NET ENERGY ANALYSIS OF ALTERNATIVES FOR THE UNITED STATES

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ABSTRACT

Overview, large scale energy models suggest ways that the flows of energy from domestic resources, from the environment, and from international exchanges support the economic system of the United States. Examination of net energy of the present and proposed types of energy sources shows little evidence that the present leveling trends of the U.S. will be reversed. Energy analysis diagrams suggest that when energy sources decline, the very high quality sectors of the economy on the end of the energy chain decrease most. Models and energy analysis suggest characteristics of life in the United States to come and programs to prepare for smooth transitions. Examination of energy systems of the environment suggest that steady state regimes (leveled economies) can be vital and of good quality for human existence. Sharp changes in public viewpoint and public policy are to be expected soon.

This is a summary of ideas concerning long range U.S. policy on energy, economics, and environment generated from evaluating models for energy analysis and synthesis in several projects and activities at the University of Florida at Gainesville, Florida.

Authors listed contributed component sections and calculations, but only the first 4 authors should be held responsible for the overall interpretations placed on the results.

NOTE. Footnote references are to explanatory notes appearing at end of this article, page 302A.

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See next page.

Part 1

MIDDLE- AND LONG-TERM ENERGY POLICIES AND ALTERNATIVES

HEARINGS

BEFORE THE

SUBCOMMITTEE ON ENERGY AND POWER

OF THE

COMMITTEE ON
INTERSTATE AND FOREIGN COMMERCE
HOUSE OF REPRESENTATIVES

NINETY-FOURTH CONGRESS

SECOND SESSION

ON

ENERGY CHOICES FACING THE NATION AND THEIR
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NET ENERGY ANALYSIS OF ALTERNATIVES FOR THE UNITED STATES

Energy flows are believed to me the basis for organization of matter, information, money, and value. Therefore energy analysis for whole systems can show quantitatively which alternatives generate the most productivity and value. Since energy principles apply to all sizes of systems, energy analysis methods apply equally to systems of life, environment, cities, regions, nations, or the biosphere as a whole.

Energy analysis is aided by diagramming with standard symbols (Fig. 1) [1] according to laws of energy flow. Simplified models in diagrammatic form help visualize where energy flows are large or where they are hidden and often overlooked. Simplified energy analysis models retain the overview and constraints of the total energy flow. Evaluated models facilitate the calculation of the available net energy of sources. *Net energy* is the energy yield minus that needed to collect and process the original energy. In this paper the energy unit used is the Calorie (Kilocalorie).

I. AN OVERVIEW OF GROWTH OF THE UNITED STATES AND THE WORLD

First consider the way world energy sources are causing change and affecting the future of the United States. Simple overview models are diagramed and evaluated to clarify the hypothesis offered.

MINI-MODEL OF WORLD GROWTH

One mini-model of the world economy expressed in the language of energy analysis is evaluated in Fig. 2a. The diagram shows the world assets as a balance between the inflow of productive processes adding to order, and the outflow due to depreciation and work. The circles are outside energy sources, the renewable energies, and the slow replacement of mineral resources by the earth. The tank shaped symbols are storages. Interaction of feedback work with different kinds of energy produces available fuel and then the assets of the human economy. Inflowing energy eventually goes out as used energy. Money is shown in dashed lines circulating as a counter flow to the main paths of work by people.

The economy and assets are maximized by good use of renewable resources and stored reserves. Values of storages and flows are written on Fig. 2b. The main uncertainty is the quantity of reserves that are accessible enough to yield net energy. Other uncertainties are the rate of depreciation of world assets.

Although this paper does not primarily concern the computer simulation aspect of energy analysis models, Fig. 2c does include the equivalent equations and Fig. 3 shows a simulation of trends based on an available world fuel reserve of 5×10^{19} Calories. Providing no new unlimited energy source is found, the shape of things to come is given the turn of the century, there is considerable question about the timing of world rise and decline because the quantity of energy in world fuel reserves in uncertain. Scenarios for the future of a fossil fuel based economy by others such as Hubbard, Cook, and Forrester have the general shape, but the timing of the crest is the uncertainty which depends on the amount of fuel reserves.

