

ENERGY TRANSFORMATION AND THE ECONOMY OF THE UNITED STATES¹

Howard T. Odum²
Chester Kylstra³ Tom Ballentine⁵
Sandra Brown² William M. Kemp²
James Zucchetto² Neil Sipe⁴

References located at end of text.

LOUISIANA STATE UNIVERSITY
CENTER FOR WETLAND RESOURCES
BATON ROUGE, LA 70803

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Dr. Howard T. Odum is Professor of Environmental Engineering Sciences and Director, Center for Wetlands, University of Florida, Gainesville, Fla. He received a B.A. degree from the University of North Carolina and a Ph.D. degree from Yale University. He has been Director of the Institute of Marine Sciences, University of Texas at Port Aransas, and Chief Scientist of the Puerto Rico Nuclear Center, in the Canal Zone. His interests include systems ecology, energy analysis, biological oceanography, and biogeochemistry.

In addition to teaching and research duties at Florida, he has served on national and international panels and committees. In recognition of his substantial contributions he has received numerous awards including the George Mercer Award of the Ecological Society of America, the Prize d'Institute la Vie, the University of Florida Presidential Medal, and the Alumni Distinguished Service Award of the Trustees of the University of North Carolina.

Dr. Odum is author of *Environment, Power and Society* and co-author of *Energy Basis of Man and Nature* (with E. C. Odum), and editor and author of many contributions to technical scientific journals, symposia proceedings, and books.

Understanding the relationship of energy and money is a basic question for the science of man and nature. The way energy influences the economy is also a very practical issue in public policy, particularly in light of U.S. dependence upon uncertain supplies of foreign oil. Whereas some principles of energetics are widely understood, such as the first law of conservation of energy and the second law of degradation of energy, other basic questions of energetics, such as the relationships of work to energy flow and the relationship of value to work are less well understood.

Studies of systems with energy analysis, diagramming, and evaluation suggest common properties of energy-transforming work in all systems. When these properties are generalized, they become additional principles of energetics, especially applicable to the real world of open systems under competition. This energetic theory includes ways for measuring the long recognized difference in the ability of energy of different kinds to do work. As the theory is validated for larger systems, it provides a way to calculate the contribution of energy to the vitality of an economy.

This paper presents a theory of energy transformation and its relationship to the circulation of money. The theory is then applied to an analysis of the alternative energy sources available to the United States.

BACKGROUND ON ENERGY TRANSFORMATION AND VALUE

By the time Schrodinger's little book appeared in 1944 (6), it was clear that energy transformations of many different kinds involve a degradation of inflowing energy, which is coupled to the upgrading of a smaller amount of the incoming energy into low entropy order (Fig. 1). That energy flow generates order has been well stated by those in many fields such as Brody (8), Brillion (9), Morowitz (10), White (11) and Adams (12). Energy capable of driving such transformations to order was regarded as potential energy by many indifferent fields of science.

When energy of the same type was being compared, it was clear that energy was a measure of the ability to do work, where work was defined as the product of force and distance. Maxwell (13) defined work as the transfer of energy. However, when energies of different types were compared they were usually related according to their degraded heat

equivalents in Calories. Since degraded heat is the only form of energy into which all other forms can be transformed with 100 percent efficiency, degraded heat equivalents were used as a definition of energy. However, it was clear to many (14) that energy thus measured was not a measure of its ability to do work. Degraded heat by definition and by the second law cannot do any work in the macroscopic world.

Energy is an ancient concept, and the word has often been used for the essence of all values. According to one translation of the old testament, the word *logos* actually means energy; the text of Genesis would thus read: "In the beginning there was energy." The natural folk use of energy has often seemed more general than the narrower quantitative definitions developed in later science. Reconciling and connecting the quantitative definitions of work and energy with the broader, more general public use of energy and work as related to value has fascinated many since the formalization of the first law of energetics in the mid-nineteenth century. Boltzman in 1886 stated the struggle for existence as the struggle for free energy. Ostwald (15) wrote extensively to identify energy use as a measure of value generated.

Scott, Hubbert (16), Soddy (17), Tolman, and others (18), recognizing the general concept of energy control of economic vitality, proposed the calculation of work as a measure of value. In 1933 this principle became entangled with a social action program called technocracy, which advocated various measures, including eliminating business. Technocrat books (19) proposed an energy certificate as a means of regulating income, but they did not consider an energy standard for the dollar in a free economy (20). The possibility that the economic system was an automatic mechanism of energy maximization was not mentioned. Whereas, in the theory given below, shifting prices of a free economy follow shifting energy amplifier values and tend to maximize power.

In retrospect the main difficulty with these energy-value efforts is that they failed to recognize that energy passing through chains is upgraded in quality and that the simple degraded heat equivalent is not a measure of the ability to do work. Energy expressed in energy quality units may be a measure of the ability to do work. The theoretical section that follows contains further explanation.

Prices and Energy of Limiting Factors

An important root of causal science is the theory of the limiting factors of Liebig (21), now enormously generalized in agriculture, physiology, ecology, and many other fields. The kinetics and energetics of interacting flows, where the source of one flow is scarce, produces curves of limiting factors described by Monod, or as Michaelis-Menton algebra, which are apparently the same as the curve of diminishing returns in economics (22). As described below scarcity varies the energy of interactive processes by varying the concentration of

interactive quantities. These comparisons of economics with the theory of limiting factors support the hypothesis that a freely operating market place may be a mechanism that has evolved to maximize power by helping the system intimately and automatically find where work potentials are larger. A review of energetics and kinetics of interacting processes was given earlier (22).

Chemical thermodynamics often concerns energy transformations of interacting substances. Energy flow is a function of the concentrations; the effect of each interacting substance on energy flow depends on its scarcity. For example, in the molecular world potential energy (Gibbs free energy) is a logarithmic function of the product of the concentrations (23). The literature concerning limiting factors in the rates of processes are described as being controlled by concentrations. The scarcest reacting quantity has the most effect on the energy transformation and thus has the greater energy value to the reaction. In the language of the theory given below, it has a higher energy quality. Although some aspects of chemical thermodynamics that follow from properties of molecular populations are not transferable to a larger macroscopic world of environment and economics, the characteristic that the energy effect of a flow depends on the scarcity of its interacting commodities is transferable.

The production diagrams in Figure 2, representative of ecological, agricultural, and chemical systems, suggest that energy flow is maximized because prices respond to scarcity. In Figure 2(a), production (P) is proportional to the product of scarce quantity (Q), which interacts with external energy source (E). The pathway from S supplies Q; pathway k_3 is depreciation. At steady state, production depends on the supply of limiting factor (Q). The resulting function is the familiar limiting factor algebra of Monod and the graph of diminishing returns. Here the energy flow in production (P) varies according to the energy source at E and the energy amplifying role of reactant Q. When Q is relatively scarce, the energy release of each unit of Q is greater.

In Figure 2(b) the same system is drawn, but with the money and price system controlling flows. Spending is shown as proportional to money demand (J); price is inverse to production (K_5/EQ) and thus inverse to scarcity of E and Q. Production is estimated as the money spent divided by price (J/p). The result of combining these expressions is nearly the same limiting factor hyperbola as in the natural system (Fig. 2[a]), except that money (M) representing downstream use is included. A mechanism of human response that adjusts prices inversely to scarcity has the result of increasing payments when energy values are higher. Because power flows in proportion to the downstream needs, the system as a whole tends to operate without accumulations. In other words, control by the kinetics of limiting factors, control by the setting of prices, and control by the energy resources turn out to be the same in interactive processes with feedback loops.

Within the traditional economics literature there has been a few efforts to relate energy to value. In the early nineteenth century,

even before the concepts of energetics were made concrete in physical science, Ricardo and Marx attempted to relate value to labor of human beings (24). Some have thought of this as an energy theory as labor does work. However, the labor of human beings is generally an amplifying interaction with other energy flows and, as in chemical reactions, will have different energy values depending on the type of interaction it amplifies. Costs of labor were not found to measure value consistently either. Thus the labor theory of value was clearly not an energy theory of value.

As the utility theory of value became prevalent, absolute theories of value were discarded and money seemed to many to be the only measure of scarcity-controlled value. It was apparently not considered that the manner in which a quantity contributed to energy flow is also a function of its scarcity.

In 1921 Fairgrieve (25) attempted to relate energy and progress. Henderson (26) and Zimmerman (27) described the resources of the world as the basis of economic vitality using energy of such resources as coals and oil as a principal determinant. These books used the definition of energy according to its degraded equivalents, which as we have already seen, is not a measure of work. There was inadequate provision for varying quality of energy.

The energetics approach to value was regarded by many as discredited, because they could not find a satisfactory function that related energy to value. Many economists regard the individual desires of people as important, and this was collectively referred to as demand. The curves of supply and demand were taken as evidence that human characteristics determine prices and that value was not limited and controlled by energy or other deterministic external factors. It was apparently not seen that the statement of supply and demand could be another way of stating the control of energy, and that human behavior may be a response trained to maximize energy flow.

Some efforts were made to measure the quality and value of the products of energy transformations in entropy-information units directly (according to the logarithm of the combination of parts) (28,9). The question was raised as to the information that had to be consumed to generate information. Use of units of disorder to measure order was impractical not only because the data were not available on microscopic configurations, but because it also required the separation of that part of the information that *was not* ordered from that part that *was* ordered. Putting a negative sign on entropy (negentropy) did not change its characteristics much. Both entropy and negentropy are zero at absolute zero and increase in magnitude as temperature increases.

In examining the chain of energy transformations towards items of high quality, Tribus and McIrvine (14) found that the actual heat content decreased as information increased. In other words the heat equivalents are not a measure of the order or quality.

The ratio of energy to entropy (or its reciprocal) has been suggested as a measure of the quality of energy (29), where energy is considered on a size scale in which populations of moving molecules and radiant energy flows are considered with the concept of temperature. Thus the quality of energy is made nearly identical with temperature and is a measure of energy concentration. This procedure does not measure most forms of potential energy that are not in the form of heat or radiational flux; it does not measure the varying abilities of quantities to release energy by interacting with lower quality energy.

Odum (30) attempted to more precisely quantify Schrodinger's concept of the necessity of consuming low entropy (degrading energy) in order to maintain order (low entropy). The maintenance metabolism (energy budget) of some steady state ecosystems was suggested as the measure of the amount of order of these ecosystems, such as the montane tropical rain forest in Puerto Rico (52). A "Schrodinger ratio" was defined as the ratio of: entropy generation rate in maintenance/entropy of the structure being maintained. This ratio was found to decrease with size of structure.

Morowitz (10) independently used a similar "L" function as the ratio of: Helmholtz free energy/flow of energy in thermal disordering necessary to maintain the order. In Figure 2 this is the ratio of the storage quantity to the drain flow.

If the energy budget maintaining an ecosystem is a measure of its order, then what function of energy would allow comparisons of different kinds of energy and different qualities of order? The quality of energy was recognized as being related to its ability to generate high quality work. Efforts to measure the potential for work have been attempted. It may be expressed as units of Gibbs free energy and sometimes is divided by environmental temperature to obtain a measure of potential for work in entropy units. The rate of generation of entropy in real, irreversible processes is the rate of disappearance of free energy divided by temperature (31). An attempt to measure potential work under the words *exergy* or *essergy* uses the difference between the sum of the various kinds of potential energy (chemical free energy, energy of gravitational energy, kinetic energy, and potential energy in heat gradient) and the energy dispersed into increased entropy (13,32). This seems to be the outflow in Figure 1. Useful outflow was also expressed as the difference between two entropies by dividing by environmental temperature.

New Efforts to Blend Energetics and Economics

Very recently, the fields of energetics and economics have been thrust upon each other in considering energy decisions toward vitalizing the economy and its survival and other public policies (33). Georgescu-Roegen has written extensively for economists to explain that the second energy law of energy requires steady inflows of potential energy to maintain value against depreciation (34). However, he does not believe that there is enough renewable potential energy to operate

an economic steady state. He appears not to have considered that many ecosystems recycle materials as renewable energy sources in a steady state. Hannon (35) has joined those advocating energy as a measure of value for consumers.

