "Unprofitable Energy is Squandered Energy," *Challenge* 23(3):28-36 (July-August 1980).
13. Hannon, B. "Energy Conservation and the Consumer," *Science* 189(4197):95-102 (1975).
14. Hicks, J. *Value and Capital*, (Oxford: Clarendon Press, 1950), p. 142.
15. Herendeen, R., T. Kary and J. Rebitzer. "Energy Analysis of the Solar Power Satellite," *Science* 205(4405):451-454 (1979).
16. Pilati, D. "Energy Analysis of Electricity Supply and Energy Conservation Options," *Energy* 2(1):1-7 (1977).
17. Bullard, C. "Energy Cost and Benefits: Net Energy," *Energy Systems Policy* 1(4):367-382 (1976).
18. O'Neal, D. L. "Energy and Cost Analysis of Residential Heating Systems," Report No. ORNL/CON-25 (Oak Ridge, TN: Oak Ridge National Laboratory July 1978).
19. Hannon, B., and J. Joyce. "Energy Conservation Through Industrial Cogeneration," *Energy* 5(4):343-354 (1980).
20. Kirkpatrick, K. "Effect of Including Capital Flows on Energy Coefficients, 1963," CAC Technical Memo. 26 Energy Research Group, University of Illinois, Urbana, IL (August 1974).
21. Hannon, B., and H. Perez-Blanco. "Ethanol and Methanol as Industrial Feedstocks" Report to Argonne National Laboratory, Contract No. ANL 31-109-38-5154, Argonne, IL (September 1979).
22. "Net Energy Analysis, an Energy Balance Study of Fossil Fuel Resources" Colorado Energy Research Institute, Colorado Springs, CO (April 1976).
23. Zavitkovski, J. "Energy Production in Irrigated Intensively Cultured Plantations of Populus, Tristis #1 and Jack Pine," *Forest Sci.* 25(3):383-392 (1979).
24. Blankenhorn, P., W. Murphy and T. Bowerlox. "Energy Expended to Obtain Potentially Recoverable Energy from Forests" *TAPPI, Forest Biology-Wood Chemistry Conference*, Madison, WI (1977), p. 277.
25. Patric, N., "Energy Use Patterns for Agricultural Production in New Mexico" in *Agriculture and Energy* (New York: Academic Press, Inc., 1979).
26. Chambers, R. S., R. A. Herendeen, J. J. Joyce and P. S. Penner. "Gasohol: Does It or Doesn't It Produce Positive Net Energy?" *Science* 206:789-795 (1979).
27. Penner, P., J. Kurish and B. Hannon. "Energy and Labor Cost of Coal Electric Fuel Cycles," Document No. 273, Energy Research Group, University of Illinois, Urbana, IL (April 1980).
28. *Statistical Yearbook for 1976*, Tables 10s and 20s, Average for 1975 and 1976 (Washington, D.C.: Edison Electric Institute, 1977).
29. Whittle, C., and A. Cameron. "Energy Requirements for Fluidized Bed Coal Combustion in 800-1000 MW Steam Electric Power Plants," Institute for Energy Analysis, Oak Ridge, TN (February 1977).

30. Herendeen, R., and R. Plant. "Energy Analysis of Four Geothermal Technologies," *Energy* 6:73-82 (1980).
31. Gunn, T. L. "The Energy Optimal Use of Waste Paper," ERG. Document 263 Energy Research Group, University of Illinois, Urbana, IL (November 1978).
32. Grimmer, D. "Solar Energy Breeders," Report No. LA-UR-78-2973 Los Alamos Scientific Laboratory, Los Alamos, NM (1978).
33. Devine, W. "An Energy Analysis of a Wind Energy Conversion System for Fuel Displacement," Institute for Energy Analysis, Oak Ridge, TN (February 1977).
34. Sherwood, L. "Total Energy Use of Home Heating Systems," Symposium on Energy Modeling and Net Energy Analysis, Colorado Springs, CO, August 21-25, 1978.
35. Rogers, D. "Energy Resource Requirements of a Solar Heating System," National Research Council of Canada, Ottawa, Canada (February 1979).
36. *Handbook of Energy Conservation for Mechanical Systems and Buildings*, R. W. Roose, Ed. (New York: Van Nostrand Reinhold Co., 1978), Chapter 9.
37. Ford, C., and B. Hannon. "Labor and Net Energy Effects of a National Ceiling Insulation Program," *Energy Systems and Policy* 4(3):217-237 (1980).
38. Hannon, B., and F. Puleo. "Transferring from Urban Cars to Buses: The Energy and Employment Impacts," in *The Energy Conservation Papers*, R. H. Williams, Ed. (Cambridge, MA: Ballinger Publishing Company, 1975), Chapter 3.
39. Hirst, E., and B. Hannon. "Effects of Energy Conservation in Residential and Commercial Buildings," *Science* 205:656-661 (1979).
40. Moden, B., D. Hatcher and H. Walton. "Marginal Costs of Energy in 1979," DOE/EIA-0184-18, U.S. Department of Energy, Washington, DC (October 1979).
41. Page, T. *Conservation and Economic Efficiency* (Baltimore, MD, Johns Hopkins University Press, 1977.)