Scenarios based on gross reserves overestimate the time that reserves will last. Scenarios should be based on net energy, that is energy yield minus that needed to collect and process the energy. In the simulation of models in Figs. 2 and 4 the decreasing net yield as one goes deeper into the ground to obtain fossil fuels is handled by a mathematical function, one that is still hypothetical. A better prediction may be one based on calculated net reserves when such a figure is generated from detailed calculations of net energy of various energy deposits in various locations, depths, and distances from points of use of the world. Energy reserves that take more energy to get than they deliver should not be counted.

The world overview models also show the circulating flow of money operating with a spending rate dependent on money supply. The ratio of the money flow to the energy flow is an index of worldwide prices. The world mini-model suggests the pattern of world energy and conditions of international exchange to which the United States must adapt. We may use the simplified world mini-model to predict the kind of causal actions impinging on the United States.

OVERALL MODEL OF THE UNITED STATES

The mini-model for the growth of U.S., shown in Fig. 4, is similar to the world mini-model in all respects except the addition of international exchange of exports and imports. A simulation of this model is given in Fig. 5. The world prices generated by the world mini-model in Fig. 2 were used to drive the U.S. model. Because reserves at home are more depleted compared to those of the world, the U.S. model crests sooner. Any energy from outside that might support growth tends to go back into products for exchange causing growth abroad instead of at home. The feedback pathway is the action of technology facilitating and processing energy into productive work. Since technology is the application of energy, it cannot provide energy if there is no source with which to operate the technology.

Since a simplistic overview model may not be convincing in suggesting trends, and since energy decisions involve choices within the system, we may take another type of overview which has more detail.

A CIRCULATION VIEW OF U.S. ECONOMY

Given in Fig. 6 is a circulation model which has the circulation of money in the GNP shown as a counter current to the flow of energies. Energy enters from outside as externals with some feedback from the main economy interacting to facilitate the flow. Energy circulates through the economy before dispersing gradually into degraded heat. Money is paid for the feedback but not for the energy in the external inflow. Note that the money flows given in dashed lines accompany lines of energy flow only within the closed loop; they do not go out to pay for the free services of nature. Money is paid only to humans

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[1] Figures appear at end of article, p. 272.

for processing energy, not to nature for the energy. Energy from outside is used gradually throughout the economic circle supporting work in a diffuse overall way not recognized at the point of first use. Money buys value only as long as the external energy inflows are sustained.

A principal difference between economic and energy analyses is the evaluation of the external inflows that ultimately determine the productivity. Recently this has been called net energy analysis.

II. Principles of Net Energy Analysis

NET ENERGY OF EXTERNAL SOURCES: YIELD RATIO

In Fig. 7 is drawn one external inflow with its feedback from the main economy, and its counter current of money that pays for the service. This is one of the external energy inflow sectors from Fig. 6. To evaluate the inflow source we may calculate the net energy defined as the difference between yield, Y and feedback, F. To be useful as a primary source there has to be net energy. Having potential for some net energy is not enough for a source to be used; it must also be competitive, justifying feedback of the valuable work from the main economy. For an energy source to be competitive the ratio of yield to feedback must be high relative to alternative sources.

ENERGY QUALITY, ABILITY TO CAUSE WORK

Whereas the net energy and energy yield ideas are qualitatively simple, they are quantitatively complicated because Calories of different type have different abilities to generate work or to interact as amplifiers to generate work. Standard teaching of energy sometimes uses the definition of energy as the ability to do work, but this only refers to comparisons of energy flows of the same type. Degraded, dispersed heat cannot do any macroscopic work, while dilute energies such as sunlight have to be concentrated at great energy cost in order to generate work. Other forms, like fossil fuel reserves, are already concentrated.

It is postulated that there is an inherent thermodynamic minimum energy required as input, in order for one type of energy be upgraded into another type of energy with a necessary dispersal of used energy as heat. If, as also postulated, surviving systems in the real world operate at the optimum rate for processing maximum useful power, then there is one rate of transformation and one minimum heat dispersal that will tend to emerge under conditions of choice and competition.

By measuring successfully operating systems competing in the real world, we may obtain estimates of the necessary heat degradation to transform one type of energy into another (at loading for maximum power). Energy analysis of real systems for transforming coal to electricity, elevated water to electricity, sun to food, wind to elevated water, etc. allows us to develop a table of energy dispersal requirements for transformation. See Table 1.

Fig. 8. defines the terms used in Table 1. The *Energy Quality Factor* is the energy input divided by higher grade of energy output. Since there is always feedback of higher quality energy in the real system, this must also be evaluated and expressed in the units of the input or the output, and included in the ratio calculation as shown in Fig. 8b or 8c. An example using a coal fired electric powerplant is given in Fig. 9.