From the study of chains of energy flow in biological and ecological systems, a concept of net production has been used to evaluate the contribution of one unit to another (8). These concepts were broadened by H. T. Odum writing on the energy subsidies to agriculture (36), and included the scale of man and nature and the economic system. This approach later became known as net energy analysis (7,37). The estimation of net energy in agriculture was continued by the Steinharts (38), Pimentel (39), Leach (40), Hirst (41), and Heichel (42), except that the full energy feedback of labor and the energy that generated human work were often undercalculated as body metabolism. Henderson (43) attempts to translate energetics concepts of ecologists and others for the economists and vice versa. A workshop by the National Science Foundation in Stanford (44) produced a very noisy mix of engineers, ecologists, economists, and others. The ways of thinking were so different that communication was difficult. The recent controversy over ways of calculation of net energy reported in *Science* (33), started with an article on method by Gilliland (45). An effort to generalize about net energy was made by Slesser and others at a European conference (46) and by us in a new book (7). Krenz (47) summarizes a large effort by man including Reardon (48), Herendeen (49) and Bullard (50) who use the input-output matrix of money flows and inverse coefficients to relate energy flow to dollar flow. These do not include the free environmental energy flows, such as the sun and wind, thus the total energy flows are low and may not include all the energy supporting the economy.

Efficiency Control by Selection for Maximum Power

In 1922 A. J. Lotka (51) proposed that maximum power was the self-design principle of energy flow in the real world where systems were always under competition with alternatives. By this theory systems that developed structure to process energy and use it well (maximize power) could eliminate other factors inhibiting their development and could displace competitors without these properties. By measuring metabolism of ecological systems from microcosms to rainforests, and by review of the properties of many other systems, H. T. Odum tried to verify the generality of this principle in previous papers and books (7,23,30,52). Selection for maximum power, however, was found to regulate efficiency at less than the maximum efficiency possible (53).

The maximum power principle is important to an energy theory as it provides the means and mechanisms by which energy flows tends to develop the characteristic designs that are observed. In isolated energy transformations, such as isolated chemical reactions, the efficiencies and rates of transformation are often not regarded as a function of the reversible potential energy difference, because pathways vary and energy barriers vary. In open real systems under competition, however,

feedbacks develop according to the maximum power principle, and energy barriers are overcome in proportion to available potential energy; those with less yield are discarded. In open systems, the final potential energy available is that amount of energy remaining after energy fed back to overcome energy barriers has been subtracted. The maximum power principle provides that of the various loadings possible in an energy transformation, the systems that survive are the ones that adjust the load and efficiency, *not to maximize efficiency of concern in the real power transformation and utilization*. The efficiency of concern in the real world is, therefore, the one that accompanies transformation at maximum power (53,54). Under the constraint of maximum power, an energy transformation has a single value according to its self design.

These antecedents suggest that there are specific energy costs for the development of high quality components. Value in the systems and the economy may be ultimately determined by the thermodynamic characteristics as organized into maximum power design.

Energy Analysis

The most general phrase for a study of energy networks and their transformations seems to be *energy analysis*, although it is more synthesis than analysis. One tradition has its roots in ecological food webs such as those generated by Petersen (55), Lindeman (45), Riley (57), Clarke (58), H. T. Odum (59), Teal (60), and many others. This tradition has become part of the ecological systems analysis in recent years, and both kinetics and energetics are often considered for the same system at the same time (23,61,62).

Boulding (63) compared mineral cycles of ecosystems to circulation of money. H. T. Odum (30,7) recognized money as a counter current to the circulation of matter and therefore energy. Other papers relating energy to various sciences and their principles are given in (23), (7), (65) and (64).

Another tradition of examining energy chains has been the systems analysis techniques of Forester (66), Watt (67), Meadows (68), Holling (69), and the modeling of the International Biological Program (IBP)(70). All of these techniques were primarily concerned with kinetics and they did not directly consider the fundamental energetics involved in many of the transformations modeled. For example, higher quality flows of the networks were not examined as energy flows, and energy laws were not used in studying kinetics. However, some common agreement developed about the designs of ecological systems.

In yet another tradition the problem of considering kinetics and energetics at the same time in whole systems was approached with network diagramming concepts and other sets of symbols. Forester (71) developed symbols for energy diagramming to analyze industrial systems. Symbols of electrical circuits were used as a language of equivalent circuits for nonelectrical systems such as water flows (72) and nerves (73). A

more abstract general language was proposed by Paynter (74) with bond graphs including an application to micro-economics (75). Koenig (76) developed another set of conventions and symbols. H. T. Odum (7) developed an energy circuit language that helped formalize and combine aspects of energy transformations from many fields of science. Thus there has been a common and sometimes parallel effort to model systems for simulation purposes and also to evaluate the significance of their energy transformations. Diagramming helps the mind visualize systems and their budgets of energy flow. From the diagramming and evaluation of energy networks new theories can emerge.

A THEORY OF ENERGY TRANSFORMATION

By combining antecedents from these several fields and the maximum power principle, some deterministic theory can be formulated for open systems of man and nature. Illustrated by diagram in Figure 3(b) is a typical energy chain that is believed to develop in many, if not all, kinds of systems because of the pressure of natural selection or of self-design toward maximum power. The following are the tenets of this theory:

a) The system that builds order, feeding back services facilitated by that order, can pump more energy into degraded heat than the system that is degrading its potential energy into heat without building order; this can happen as long as the energy available is sufficient to replace deterioration and depreciation.

b) Energy is converted into order by such transformations because the order stored has the ability to feed back, as an amplifier, and to cause more energy to flow than is in its own heat content. By this view, Fig. 1 is an incomplete view of typical transformations because it lacks a high quality feedback. Energy transformations that do not have this property are selected against, since they would not maximize power of the main system.

c) Higher quality energy flows, whether feeding back or coming from outside the system, generate more power when they are interacting with low quality flows as an amplifier than if they are used in place of the low quality energy. Energies of different quality develop interactive designs rather than acting separately.

Most transformations are an interaction of one flow of low quality with one of high quality producing a transformation of intermediate quality.

d) Energy upgraded in one transformation may be further upgraded in additional transformations so long as the feedback in each case supplies as much stimulus to the main energy flow as it drains.

e) Many energy transformations going along the energy train towards higher quality also involves spatial convergence. Most energy

transformations involve feedback diverging outward (Fig. 3).

f) In estimating the efficiency of conversion from one level to another there has to be an evaluation of the energy effect of the feedback as an amplifier and the energy used in producing the feedback. These may not be the same except for some systems in some steady states. Over long periods there may be a tendency for these to become equal.

g) The energy transformation observed between two levels of quality may be taken as an estimate of the inherent energy required for that transformation. Figure 4 shows the way the energy quality factor between two energy types is calculated from a diagram that summarizes the flows observed in a real competitive situation. The quality of energy flow #2 can be expressed in Calories of the quality of energy flow #1 by calculating the ratio of energy flow #1 to energy flow #2. First, however, the contribution of flow #3 is expressed in quality units of flow #1 and added to flow #2 (see left dashed line) or expressed in quality units of flow #2 and subtracted from flow #2 (see other dashed line). Examples of such a calculation for the energy change are given in Figures 5-7.

It is useful to develop a table of approximate energy conversion factors so that energy flows of different types can be compared. Table 1 has energy transformation values presented in solar equivalents and coal equivalents where coal equivalents were defined as coal collected ready for use as at a power plant.

Energy used to generate all systems may be compared by converting all forms of energy to the same quality, such as coal equivalent or solar equivalents. Some equivalents in work of some others are in Table 1.

The total vitality of any system such as the economy of the United States is a function of the total potential energy flowing into work as measured by the expression of all energy flows in one quality. To obtain the maximum potential requires that low and high quality energy inputs interact for maximum work. The actual work may be less than this potential because the ratio of high quality energy to low quality energy may be out of balance. For example, an area with a very high fossil fuel use over a small solar area has little low quality energy with which to achieve the potential of the higher quality fossil fuel. Therefore the higher quality energy gets used for lower quality purposes and thus has less potential than its original energy cost.

These concepts of energy apply to flows usually described as matter and information, for these often contain high multiplier abilities.

Energy Basis for Economic Vitality

Given in Figures 8 and 9 are two simplified models of flows of energy and the circulation of money. Potential energy is pumped into the system by the feedback from stored assets (high quality energy)

replacing losses due to depreciation. This causes growth at first, and the eventual leveling, if the rate of supply of energy is regulated at its source. Notice that all the energies are exogeneous; they are sometimes referred to as externalities in economics. Money exchanges only occur in the loop that feeds back energy from the economy. Money circulates in the system; energy flows through and out as it is used. Money retains its value only so long as potential energy is flowing in and out of the system. For example, if the money flows at a constant circulation rate, and there is a 50 percent decrease in inflow of the energy, then the money represents less work and is inflated by that percent. As Figure 5 shows, the economic systems recognize only the energy spent in feedback from the economy and not in the energy from the external source. External energies are absorbed into the economy and gradually released throughout. The situation is like a giant flywheel with many people pushing on the side (Fig. 8). The flywheel absorbs their energies and distributes them equally throughout the circle. If the inflowing energy tends to be distributed throughout the system, the ratio of equal energy flow to money flow may be used to estimate the contributions of energy going into complex goods, services, and labor.

Circulating money cannot be used as an indicator of the contribution of externalities. However, energy evaluation can estimate the contribution of externalities as shown in Figure 10. The contribution of an externality to the system represents net energy to the system if it contributes more to the main economy than is fed back from the main economy. The feedback must, however, be expressed in units of the same quality as that being contributed.

Energy in feedback can be calculated from money data using a money/energy ratio. One source of the ratio is from the aggregated calculation of money flow (GNP) to total energy flow as in Figure 9. The ratio of energy flow to money flow in 1975 was 19,000 Cal/dollar, where both the fossil fuels and the energies of the environment were added. The energy of the sun was converted into coal equivalents by dividing by 2000 as given in Figure 5 and Table 1. Others such as Herendeen and Bullard (50) have prepared tables of external energy inflows associated with the many sectors of the economy by using input-output models. In estimating the energy that is feeding back, we include the energy spent on labor developing its functions and quality.

Where human beings are involved, much of human life and its various costs may be essential to work performance. There may be waste but we are not sure of what it is and prefer to use energy-dollar conversion on all wages as representing observed labor involvement.

Energy sources are defined as primary if they give a net yield. Other sources are defined as secondary if they yield less than they use. Secondary sources are a means of adding energy to the system to supplement primary sources. The economy uses net energy from primary sources to subsidize the energy deficits of secondary sources and to support consumer functions that may have no role in bringing energy from outside but may have that amplifier effects.

Net Energy of Primary Sources for the United States

Alternative energy sources available to the United States are many, and some of these are evaluated in the paragraphs that follow using net energy and yield ratio as the criteria for evaluating their contribution to the economy. Yield Y and feedback F in Figure 10 are evaluated in coal equivalents (CE). Representative examples of the various kinds of energy systems have been evaluated and are given in Table 2, arranged in order of decreasing net energy. The analysis process begins with moderately complex diagrams showing flows of money, capital, energy, fuel, goods, services, and environmental interactions. These are then evaluated with appropriate data and are then aggregated into a simpler form as given in Figure 10. Additional examples and calculations were given in a recent congressional testimony (37).

Fifty-one percent of fuels to the United States are coming from international exchange at about \$12 per barrel (1977). Figure 11(a) shows that the energy of the economy involved in \$12 represents a return of 1 Calorie for every 6 obtained by the U.S. (expressed in equivalent units). Thus a preponderance of the energy base of the United States presently has a yield of about 6 to 1 at a time when the U.S. economy has not been far from steady state, neither declining nor growing much in the period from 1973 to 1976. The present ratio is much lower than the ratio of 40 to 1 or more characteristic of oil from Texas when rich deposits close to the the surface were being used.

A recent detailed analysis of western strip mined coal by Ballentine (78) showed yield ratios between 4 to 1 and 14 to 1, depending on the distance of shipment and the type of energy distribution to the consumers. One of the energy analyses is shown in Figure 12 for coal shipped 1,000 miles, one-third as electric power and two-thirds as transported coal for heating, yields a 6 to 1 ratio. If such sources of coal are used to supply existing industries and consumers of the United States, the effect may be similar to that of foreign oil. However, the oil system already has made its capital investments for processing, whereas some of the coal processing installations have yet to be built.