Energy analyses of representative processes give us the energy quality factors of Table 1 and also are useful in estimating net energy contributions. Figs. 9–24 have these energy analyses.

The potential energy used (dispersed into heat) is the cost in energy terms of upgrading quality. It is postulated that in real competitive, surviving systems under pressure to develop maximum useful power, that energy tends to be upgraded only when it is feeding back as an amplifier with as large a stimulation effect on the upstream energy chain as the energy utilization is a drain. The reason postulated is that chains without the feedback would drain their own sources, putting them in competitive disadvantage causing eventual replacement.

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	Number of figure	Calories equivalent to 1 calorie of coal
Solar heating	23	11,000
Solar energy in photons	22	22
Uranium ^{235} as mined	20	3,140
Photosynthetic products, uncollected	10	20
Geothermal steam (volcanic area)	19	1.6
Gulf of Mexico oil	12	1.4
Alaskan oil	13	1.4
Western coal before mining	15	1.1
Coal already mined	(1)	1.0
Tidal energy, 20 ft. tide	18	.6
Heating gas	16	.55
Elevated water	17	.32
Electricity	9	.27

[1] By definition.

COAL EQUIVALENTS (CE) FOR COMPARING WORK ABILITIES

To help with net energy calculations and other comparisons of energy flows as to their energy cost, it is convenient to convert all types of energy into coal equivalents using the energy quality factors of Table 1. Coal equivalents are convenient to use, since most people have a feeling about the work that fuels can do running the heat engines of our economy. Coal equivalents are abbreviated: (CE).

In order to convert energies such as solar energy to fossil fuel equivalents, it is convenient to put energy quality factors together in a chain as shown in Fig. 10.

High quality energy such as electricity or protein is believed to be flexible and a type into which other types can be converted. Conversions to electricity as a common denominator allow comparisons between types not readily intraconverted. It is postulated that two pathways for converting energy types should give similar results if both are operating in the real world under conditions of maximum power selection. If they did not give similar results, one would be more efficient and displace the other, and by definition would be the one you would use.

USE OF ECONOMIC DATA TO ESTIMATE DIFFUSE, HIGH QUALITY, FEEDBACKS

In many energy analyses the feedbacks of work (F) from the general economy (Fig. 7) are mixtures of labor, goods, and services given as dollar flows. Wherever these may be adequately represented by an average cost in energy terms, one may estimate the energy utilized throughout the economy to generate the feedback by proportion where both energy flows are expressed in equivalents of the same quality (such as coal equivalents).

$$\frac{\text{Feedback Energy}}{\text{Total Energy of the Economy}} = \frac{\text{\$ Flow of Feedback}}{\text{\$ GNP}}$$

The ratio of total energy to total money flow in our determinations includes the free natural energies of sun, wind, waves, etc. as well as purchased fossil fuels. Fig. 11 indicates how the ratio of kilocalorie flow to dollar flow is calculated. Solar energy is expressed as coal equivalents and added to fossil fuel. This ratio changes each year with inflation.

Some semantic arguments about net energy work involve a question of double counting. When feedback energy is estimated with a kilocalorie per dollar factor, some of the energy is included that is circulating back from the source of interest. For some purposes, where needed, this can be subtracted in order to find the independent energy involved.

TABLE 2.—EVALUATION OF NET ENERGY OF SOME PRIMARY ENERGY SOURCES

Type	Figure	Yield ratio[2]
Geothermal power (volcanic region)	19	57.4
Hydroelectric power	17	19
Tidal power (20-ft tide)	18	13.7
Western coal and 1,000 mi transport	15	10.6
Alaska oil	13	6.3
Gulf of Mexico oil	12	6.
Near East oil by exchange, 1975	14a	5.7
Oil in exchange for grain, 1975	14b	4.4
Nuclear fission power	20	2.7
Low energy agriculture [3]		2.1
Low energy forestry	22a	1.5
Nuclear fission with an accident	21	1.4
Wind powered electricity (10 mi/h)	23	[4].28

[1] Yield ratio greater than 1. Wind is not a primary source.

[2] Yield divided by feedback, both in equivalent energy units of same quality (coal equivalents). Energy costs of distributing energy to consumers are not included.

[3] High energy agriculture is not net yielding. Low energy agriculture is.

[4] No net.

III. Net Energy of Alternative Energy Sources

Given in Figs. 12–24 are results of energy analysis of numerous types of energy source. The energy yield data for these are compared in Table 2. If these values are representative, they suggest wide differences as to which types of energy sources can be used for our main economy. The ones with higher net energy yield ratios are the ones that we find really dominant in the real world providing primary energy, especially foreign oil and coal. Others are net yielding only in special areas.

The energy sources at the top of the list have high yield ratios and support a higher level of economy. Hydroelectric, tidal, and geothermal energy sources are rich, but there are limited amounts, and these are local.

Nuclear fission starts with a concentrated, high energy process, but much of the energy is dispersed in getting the temperature down to a value where engines can operate. As Table 1 and Figure 20 show, only one Calorie of useful work equivalent to coal results from 22 Calories of uranium ^{235}. The yield ratio of nuclear energy is less than that of coal. Uranium^{238} requires breeder (net energy unknown).

Nuclear fusion starts with an even more intense heat and thus may be even more costly in energy feedback required to control it. There is no evidence yet that it can yield net energy to the lower energy world of man and the biosphere.

The yield ratios of fossil fuel available to the U.S. by exchange or from our remaining deposits are apparently mainly between 5 and 11. Without these, there remains the lower energy agriculture of our forefathers with an energy level one half to a third of the present.

IV. Use of Net Energy for Secondary Sources

We defined net energy as that energy entering the main economy over and beyond that necessarily feeding back, and we compared net energies in a variety of energy sources. Next we ask, what do effective surviving systems do with their net energy? Our hypothesis from the maximum power principle suggests that they feed back excess energy into gaining more energy. Shown in Fig. 25 are three alternatives, any one of which may offer the most auxiliary energy in a particular situation.

If there are more energies to be tapped (Fig. 25a) from the same source, the system can increase its structure of the same type so as to pump in more of the same type of energy. This is growth. An example is the growth of U.S. economy which caused more oil drilling in the early part of this century.

Suppose primary sources available for further growth are limited. If there is energy to be obtained from auxiliary sources, net energy can be used. The system can use its net energy for diversification of sources. An example is building and maintaining structure for tapping a new type of energy (Fig. 25b). For example, some of the net energy of the U.S. economy in the last two decades was used to develop atomic energy.

If there are energy sources abroad available for exchange, net energy can be used to develop products, goods, or services that are valuable to the foreign country for exchange. For example, the U.S. sales of grain and airplanes maintains the balance of payments necessary to purchase foreign oil (Fig. 25c). Secondary sources need not be as highly yielding as the primary sources. They may not even be net energy yielding, as long as there is a surplus of rich net energy from primary sources to feedback as a subsidy.

However, our hypotheses about surviving systems maximizing power suggests that they do not feed back net energy to a secondary source unless there is as much matching energy available from that source as there is from alternative opportunities.

MATCHING OF HIGH QUALITY AND LOW QUALITY ENERGY

Another way of explaining why feedback of high quality energy favors maximum power concerns our hypothesis of matching high quality energy with low quality energy. High quality energy brings more energy into a system when it is used as a multiplier to help process low quality energy than if it is used in place of the low quality energy. Conversely low quality energy can attract the matching of high quality feedback since the interaction maximizes the useful contribution of both of them to maximum power. Figure 26 shows feedback of high quality energy to match low quality energy.

MATCHING WITH LOW ENERGY SOURCES

Since the secondary sources are partly dependent on feedback from the net energy of the richer primary sources, they may become less yielding or non-yielding if the primary sources decline. Expressed another way, the secondary activities use goods and services at prices that are low because of the rich energy flows used throughout the economic circulation that came from primary sources. For example, when fossil fuel prices went up sharply in 1973, the net energy available to subsidize nuclear energy declined and it became less economic.

When all of the available primary and richer secondary sources are being utilized, the net energy is fed back to pump energy flows of lower and lower quantity and quality. Shown in Fig. 26 is the average relationship in the U.S. between high quality energy feedback and external energies of low quality from the environment, the renewable sources. The environmental energies are expressed in coal equivalents by dividing the solar energy of the U.S. by the quality factor, 2000.