Nuclear energy in light water reactors as used in the United States was examined by C. Kylstra and Ki Han (Fig. 13 and Table 3). The analysis includes energy required for mining, milling enrichment industry, power plants, costs of waste storage as known in 1970, and the non-military services of the Atomic Energy Commission.

Table 3 summarizes the detailed calculations from reference (83) for the steady state net energy and yield analysis. The table shows the typical 1970 energy flows, and the accumulated energy flows up through 1972; the steady state data can be interpreted as the average integrated values over the lifetime of the nuclear power plants in operation in 1970, or as the constant yearly values for the case of no growth after 1970.

The ratio of energy into society compared to energy from society

for nuclear power is 2.7 to 1 (Fig. 13[b]), considerably less than the net energy from coal and oil. In other words, nuclear energy is being subsidized by fossil fuel, since richer sources supply net energy that is available for feedback into the lesser sources. This study, as well as an earlier study by Pong Lem (83) showed that the accumulated energy from nuclear energy, considering all yields and costs to 1974, was still less than the energy inputs to the nuclear system. Models indicate that the accumulated energy will become net yielding in the 1990s. If present plants serve as expected throughout their lifetime, they will provide the net energy given in Figure 13(b). Pong Lem calculated that displacement of land from normal contribution to the economy in the event of a major accident would reduce the net energy considerably.

Energy in sunlight must be considered for two classes of systems. First is the net energy when sunlight is used in an ancient way as in subsistence agriculture (Fig. 14). The net yield is 1.2 to 1 (84). Solar energy is dilute and needs to be concentrated; when used in this classic way, it is a net energy source. However, when there are large concentrated feedbacks of materials, goods, services, and equipment to a relatively small area of solar surface as in solar technology, there is no net energy. For example, examine the calculations of Brown and Zucchetto (85) for commercial solar water heaters used in Miami, Florida (Fig. 15), in which 99 percent of the energy was fossil fuel based and used for construction and maintenance of the solar equipment. As cost of fuel becomes higher, solar technology will not become cheaper since it is really a fossil fuel device. It does use less fossil fuel than a gas or electric heater, however. The savings of the solar heater in place of a fossil fuel heater may not equal the earnings of alternative uses of the money and capital energy. Other proposed sources, which are not net energy yielders, are low velocity winds and oil shale.

Several of the types of primary energy sources given in Table 3 have high yield ratios (hydroelectric power, tidal electric power and geothermal electric power). Each of these sources is of high quality and thus supports the conversion of energy into even higher quality forms. However, these sources are not large enough in extent to have much effect on national policy of the United States. As there are apparently no sources of large extent with higher yield ratios than those being used at present, it is not likely that the economy of the United States will grow much more or that the standard of living per person can increase without reductions in population.

Evaluating Secondary Energy Sources

The net energy from primary sources is that available to subsidize secondary sources, which by definition are those that take more energy than they yield. Nonetheless, by yielding some energy they help to maximize the power of the whole system so that those activities that develop secondary sources are the choice for use of net energy.

To evaluate these it is convenient to use an *investment ratio* as defined in Figure 16. Here the energies that are purchased and acquired

from the main economy, either as fuels or as goods and services, are compared to the nonpurchased energies supplied free from the environment and external to the economy. When the environmental energies are large, this potential energy can attract matching high quality energy in the form of economic investment and yields services and sales that compete well in price because of their free subsidy. If there is no free environmental energy, there is no free source from an externality and there is little to attract purchased energies for investment. Even if purchased energy is invested, there is little to help make the new activity economically competitive.

Examples of the use of free energies that attract investment, and that are competitive although not net energy yielding, are: industrialized agriculture, tourism, fisheries, and modern forestry (Table 4). To gain some perspective about what might be competitive, we can calculate the ratio of fossil fuel flow to the rate of flow of natural energy within the United States economy. This ratio is 2.5 to 1 if both are expressed in coal equivalents. Where a proposed environmental interaction or energy source is much greater than 2.5 to 1, we may infer that such projects are less economic and may not compete as more energy for the process must be purchased and less energy is supplied free from the environment. We propose then that the investment ratio be used to evaluate a system's carrying capacity.

The ratio of energy invested through the economy to that supplied from the environment for conventional tertiary treatment is very high (Table 4). Conventional tertiary treatment makes intensive use of fossil fuel and uses little to no environmental energies. Experiments have shown that cypress swamps of Florida can be used effectively for treating secondary sewage effluent (87). A benefit of this treatment method was increased growth of high quality cypress wood. This net increase in wood production could attract economic investment for such activities as harvesting, processing, and manufacturing. In this case the free work of the environmental energies supplemented the purchased energies. The investment ratio for this process was very much lower than for the conventional process.

An energy analysis of the cooling towers at the Crystal River power plant, Florida, gave a high investment ratio (Table 4). The alternative to the cooling tower was to use the estuarine waters for cooling. After seven years of using the estuary, there were still some decreases in productivity in the 790 ha of estuary and stress on entrained animals and plankton (91). However, even accounting for all these losses in natural energy flows, the investment ratio for the use of the estuary for cooling was considerably lower than for the use of cooling towers (Table 4). The possible load on the environment elsewhere due to the cooling towers is greater than the protection it gives to the local estuary. If such environmental protections by technological means should be typical, it would mean that the Environmental Protection Agency is engaged in a wholesale stress on the environment opposite to its mission and intent and contrary to the intent of law.

Energy analysis in which all flows are put on an equal quality basis provides a means for comparing heterogeneous processes. Energy evaluation of primary and secondary sources and of environmental interactions or other externalities is a means to predict in advance what will be cost-benefit effective. It may be the best way to evaluate decisions when externalities are changing their energy contributions.

Long Range Prospects

The future depends on the net energy of primary sources. Since there are no operating pilot plants from which one may estimate energy that must be fed back to maintain fusion, it is not possible to calculate net energy for this process. However, there is one reason to suspect that the yields of net energy may not be large, if positive. Where energies are very intense (temperature high) much of the energy has to be discarded in reducing temperature to a level that may be utilized and coupled to machines and other processes of man in a lower temperature world. Part of the disappointingly low energy yield of current nuclear plants comes from the need to cool down the high temperatures of the core before it can be used to operate machines. As the temperature of fusion is much hotter at its center of reaction than fission, the energy required to contain and reduce the temperature should be much larger and the net energy much less.

This may be compared with subsistence agriculture with a yield ratio of 1.2, which provides only 1/30 of the current net energy. Elsewhere in the world where rich energies are still available to the economies of other countries, there is an opportunity for growth for a time. According to various scenarios (37,68,92,93) such world growth may crest around the year 2000, declining thereafter. In the period between now and then, the United States has a good opportunity to hold its present level of energy support and economic vitality, because it has favorable solar agricultural conditions for food production that may be exchanged for oil (Fig. 11[b]).

From the point of view of world stability and maximizing power, Project Independence may be incorrect, as it would lead to a terribly dependent situation thereafter. The current pattern of using foreign oils first leaves more energy available to the United States (theirs now and ours later). The current pattern also contributes to a more stable balance of world power than if the United States were to collapse having used up its own energy sources at a time when the rest of the world was still expanding its energy operations.

SUMMARY

Evaluations of energy flows in models summarize the complex systems of man and nature, provide overviews of system design and energy transformation and provide insight into the alternatives for public policy decisions. A theory of energy transformation provides corollaries for

predicting (a) designs that develop in self-organizing system, (b) the contributions of energy to work, and (c) a scale of energy quality. Evaluation of energy inflow from externalities in units of similar quality provides a theory of value believed to be the basis for economics. Energies from free externalities that are attracting investments provide quantitative measures of the contributions from primary and secondary energy sources to economic vitality and means for inferring the level of value to be expected in the future.

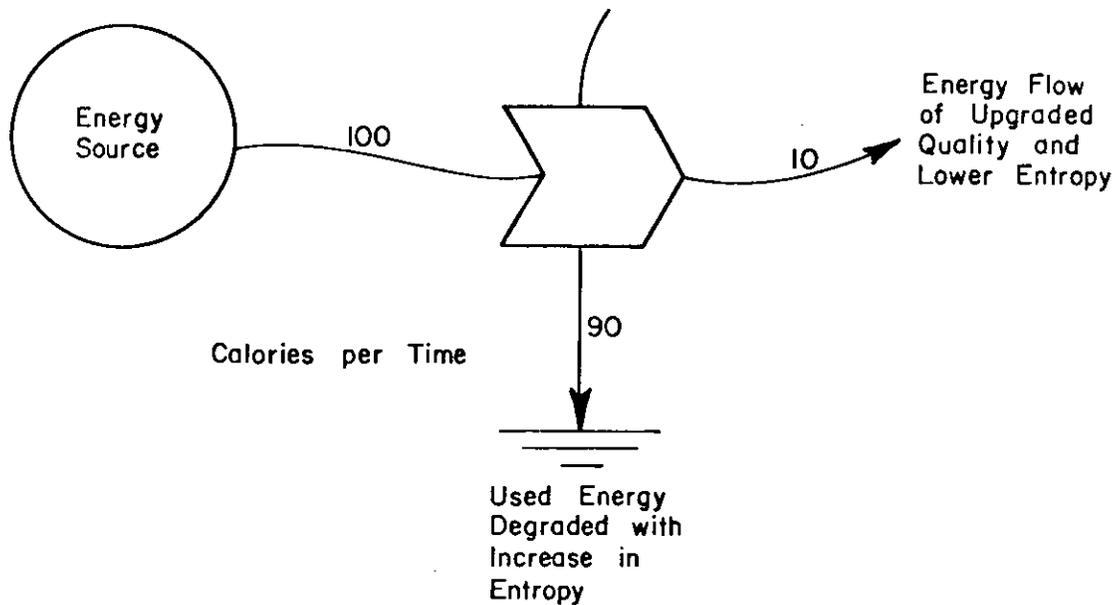
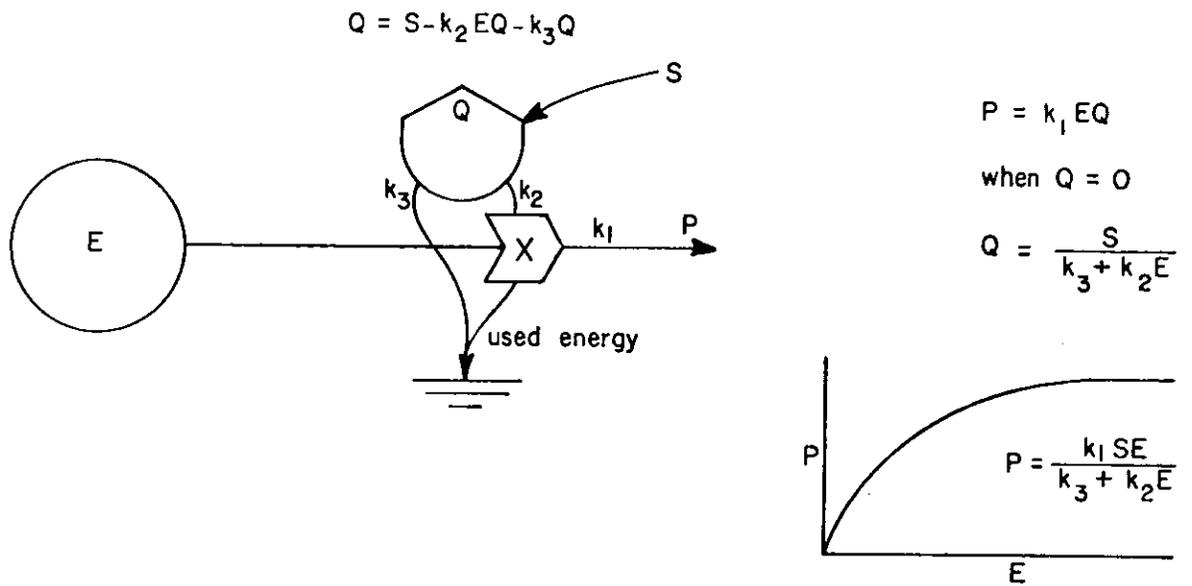
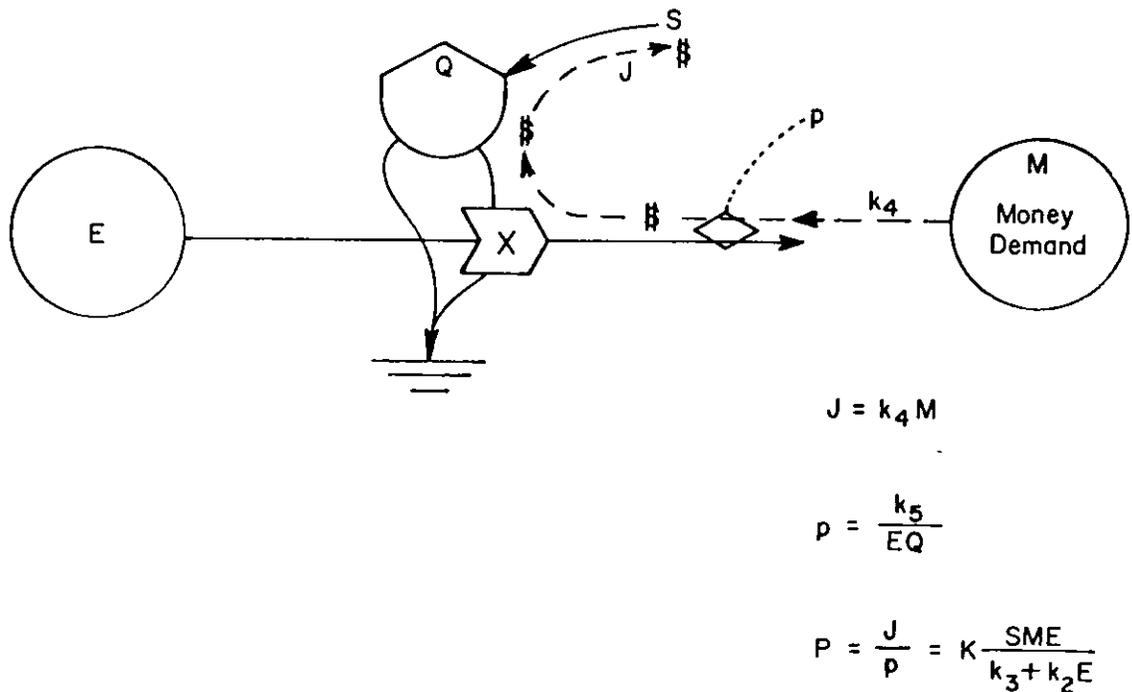