Secondary energy sources which are currently considered in the U.S. are those where the feedback of energy from the main economy is larger than the inflow of external energy that it stimulates. Here the rich, high quality energy based mainly on fossil fuels is interacting with a smaller auxiliary energy. Fig. 26 shows the situation with energies expressed in common quality units (coal equivalents). Although smaller than the feedback, flow from secondary sources does add energy, and the system as a whole increases its total useful power flow, helping it maximize its ability to compete. The net energy of primary sources is used here as a feedback subsidy to bring in more energy.

INVESTMENT RATIO FOR EVALUATING LOW ENERGY SOURCES

The contribution of a low quality energy source can be compared with the feedback of high quality energy fed back to process it. If less energy is supplied per unit feedback energy invested than for available alternatives, the source is a poor one and the plans for such development may be ill advised. We define the *investment ratio* as the feedback divided by the inflow where both are expressed as Calories of the same quality (such as coal equivalents). The investment ratio in Fig. 26 is 2.5/1 (for total fossil fuel to total solar energy expressed in coal equivalents). This ratio is a usual one in the United States and is useful as a reference number for deciding when a feedback is well matched (ratio is lower) and when it is poorly matched (ratio is higher).

INVESTMENT RATIO FOR PREDICTING WHEN INVESTMENTS ARE ECONOMIC

In Fig. 27 money flow has been added to Fig. 26. The sales of goods or services is dependent on two energy sources: (I) the external, low quality, and free pathway not accompanied by money; and (F) the high quality feedback from the economy which has to be purchased with money. Note the payments of money exported to the right.

When there is much energy from the free source (I) contributing to the production of output for sale, the sale price can be less and the activity captures the market. Consequently more money comes in which can buy more of the rich energy.

Situations with lower than usual investment ratios are economic and grow. Situations where the investment ratio is higher than usual are poor uses of rich energy because they are poorly matched. Our hypothesis is that they fail economically. Table 3 contains results of some calculations of investment ratio.

The investment ratio does seem to be inversely correlated with economic success. This simple evaluation can help us quickly decide which alternatives are energetically questionable and explain what was wrong with well intentioned plans that did not succeed.

TABLE 3.—EVALUATION OF SOME SECONDARY[1] ENERGY SOURCES AND ENVIRONMENTAL INTERACTIONS

	Number of figure	Investment ratio[2]
Undeveloped counties of North Florida	(3)	1.7
Oyster catch and sales	33	2.2
Dilute housing with vegetation, 1 person per acre	34	2.5
Estuarine cooling of powerplant	29a	3.6
Swamps for tertiary waste treatment	31	3.8
Miami, Fla	(3)	4.0
High energy agriculture	(3)	5.0
U.S. sewage treatment	34	117.0
Cooling tower at Crystal River	29b	160.0
Technological tertiary treatment	30	1,800.0
High density city building	(3)	2,000.0

[1] Sources without net energy but with low enough investment ratio to be economic, i.e. approximately 2.5 or less.

[2] Ratio of feedback energy (usually purchased) to free external inflow where both are in equivalent units of the same quality.

[3] See footnote (33).

ENERGY INVESTMENT AND COST BENEFIT ANALYSIS

When the net energies of high quality are supplied to stimulate more energy, that is energy investment. The money that is circulated in the process often starts out as investment capital that starts the system as shown in Fig. 28. After the energy is flowing, sales and services are generated that circulate money to pay for the continuing flow of feedback energy as in Fig. 27.

Cost benefit analysis in money terms is usually a comparison of the investment flow in Fig. 28 (cost) with the regular flow of money flow that runs on its own afterward in Fig. 27 (benefit), with some additional amounts included in the consideration, such as the money that would have been earned in alternative investments and moneys that would have been flowing without the new system. The energy investment ratio helps determine in advance if there are enough energies for the anticipated money flows to develop. The investment ratio can be used as an "energy cost benefit" method.

ENVIRONMENTAL IMPACT AND TECHNOLOGY

The interactions of the economy of man and the environment are sometimes called environmental impact, but they are also a coupling of environmental energy flows with those of the developed economy running on fuels. Whether the coupling is serving to organize the environmental inflows with the feedback from the economy in a competitive way likely to survive is estimated from the energy investment ratio. A situation with too high an investment ratio wastes high quality feedback energy, overloads the environment as compared to other uses, and is not economic. This system, if set up, will not survive and neither the economy of man nor of nature is served by coupling designs that are temporary and fail. Consider an important case in environmental protection, the problem of disposal of thermal waste from power plants.

COOLING TOWERS

In Fig. 29 energy analysis compares alternatives for absorbing thermal waste. A cooling tower is compared with estuarine cooling that had been in service for 8 years at Crystal River, Florida. An unfavorably high investment ratio would exist if so much valuable fossil fuel energy were invested for so small an improvement of environmental productivity.

If this example is typical, one suspects that general policies of environmental protection that require such high ratios of energy investment to environmental improvement are not good use of conservation dollars or energy. Whenever a dollar is invested in the United States, 30% of the 19,000 Calories of coal equivalents flowing is due to the energy contributed from the environment. When the feedback investment is very high, it means that the environment elsewhere, where goods and services are developed, may be loaded and stressed more than the protection action is helping environmental systems locally. The flow of 110 in Figure 29b is much larger than the protection flow of 3.4.

TERTIARY TREATMENT

As indicated in Fig 30, tertiary treatment by technological means is another case of excessive use of high quality fossil fuel equivalents for an environmental purpose that is not economic, nor competitive and is not as good as other environmental interface systems (See below). Where the density of housing development is so great that technological treatment seems required, the development may be too dense to be economic. The investment ratio is too high. Waste waters with nutrients are a potential source of productivity and should not require large expenditures for treatment.

INTERFACE ECOSYSTEMS

Better alternatives with a better ratio of high value investment to environmental energies are *interface ecosystems.* These partly controlled areas can be developed between waste effluents and the public environment. This is illustrated, in Fig. 31, for Florida experiments that use cypress swamps for waste receiving. Interface ecosystems contribute to economic vitality and have much lower investment ratios than environmental technology. Interface ecosystems are a way of using the work of solar energy to recycle waste in a better design of humanity and nature.

ENVIRONMENTAL TECHNOLOGY GENERALLY

National policies may need substitution of interface ecosystems and other lower energy patterns in place of energy rich technological alternatives with high investment ratios. In Fig. 32 is an overall estimate of the purchased high quality energy feedback in U.S. sewage waste treatment compared to the energy of the environment involved. The high investment ratio in treatment plants and cooling towers relative to their environmental energy benefit raises serious questions about the environmental protection policies of the United States. Are these policies a good use of auxiliary energy?

HARVEST OF ENVIRONMENTAL PRODUCTS

The harvesting of wildlife, fisheries, and forest products from environmental areas are feedbacks from society that invest net energy to develop these yields from secondary sources. See Figures 22a. 31 and 33. There is a gradual increase of the energy invested and money circulating as fishery products move from fisherman to wholesaler, to retailer and to the table. Our theories suggest that the investment ratio which is economic per Calorie of environmental energy involved is 2.5 to 1.

INDUSTRIALIZED AGRICULTURE

Many kinds of agriculture are now intensely supported by feedback of high quality energy from the economy. Industrialized farming has become more like a consumer process and less a producer. Energy analyses of main classes of agriculture (Table 3) have now shown investment ratios higher than 2.5 to 1.

SECONDARY ENERGY SOURCES OVERSUBSIDIZED

Although not all sectors of the U.S. economy are examined in detail, enough examples of environmental technology, and agricultural production are examined in Table 3 and Figs. 29–32 to indicate very large flows of energy feeding back from the net energy of primary sources to interact with secondary energy sources of the free environment. However, the very high investment ratios in many of these practices suggests that these patterns are being operated with too much technology to be economic. Much improvement in national energy use could be obtained by lowering these ratios, spreading out the use of the high quality feedback over more of the free secondary sources.

HOUSING DENSITY

Housing that is dispersed drains values from the environment in panorama, aesthetics, green belts, waste absorption, noise buffers, microclimate, water quality control, etc. Overcrowded housing loses values that have to be made up with purchased services that raise costs and taxes. Figure 34 shows an example of housing with an average investment ratio, one that includes services of vegetation and water controls of considerable part of natural system remaining. Dense, high rise housing that has had problems has a much higher investment ratio than 2.5 and is apparently uneconomic.

Cities like Miami with higher investment ratios are stopping growth whereas Florida counties with lower ratios are still growing. See Table 3. The average size of a lot in the United States only provides a small match of environmental energies for the invested energy flow of the house. The investment ratio in Fig. 35 is 145.