Figure 1. Energy transformations upgrade some energy by degrading larger amounts into used heat. Feedback is omitted here but included in later figures. Symbols are those of the energy circuit language (7).



(a) WITHOUT MONEY



(b) PRICE (p) CONTROLLED BY SCARCITY

Figure 2. Diagrams of energy flow and kinetics of production with and without money.

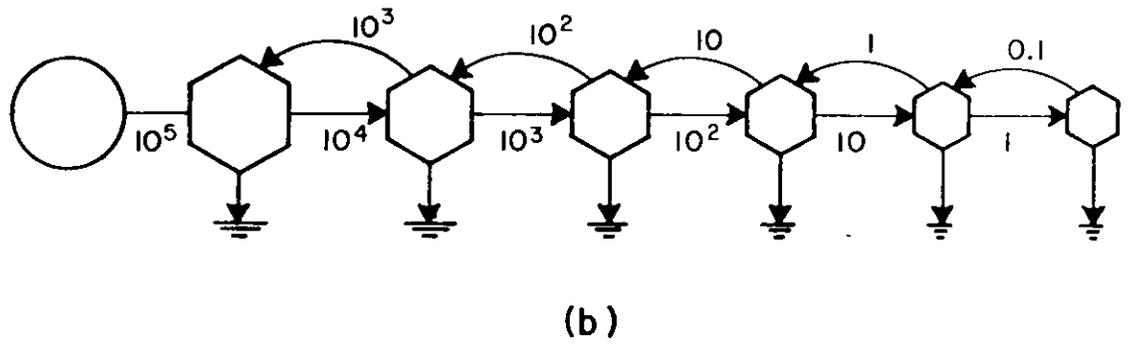
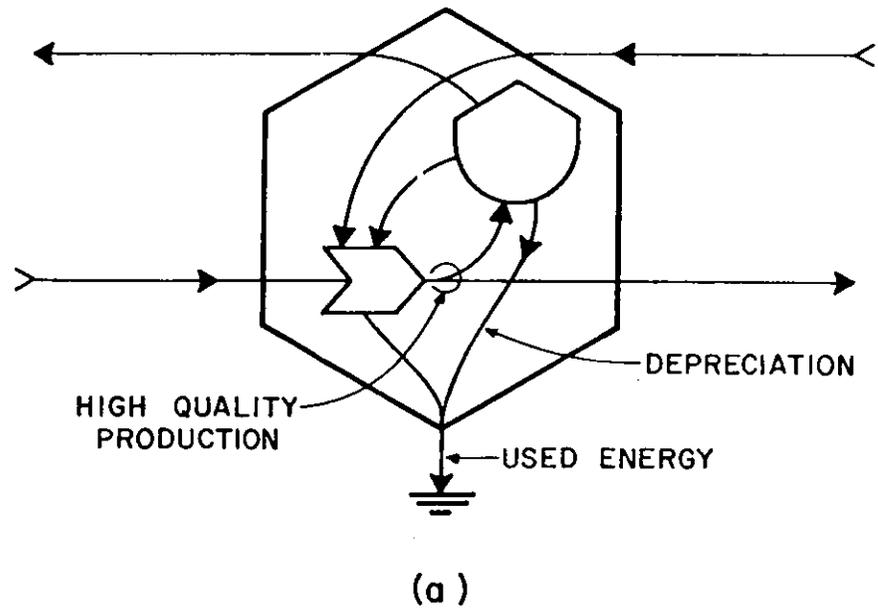


Figure 3. Typical chain of energy transformations and feedback. (a) Energy flows in one unit; (b) chain of units.

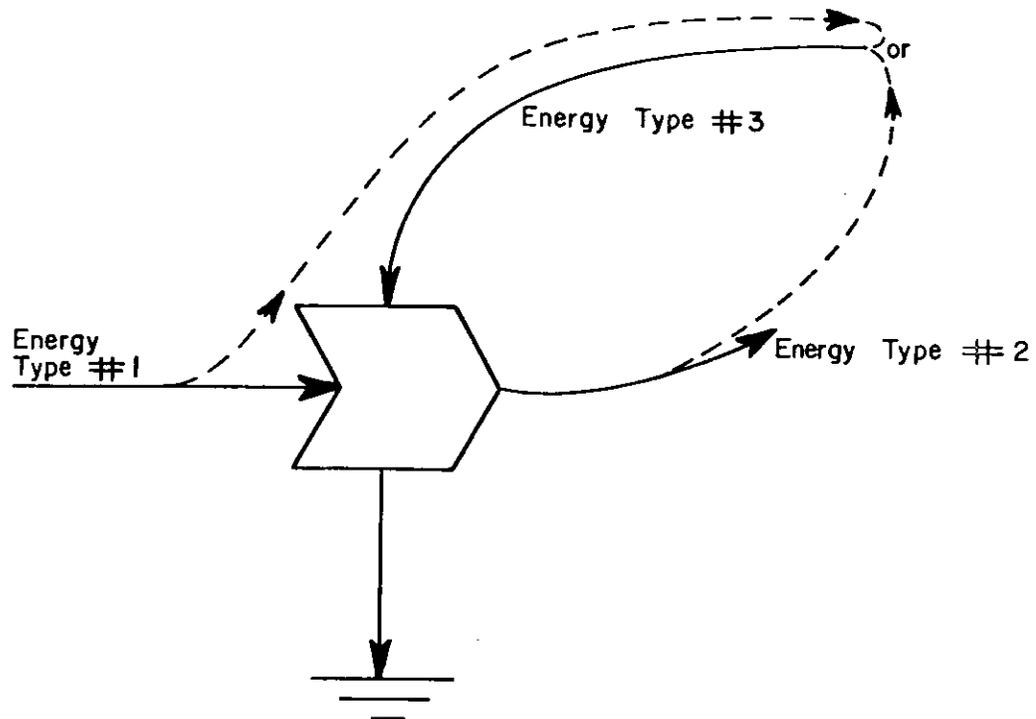
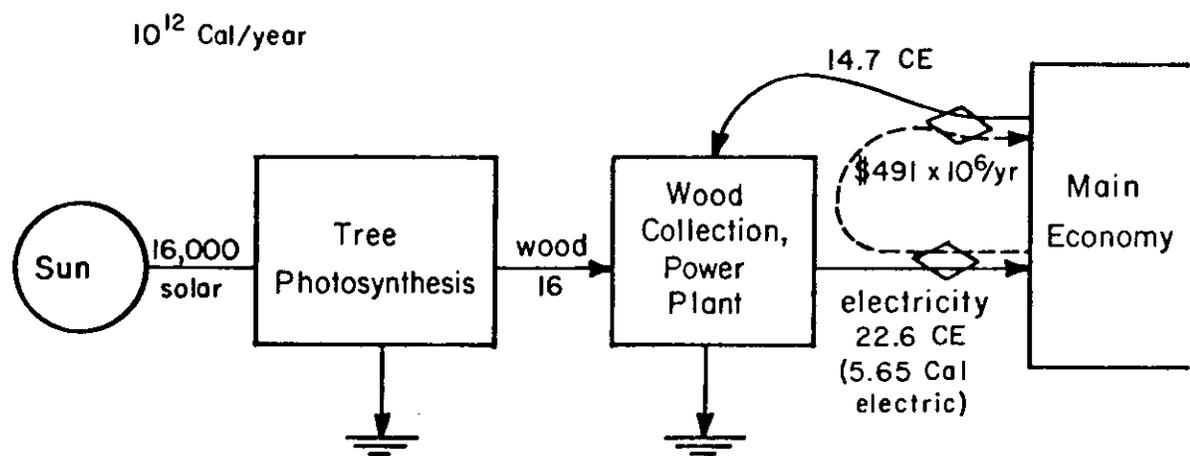


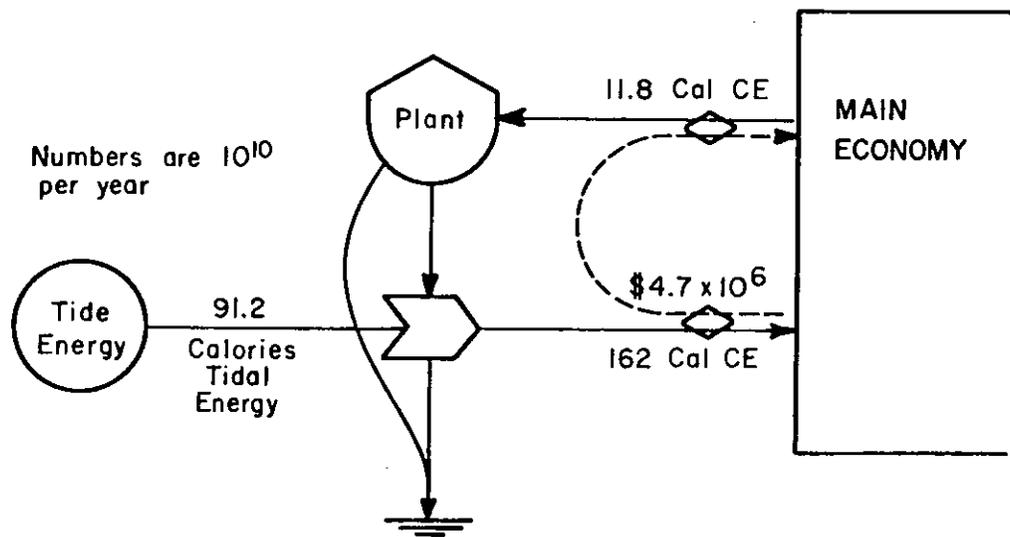
Figure 4. Diagram for calculating transformation factors for converting one quality of energy to another. Type 2 is related to Type 1 after Type 3 is expressed in equivalents of one of the other types and either added or subtracted.



$$\text{Energy Quality Factor} = \frac{16,000}{22.6 - 14.7} = 2027$$

Figure 5. Energy transformation in concentrating solar energy (77).

La Rance, France

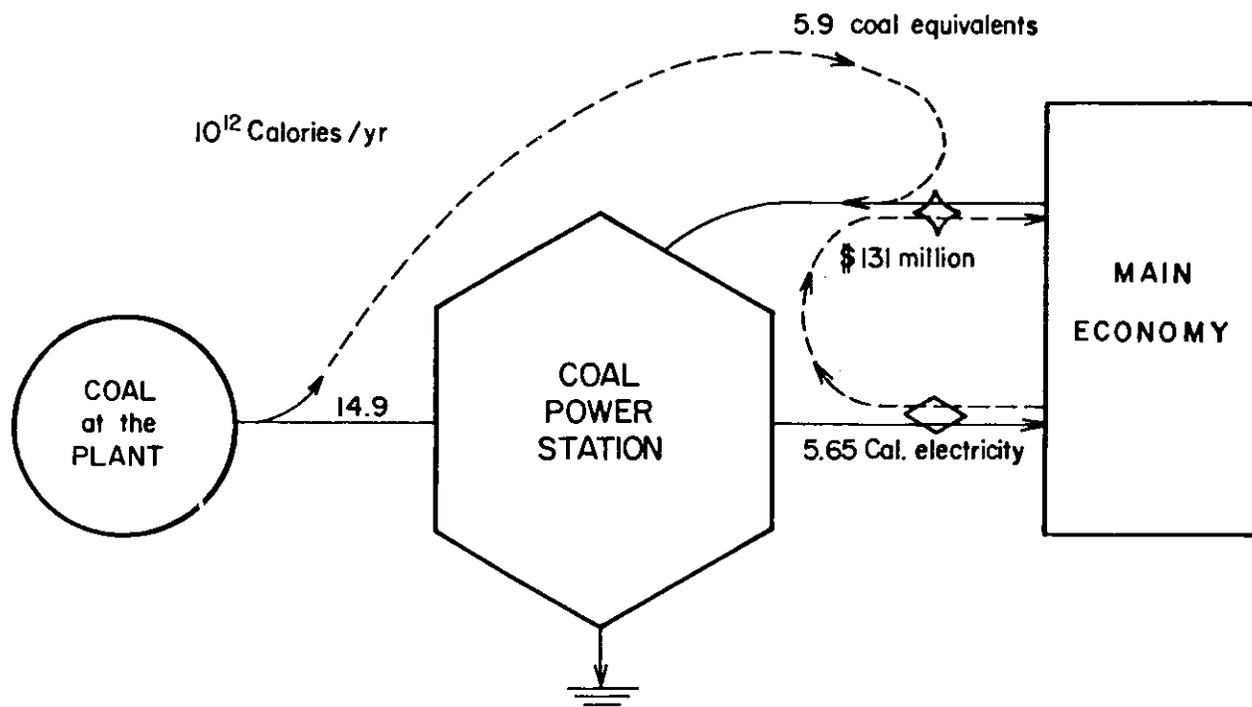


$$\text{Energy Quality Factor} = \frac{91}{150} = 0.6$$

$$\text{Yield Ratio} = \frac{162}{11.8} = 13.7$$

$$\text{Net Energy} = 162 - 11.8 = 150 \times 10^{10} \text{ Cal CE}$$

Figure 6. Energy transformation in concentrating tidal energy (79).



$$\frac{I}{O} = \frac{14.9 + 5.9}{5.65} = 3.7$$

Figure 7. Example of energy quality calculation; coal electric power generator. Details are in reference 80. Energy quality factor is 3.7 Cal. coal per Calorie electricity.

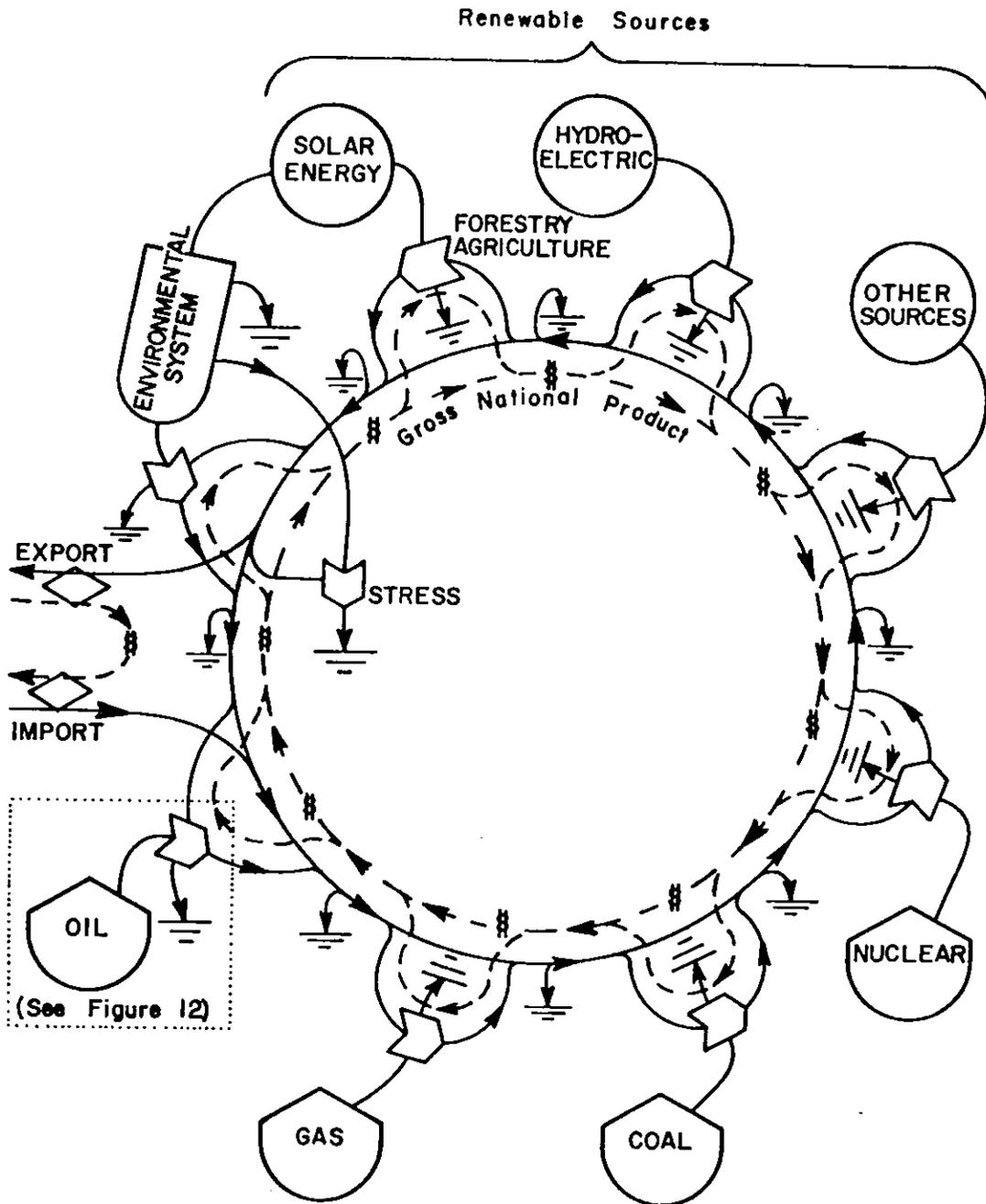
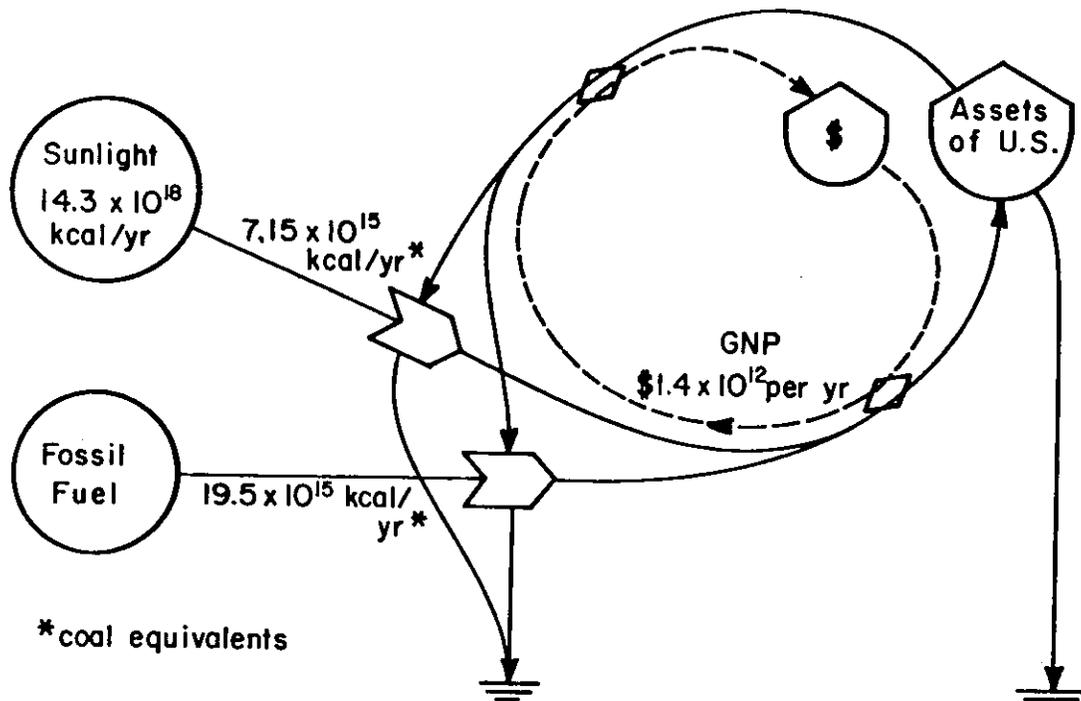


Figure 8. Relation of external energy flows to the circulation of energy and money within the economy. Energy circulates counter-clockwise and money clockwise.

1975



$$\frac{\text{Total Energy Flow}}{\text{GNP}} = \frac{26.7 \times 10^{15} \text{ kcal/yr}}{1.4 \times 10^{12} \text{ S/yr}} = 19,000 \text{ kcal coal equivalents per } \$$$

Figure 9. Summary of the energy support to the economy of the U.S. separating fossil fuels from the renewable free energy sources. A ratio is given of all energy flow expressed in coal equivalents to money flow (81).