V. EVALUATING ENERGY FLOW OF INTERNAL SECTORS, CONSUMERS

So far we have considered energy effectiveness of primary sources and secondary sources both of which have external inflows of energy. Next consider sectors of the economy which receive energy and feedback work mostly within the system as shown in Fig. 36. Notice the closed loop by which energy enters and leaves the consumer unit. Whereas producers generate net energy from primary sources and supplement with secondary sources, terminal consumers only feed back energy. Here the energy inflow develops additional structure and high quality specialized work, whose justification is the stimulus and valuable service it returns to the economy (see pathway F).

Our hypothesis about successful designs for consumers and their services is that the feedback stimulates the pathway with amplification as much as the use of energy drains it. For example, in Fig. 34 the amplifier action of the high quality feedback is 10 times and the energy required to develop the high quality energy is 10 Calories per Calorie. For example, work on maintaining hospitals should cause as much energy effect in making possible more work by healthy people as was spent. A 10% cost should have a 10% stimulus.

An example of energy flows in an internal sector is given in Fig. 37 for health. Inflow of external energy is small in this loop, but the accumulated energy spent throughout the economy is large.

Because consumers are distant from the lower quality energy sources, consumer flows are high quality as measured in coal equivalents. See Table 4.

VI. MORE DETAILED MODEL OF THE UNITED STATES

It may be useful for some purposes to diagram the sectors of the economy and its life support from the biosphere in more detail as in Fig. 38. The components of the economy are arranged with high quality flows on the right. For different purposes, the grouping and simplification could be done differently.

VII. ENERGY QUALITY CHAINS FOR EVALUATING RELATIVE CHANGES IN ECONOMIC SECTORS

It is observed that surviving systems of many kinds develop energy webs and chains, such as the simplified one in Fig. 10, with larger quantity and lower quality energy flowing in on the left, being upgraded in quality and reduced in Calorie quantity in each stage passing to the right. Examples are food chains, chains of eddies in fluids, and chains of activated molecules in gases, among others. The stages of energy transformation in our economy also generate a series with a high quantity of low quality activities (i.e. jobs with low pay and training) on the left and a small number of highest quality activities (with high pay and training) on the right. See Fig. 38 for the U.S. pattern.

When the quantity of the input energy decreases as when less fossil fuels are used and when the total energy is decreased, there are decreases in the high energy activities, with some disappearing. In Table 4 are some high quality flows of our society and their energy quality factors indicating how many coal equivalents are required for development of each. Many flows with high quality were observed to decrease when energies decreased in 1973. Demand fell for electricity, beef, luxury gasoline, paper, aircraft travel, advertising, and college graduates.

Among the fossil fuels, natural gas is of higher quality energy than oil and oil a higher quality than coal. Energy is required to convert coal to liquid fuel and liquid fuel to gas and the flexibility and ability to stimulate the economy is in the same order. A shift from natural gas to oil and oil to coal is a lowering of the quality of energy operating the economy and this trend shifts flows to the left reducing high quality activities.

TABLE 4.—EVALUATION OF ENERGY INVOLVED IN HIGH QUALITY FLOWS OF U.S. ECONOMY

Item	Footnote	Energy quality: calories of coal per calorie heat[1]
Coal		1
Electricity	15	4
Food at supermarket	41	24
Average human service in United States	42	126
College educated service	43	312
Doctors' service	44	1,250

[1] Reciprocal of factor used in table 1.

VIII. PUBLIC POLICY PREDICTIONS FROM ENERGY ANALYSIS

Consideration of the primary and secondary energy sources available to the United States, the structure that can be supported in an economy of intermediate energy, and the patterns of energy quality in the United States suggests some trends to be expected. In anticipation of what must come, some public policies are recommended to facilitate smooth transitions.

DOMESTIC ENERGY SOURCES

The hard fact is that more and more energy is required per Calorie of fossil fuel and Uranium to obtain energy as mining and drilling goes deeper and further afield. As the net energy declines, the quality of energy also declines, and the percentage of our economy that has to be involved in energy processing increases, displacing other activities. These trends show up as increasing the relative cost of energy. Our discussion of net energy shows nuclear energy with an uncompetitive yield ratio even without including the potentially large costs of an occasional accident or the increasing costs of waste storage. Atomic reactors will not be a long range solution because the reserves of uranium have no longer life than those of fossil fuel.