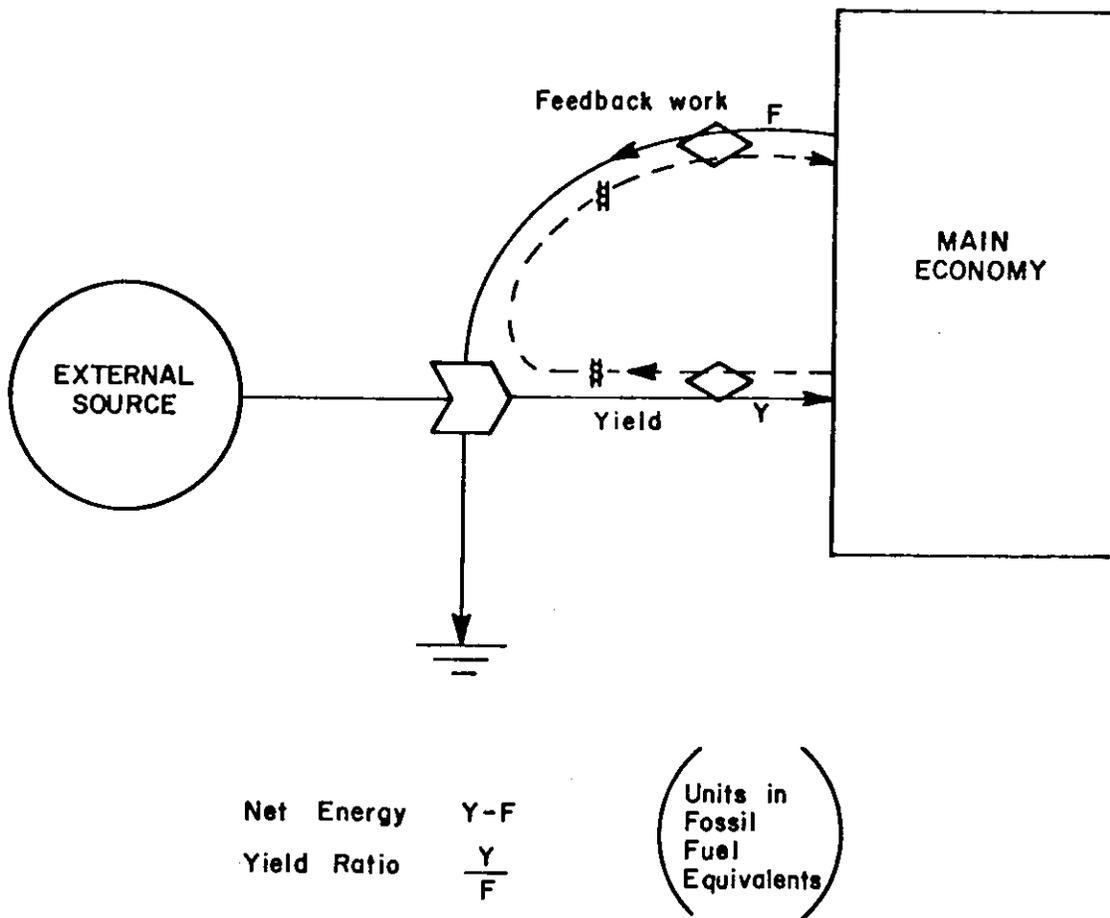
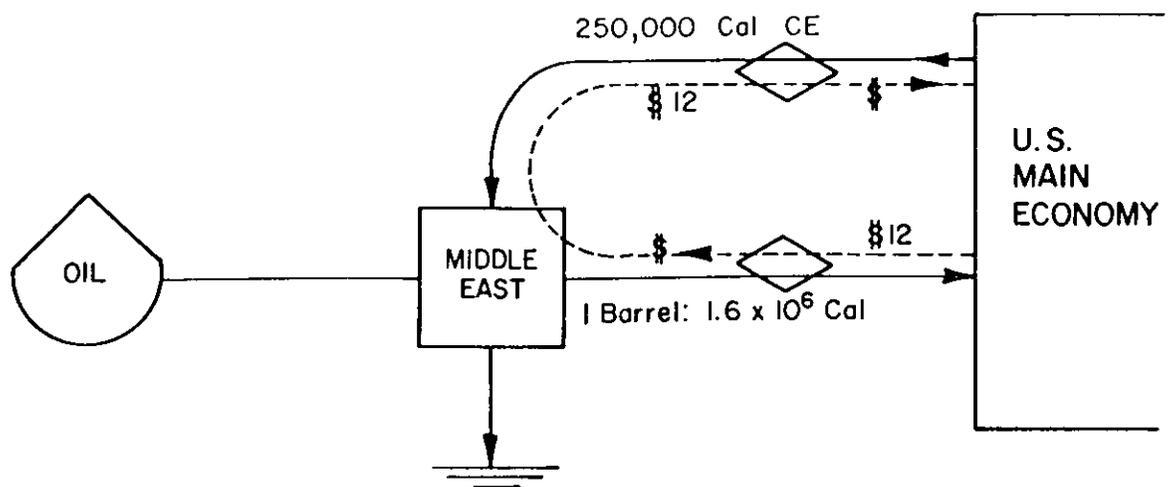
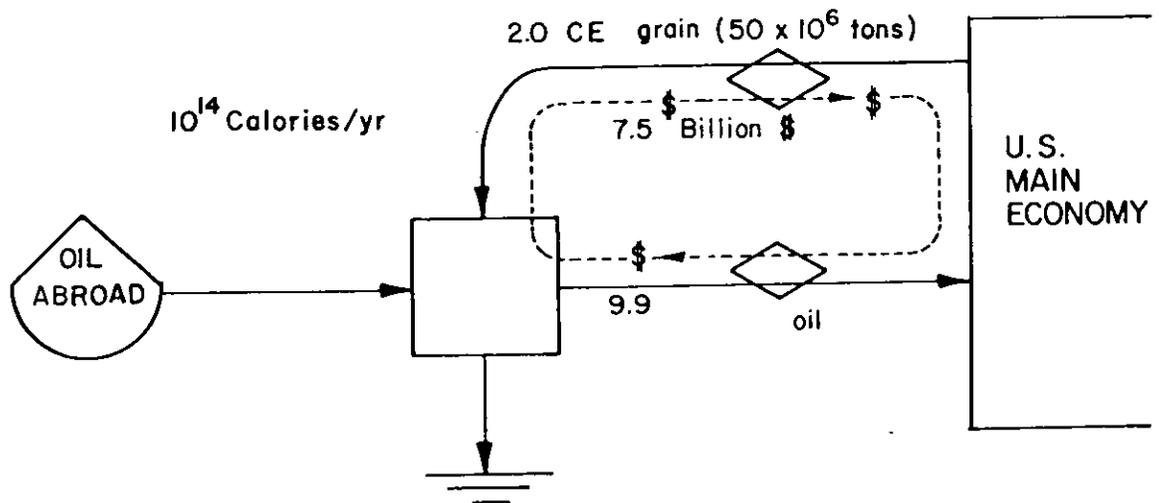


Figure 10. Diagram showing the use of the yield ratio and net energy to evaluate an external energy source.



(a)



(b)

Figure 11. Net energy summary of oil obtained in foreign exchange. (a) Purchases with 1975 prices from foreign sources. Details are in reference 82. After refining yield is 1.42×10^6 CE and yield ratio is 5.7; (b) net energy from sale of grain at 1975 prices. Details are in reference 82. After refining the yield is 8.78×10^{14} CE and the yield ratio is 4.4.

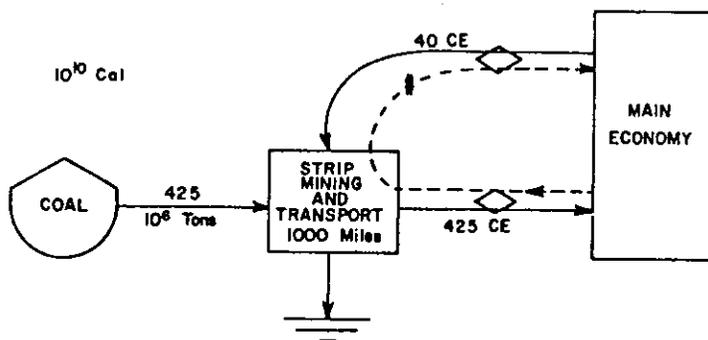
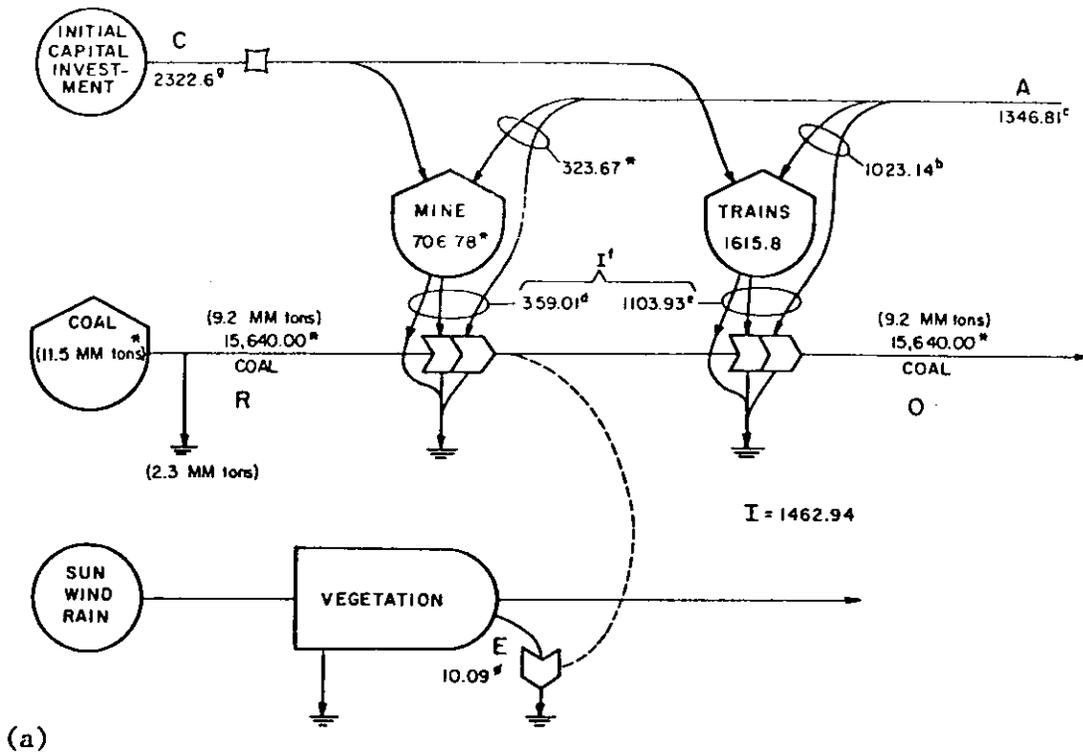
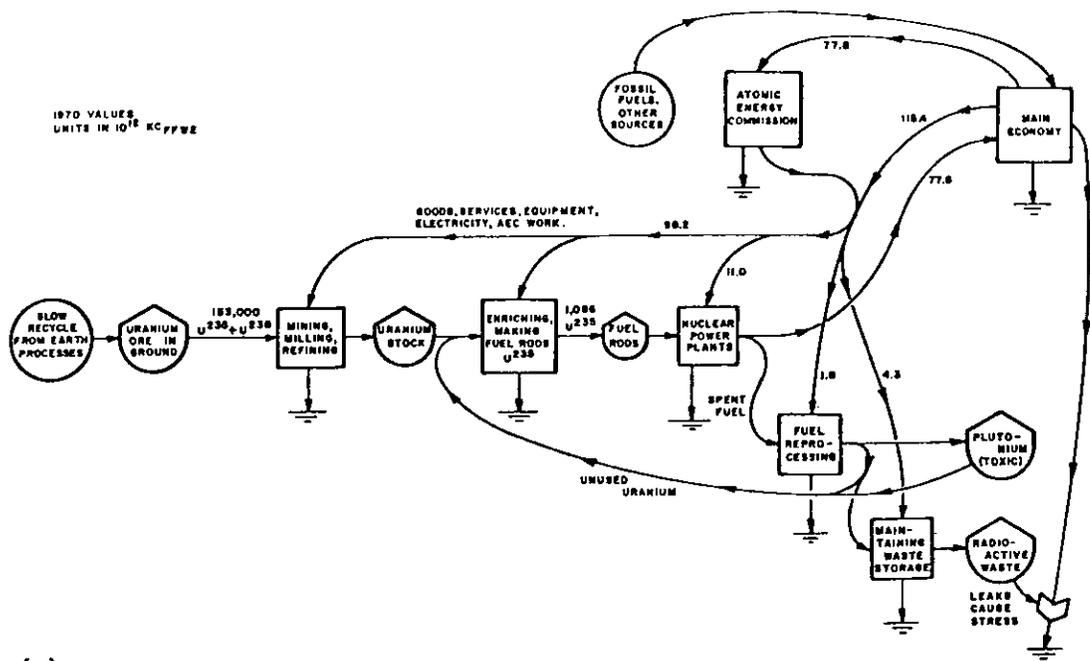
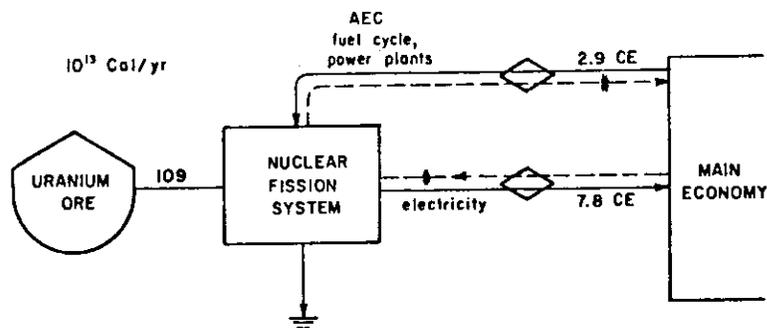


Figure 12. Net energy of typical strip mining of western coal mining followed by transportation 1,000 miles. (a) Details; (b) summary (78).



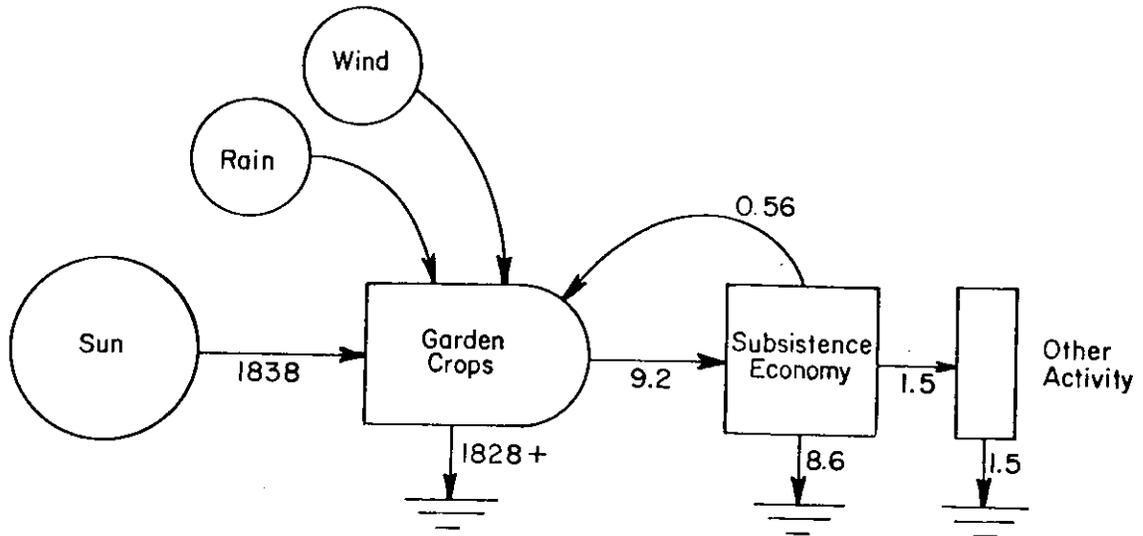
(a)



(b)

Figure 13. Energy analysis of light water nuclear system including all subsidies known (83). (a) Moderate detail; (b) summary of steady state net energy of light water nuclear system. The yield ratio is 2.7. The 10.2×10^{13} Cal/yr source flow is for U-235 steady state fission energy in conventional reactors. If the potential energy content of U-238 is included, which will be mainly released by breeder reactors, the value becomes $1,380 \times 10^{13}$ Cal/yr.

10^6 Calories Heat Equivalents per year



10^6 Calories Coal Equivalents

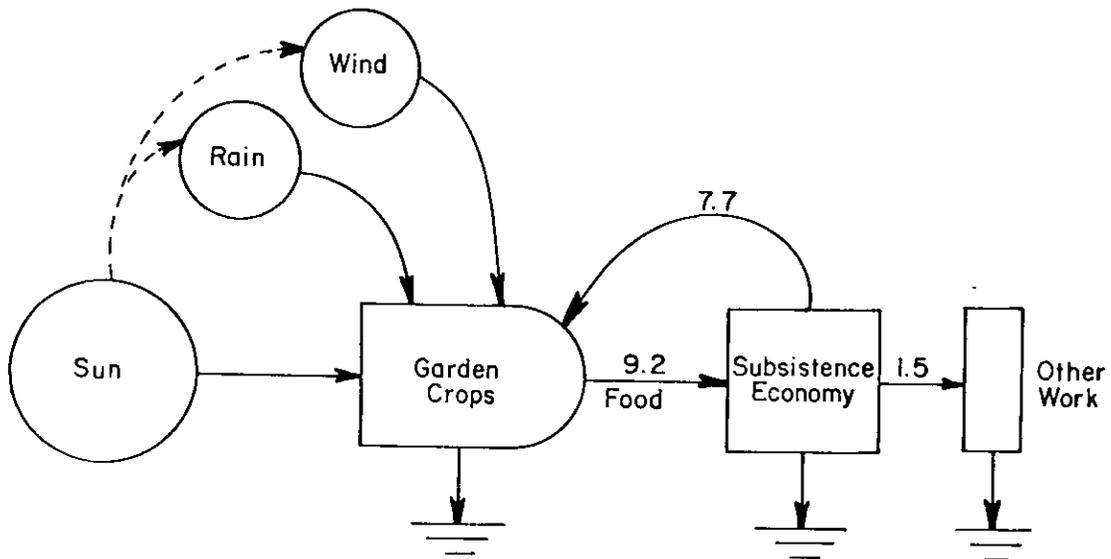


Figure 14. Subsistence economy of man on solar energy without inflow of nonrenewable resource (84).

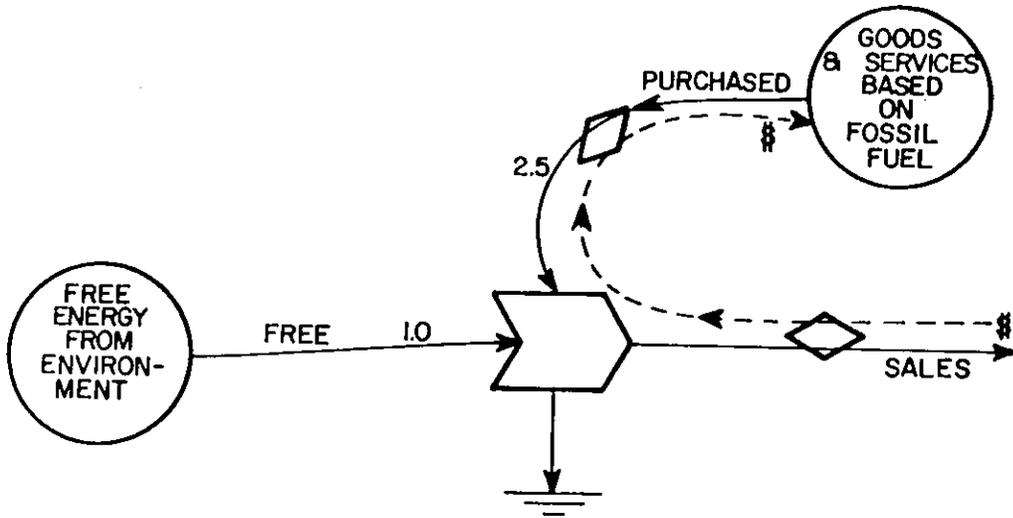


Figure 16. Definition of investment ratio. Diagram showing matching of purchased high quality energies in interaction with free natural energies. Ratio is for the United States.

Table 1. Evaluation of energy quality; estimates of energy required for transforming energy of different quality to that of coal under competing circumstances.

Energy Type	Calories equivalent to one Calorie of sunlight	Calories equivalent to one Calorie of coal
Solar heating ^a	5	11,000.0
Solar energy in photons ^b	1	2,000.0
Uranium 235 as mined ^c		22.0
Photosynthetic products, uncollected ^d	100	20.0
Geothermal steam (volcanic area) ^e		1.6
Gulf of Mexico oil ^f		1.4
Alaskan oil ^g		1.4
Western coal before mining ^h		1.1
Coal already mined ⁱ	2000	1.0
Tidal energy, 20 ft tide ^j		0.6
Heating gas ^k		0.55
Elevated water ^l		0.32
Electricity ^m		0.27

(a) Based on Figure 15.

(b) Based on Figure 5.

(c) Based on Figure 13.

(d) For situations when gross photosynthesis is 1%.

(e) Gilliland (45).

(f) Based on a case history of drilling in the Gulf; including 10% for refining.

(g) Based on 1.5 million Calories per barrel; feedback includes energy equivalents on dollar costs plus fuel in refining; 11.3% lost in refining, including 5% as coal equivalents of environmental productivity diverted by the 5000 acres installations in refining, \$.81 per barrel in operating costs of pipelines and installations, \$.02 in environmental costs.

(h) See Figure 12 (78).

(i) Source of concentrated fuel to heat engines taken as standard.

(j) See Figure 6.

(k) Based on coal conversion to gas of 55% including feedback energy (78).

Table 1. (cont.)

- (1) Calculation by Don Young for 100 feet elevation of dam; 90% efficiency of conversion of potential energy of elevated water to electricity; energy of feedback estimated by multiplying the energy cost of \$.64/kilowatt by 25,000 Calories per dollar; coal equivalents found by multiplying electrical output by 3.6 Calories/Calorie as given in Figure 7; 8.25 million Calories per year generates 27 million coal equivalents from which 1.4 coal equivalents of feedback cost are subtracted.
- (m) See Figure 7.

Table 2. Evaluation of net energy of some primary energy sources.^a

Type	Yield ratio ^b
Geothermal power (volcanic region) ^c	57.4
Hydroelectric power ^d	19.0
Tidal power (20 ft tide) ^e	13.7
Western coal and 1000 miles transport ^f	10.6
Alaskan oil ^g	6.3
Gulf of Mexico oil ^h	6.0
Near East oil by exchange, 1975 ⁱ	5.7
Oil in exchange for grain, 1975 ⁱ	4.4
Nuclear fission power ^j	2.7
Low energy agriculture ^k	1.2

- (a) Defined as a source with yield ratio greater than one. (Wind at 10 mph is not a primary source if directed to electricity).
- (b) Yield divided by feedback, both in equivalent energy units of same quality (coal equivalents). Energy costs of distributing energy to consumers are not included. See Figure 10.
- (c) Gilliland (45).
- (d) See footnote 1 in Table 1. Based on 90% transformation and 5% feedback for plant and operation.
- (e) See Figure 6.
- (f) See Figure 12 (78).
- (g) See footnote g in Table 1.
- (h) Based on analysis of a case history in the Gulf of Mexico and 10% for refining.
- (i) See Figure 11.
- (j) See Figure 13.
- (k) High energy agriculture is not net yielding. Low energy agriculture is. See Figure 14.

Table 3. Nuclear system energy flows.^a

Society Income	Typical 1970 10 ¹² KC/yr	Steady state 1970 reference 10 ¹² KC/yr	Accumulative through 1972 10 ¹² KC
Gross production (of electricity)	77.8	77.8	495.0
<u>Society Costs</u>			
AEC related	24.3	15.2	709.0
Completed power plants (includes all nuclear industries)	10.1	1.92	238.0
Ordering rate of power plants	117.0	--	--
Operation, maintenance of power plants	0.9	0.9	8.4
Fuel cycle	104.4	<u>10.75</u>	<u>525.0</u>
	Total	<u>28.8</u>	<u>1480.0</u>
	Net =	49.0	- 985.4
	Gain =	2.7	

(a) Reference 83. (AEC report) $\frac{\text{Gross Production}}{\text{Total Cost}} = 33.6\%$

Table 4. Evaluation of some secondary energy sources^a and environmental interactions.

	Investment ratio ^b
Undeveloped counties of north Florida ^c	1.7
Oyster catch and sales ^d	2.2
Dilute housing with vegetation 1 person per acre ^e	2.5
Estuarine cooling of power plant ^f	3.6
Swamps for tertiary waste treatment ^g	3.8
Miami, Florida ^h	4.0
High energy agriculture ⁱ	6.7
U.S. sewage treatment ^j	117.0
Cooling tower at Crystal River ^k	160.0
Technological tertiary treatment ^l	1800.0
High density city building without buffer area ^m	2000.0

- (a) Sources without net energy but with low enough investment ratio to be economic, i.e. approximately 2.5 or less.
- (b) Ratio of feedback energy (usually purchased) to free external inflow where both are in equivalent units of the same quality. See Figure 15.
- (c) Total natural energy input = 27.12×10^{12} ; fossil fuels consumed = 45.3×10^{12} Kcal CE/yr.
- (d) Boynton (86).
- (e) Solar area $4000 \text{ m}^2/1.5$ million Cal/yr/ m^2 ; 1 Cal coal equivalent per 2000 Calories sunlight; housing cost 300 \$/yr, 25,000 Cal/\$.
- (f) Odum et al., (91).
- (g) Area of swamps 4000 m^2 ; solar energy 1.5 million Cal/ m^2 /year; 367 \$ flow in costs of distribution; 19,000 Cal/\$ (87). Solar energy converted to coal equivalents using factor of 2000.
- (h) Zucchetto (88).
- (i) 5000 kg per hectare from H. Walters, Science 188:524 (1975); 4 Cal/g; 2.5 Cal fuel input per Cal food [Pimentel et al. (39)]; 1.5×10^{10} solar Calories/yr/hectare; 2000 Cal coal equivalents/Cal sunlight.
- (j) Environmental energy calculated as: $1.4 \times 10^8 \text{ m}^2$ in primary and secondary treatment plants times solar insolation and divided by 2000 Cal solar energy per Calorie of coal. Organic matter of sewage 22×10^{12} Cal CE per year from [EPA 1974 (89)]. Goods and services 60×10^{12} Cal/yr calculated from 2.4×10^9 \$/yr times 25,000 Cal/\$ [Smith 1968 (90)].

Table 4. (cont.)

- (k) Damage to estuary (3.4×10^9 CE/yr) was measured as loss of half of productivity of inner bay metabolism plus screen mortality plus plankton entrainment each expressed in coal equivalents (91); investment from the economy estimated from cooling tower cost (17 million \$ per year) and 20,000 Cal/\$ plus potential energy content in heat released calculated as Carnot ratio for 6 degree temperature times Calories released.
- (l) Diverted solar energy of 10 acres is 1.5×10^6 Cal/m²/yr: Feedback for 2.8 million gal/day secondary waste is \$90,000/yr multiplied by 25,000 Cal/\$.
- (m) Solar energy 4000 Cal/m²/day divided by 2000 Cal sun per Cal coal is 2 Cal CE/m²/day; fossil fuel consumption in concentrated city zones = 4000 Cal/m²/day.

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3. Department of Nuclear Engineering Sciences, University of Florida, Gainesville, FL, 32611.
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79. Estimated with data from F. Lawton in Tidal Power, T. Gray and O. Gashus, eds. (Plenum Press, N.Y., 1972); 705 tidal rises per year and 7 m tidal height; area of tidal pool at Rance, France 2.2×10^{11} cm², energy feedback estimated by multiplying 24,000 Calories per dollar times annual cost of \$4.7 million dollars. Electrical output 544 million kilowatt-hours per year multiplied by 860 Calories per kilowatt hour and by 3.6 Calories coal equivalents of a Calorie of electrical energy (Fig. 7).
80. A 1000 megawatt coal fired electric power plant, 75% load, 3 cents per kilowatt hour, 38% efficiency of heat conversion to electricity,

\$25,000 Cal/dollar used to estimate coal equivalents of purchased goods and services.

81. Sunlight for the U.S. divided by 2000 to obtain estimated coal equivalents from renewable environmental source. Area of U.S. $9.52 \times 10^{12} \text{ m}^2$ times $1.5 \times 10^6 \text{ Cal/m}^2/\text{yr}$. 1975 fossil fuel consumption estimated from Bureau of Mines data for previous years.
82. Coal equivalents of \$12 obtained by multiplying by \$12 of foreign exchange by 21,000 (Cal/dollar for 1974). Foreign exchange of 50 million tons of grain and price of \$150/metric ton multiplied to obtain money for oil purchase at \$12/barrel. Coal equivalents of grain (1 Cal per Cal) obtained from Pimentel et al. (39) and 4 Calories per gram.
83. Notes for Table 3 and Figure 13 from report by C. Kylstra and Ki Han Energy Analysis of the U.S. Nuclear Power System (p. 138-200 in annual report to ERDA Contract E-(40-1)-4398, 1975):

1. Gross Production

- a. 1970 Typical and Steady State Flows

The 1970 Central Power Station Electrical Production was $23.6 \times 10^6 \text{ MWe hr}$, at a load factor of 38%. Using an average load factor of 46.6%, a more typical value would have been $28.9 \times 10^6 \text{ MWe hr}$. Converting into Coal Equivalent heat units, $(28.9 \times 10^6 \text{ MWe hr/yr}) \cdot (1 \text{ heat unit}/.32 \text{ Ele unit}) \cdot (86 \times 10^4 \text{ KC/MW}) = 77.8 \times 10^{12} \text{ KC/yr}$

- b. 1972 Accumulated

The accumulated production through 1972 was $184.18 \times 10^6 \text{ MWe hr}$. $(184.18 \times 10^6) \cdot (86 \times 10^4/.32) = 495 \times 10^{12} \text{ KC}$

2. AEC Related

The AEC affects all phases of the nuclear system, through regulation, control, research, development, and operation and ownership of facilities. Additional efforts in the areas of fusion, military, and other activities complicated determination of dollar and energy expenditures related to the U.S. Nuclear Power System (Light Water and Breeder Reactors).

- a. 1970 Typical Flow

The total AEC budget for 1970 equals $\$1.866 \times 10^9$, a lower value than previous or later years. Using $\$2 \times 10^9$ as a more representative value, and estimating that approximately 50% of the AEC's activities are Nuclear System related, gives: $(\$2 \times 10^9) \cdot (24,300 \text{ KC}/\$) \cdot (.5) = 24.3 \times 10^{12} \text{ KC/yr}$

- b. 1970 Steady State Flow

Research and Development activities would be minimal at steady state, plus all aspects of regulation. The fuel cycle would be proportional to the steady state level of reactors (see 3 and 5 below). Assume mining and enriching activities reduced

$$(59.35 \times 10^{12}) \cdot (.033) = 1.96 \times 10^{12} \text{KC/yr}$$

c. 1972 Accumulated

Completed power plants in 1972 total 87.9×10^{12} KC of expended energy throughout the nuclear industry. Energy already expended for power plants under construction is estimated using the number of power plants under construction in early 1970 as 39,288 MWe. Assuming that 1/2 of the energy is expended by 1972, gives:

$$\text{completed} = 87.9 \cdot (39,288 \text{ MWe}) \cdot (.5) \cdot (400 \times 10^3 \$/\text{MWe}) \cdot (19,000 \text{ KC}/\$) = 150 \times 10^{12} \text{KC}; \text{ thus the total accumulated} = 237.9 \times 10^{12} \text{KC}$$

4. Operation, Maintenance of Power Plants

The operating and maintenance cost for supporting industry for power plants is included in item 3. For power plants, direct operating and maintenance costs are estimated as 10% of total power production cost, or as 1.5% of total capital cost.

a. 1970 Typical and Steady State Flow

Using the total energy of 59.35×10^{12} KC as the stored energy in power plants in 1970, the maintenance and operation expenses are:

$$(.015) \cdot (59.35 \times 10^{12} \text{KC/yr}) = 0.9 \times 10^{12} \text{KC/yr}$$

b. 1972 Accumulated Flow

The accumulated operation and maintenance flows are obtained by multiplying accumulated structure for each year by 1.5% and accumulating through 1972:

$$(560 \times 10^{12} \text{KC-yr structure}) \cdot (.015 \text{ cost/yr structure}) = 8.4 \times 10^{12} \text{KC}$$

5. Fuel Cycle

The fuel cycle includes everything in the uranium processing process, starting with the removal of the uranium ore in the ground to the storage of radioactive waste, plus the recycling of spent fuel and plutonium and uranium.

The direct AEC costs associated with the fuel cycle are already included in item 2.

a. 1970 Typical Year

The sum of the mining, milling, conversion, enrichment, and fabrication cost for 1970 was 98.23×10^{12} KC/yr, producing $1,086 \times 10^{12}$ KC/yr of U-235 fuel. The other direct society costs are related to the actual use rate of U-235, of 102×10^{12} KC/yr.

These are the reprocessing costs of 1.83×10^{12} KC/yr and the 1970 costs for radioactive waste disposal, of 4.3×10^{12} KC/yr. Thus, the total fuel cycle costs are:

$$(98.23 + 1.83 + 4.3) \times 10^{12} \text{KC/yr}$$

b. 1970 Steady State

If the processing of uranium matched the 1970 consumption rate, the $98.23 \times 10^{12} \text{KC/yr}$ figure from item 5a above would be reduced to $9.23 \times 10^{12} \text{KC/yr}$. The reprocessing and waste disposal costs would be the same. Thus, the total is:

$$(9.23 + 1.83 + 4.3) \times 10^{12} = 15.36 \times 10^{12} \text{ KC/yr}$$

This value must be further reduced by the amount of plutonium produced and consumed in the reactor. Estimating approximately 30% of power comes from plutonium yields $10.75 \times 10^{12} \text{KC/yr}$.

c. 1972 Accumulated

The mining and milling costs are $1.4 \times 10^6 \text{KC/Kg}$ of U_{308} . 65,900 tons were mined for domestic power use by 1972:
 $(65.9 \times 10^6 \text{Kg}) \cdot (1.4 \times 10^6 \text{KC/Kg}) = 92 \times 10^{12} \text{ KC}$

Conversion, enrichment, and fabrication cost is $9.05 \times 10^6 \text{KC/Kg}$ of U_{308} . 43,500 tons were delivered to power companies by 1972:

$$(43.5 \times 10^6 \text{Kg}) \cdot (9.05 \times 10^6 \text{KC/Kg}) = 394 \times 10^{12} \text{ KC}$$

Reprocessing costs are related to the total burn up or consumption of uranium. This can be estimated from electrical production

$$(495 \times 10^{12} \text{KC Ele Acc} / 77.8 \times 10^{12} \text{KC Ele 1970}) \cdot (1.83 \times 10^{12} \text{KC}) = 11.64 \times 10^{12} \text{ KC}$$

Waste disposal costs are also related to production, and thus are $(495/77.8) \cdot (4.3 \times 10^{12} \text{KC}) = 27.36 \times 10^{12} \text{ KC}$

Thus, total cumulative fuel cycle costs are

$$(92 + 394 + 11.6 + 27.4) \times 10^{12} \text{ KC} = 525 \times 10^{12} \text{ KC}$$

Preliminary estimates of net energy of nuclear power are given by Pong Lem. Energy Required to Develop Power in the United States. Ph.D. Diss., U. of Florida, Gainesville, 1973.

84. Subsistence agriculture based on data from R. Rappaport, Scientific American 225:104 (1971). Solar energies based on incident sunlight of $1.8 \times 10^6 \text{Kcal/m}^2/\text{yr}$ on an agricultural plot of 1021 m^2 . From this plot was yielded 16 garden crops with a value of 9.2×10^6 food Calories/yr. The quality of food calories is estimated to be 1 Calorie coal equivalent per 1 food Calorie. This estimate was based on the energies involved in raising 8 garden crops (42). Feedback of $.56 \times 10^6$ Cal/yr human labor was converted to Cal CE based on the relationship of 1 Cal human work per 14 CE (E. Hirst Science 184:137).
85. The solar water heater was assumed to have a 10 yr lifetime. The following numbers refer to the circled numbers on Figure 15a:

(1) Average mean daily insolation for Miami, Fla. area is 4500 Kcal/m²/day. Area of collector was 4.46 m². Yearly insolation = 4500 Kcal/m²/day x 365 days x 4.46 m² = 7.33 x 10⁶Kcal/yr; (2) Water consumption for family of four = 4 x 20 gal/person·day x 365 days/yr = 2.92 x 10⁴gal/yr; (3) Assume 65% efficiency. Heat loss = 7.33 x 10⁶Kcal/yr x .35 = 2.56 x 10⁶Kcal/yr; (4) For 10 yr system lifetime assumed 10% depreciation per year; (5) For 10% heat loss from water tank and water heated by 35°C, heat required is 2.92 x 10⁴gal/yr x 3.785 Kg/gal x 1 Kcal/Kg -°C = 4.3 x 10⁶Kcal/yr; (6) Additional electrical energy during winter months is 476.3 Kwh/yr x 860 Kcal/Kwh x 4CE/Kcal = 1.64 x 10⁶CE/yr; (7) Electrical Energy = 476.3 Kwh/yr x 860 Kcal/Kwh x 960 Kcal/Kwh x 4CE/Kcal = 1.64 x 10⁶CE/yr; (8) For interest rate of 10%/yr amortization factor = .163. For new house, cost of heater is \$657 x .163 = \$107/yr; (9) 10% heat loss from tank = .1 x 4.3 x 10⁶ Kcal/yr; (10) \$107/yr x 25,000 Kcal/dollar = 2.7 x 10⁶Kcal/yr; (11) Assuming 10% loss from tank total heat required = (4.3 + .43) x 10⁶Kcal/yr = 4.73 x 10⁶ Kcal/yr; (12) Cost = 476/yr x (\$.023/Kwh + \$.009/Kwh) = \$15.24/yr; (13) Cost for new house = \$657 x 25,000 Kcal/ dollar = 16.4 x 10⁶Kcal. Cost for old house = \$801 x 25,000 Kcal/ dollar = 20 x 10⁶Kcal.

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