GROWTH AND LEVELING

Whereas a yield ratio of 36/1 was available at prices of oil before 1973, the yield ratio of primary sources are now about 6/1 for domestic energy and foreign oil exchange. This ratio will gradually decrease.

Our experience of 1973–76 suggests that the 6/1 ratio does not produce growth for the United States. As the net energy of fuels to the U.S. goes down so will the activities that can be sustained.

FOREIGN SOURCES

Foreign oil sources, in the long run, will also become less and less available and will require more energy into exchange to obtain the fuels. Energy required to obtain energy will increase abroad. The countries with rich energy will exchange it for high quality goods and services accelerating their industrial growth, and thus increasing the utilization of their own oils.

PROJECT INDEPENDENCE

The maximum power principle suggests that energy sources with the highest net energy yield ratios will be used first. The price, and thus the yield ratio to the U.S. from abroad depends on the yield ratio of U.S. reserves that are available in competition. If U.S. reserves were used to be independent now, there would be neither independence nor means to control world prices later. If the U.S. uses its oil first and tries to operate on lower yield ratios of poorer grade oil, coal, or nuclear energy, while the rest of the world has access to a higher yield ratio, its economy will not compete and its energy per capita and productivity will decline.

Much of the present energy efforts toward large centralized nuclear plants or coal plants making electricity may be ill-advised. In times of declining energy quantity and quality, the economies of scale shifts to smaller dispersed units and energies are needed for lower quality uses; demand for electricity is less and with it a drop in electric heating, luxury appliances, air conditioning, and frozen foods.

Efforts to develop solar technology can contribute little because of the poor investment ratio. The way to use more solar energy is to use more land and seas in agriculture, forestry, fisheries, with less intensive inputs of bought products.

Instead of upgrading coal to gas or electricity, the economy will downgrade its uses, its high quality roles and its waste.

Although the public has not learned yet, the "miracle of technology" was the indirect application of high net energy and high quality fuels. Technology cannot supply energies that don't exist.

The final verdict is not in on fusion, because its net energy status is much in doubt, but it is not wise to count on it being large for the reasons given.

If present approaches are not fruitful what are the needs? Should we start preparing and designing patterns for a lower energy world without the large uses of high quality energy in transportation, communication, luxury, information, tourism and world domination?

INFLATION

Inflation is driven (among other causes) by increasing energy needed to get energy. Whenever the yield ratio drops, the work per dollar flow drops. Inflation can be eliminated by adjusting money flow to be in constant ratio to energy flow. One way is to cut salaries and prices in proportion to energy flow. In this way the decreasing energy is spread out evenly and unemployment is avoided. A major change in attitude of labor unions is required, but they could take the lead in bringing this policy about. If the energy flow—money flow ratio were held constant, the dollar would become an energy certificate and the economy would be on an energy standard—an old idea that goes back to Howard Scott, Marx and others, although it was not correctly formulated quantitatively, because energy quality was not used and because they did not understand that dollar value depends on *rate* of energy flow.

Welfare is also inflationary since it circulates money without requiring work, as do unemployment payments, food stamps, and other subsidies.

War is inflationary since it circulates money while diverting energy values.

DEFICIT FINANCING

The pumping of an economy by deficit financing or other steps that increase money supply and circulation may work where unused energy is available to serve new activity and expand the energy base with growth. However, if rich energy flows are not available to support expansion, the adding of money adds no work and only inflates. If there is inflation there is incentive to spend money before it loses value. Money circulates well. It is an open question whether circulation will be inhibited without deficit financing in times of leveling or declining energy. Many nongrowing systems, such as some climax forest, seem to maintain effective circulation.

UNEMPLOYMENT

The scenario of leveled or declining energy may produce some unemployment because of transitions in types of jobs, but a lowering of high technology and machine work returns to people many jobs now done by machines, although this also includes a drop in level of luxury per person.

Federal programs of work may circulate money without insuring that the work done is energy effective—that it has a competitive investment ratio. If the work is not productive, such attempts lower total productivity, increase inflation, and lower the energy per capita.

Federal government activity is centralized, concentrated, high quality energy that will tend to decrease as overall energy levels fall. Thus federal programs are not the way to help in declining energy periods.

MILITARY DEFENSE

Military budgets must contract in proportion to the total energies, and defense umbrellas should have as good an investment ratio as any energy investment. In this case, the investment is the energy expenditure on defense and the matching energy is the additional energy that the umbrella causes to flow into the economy.

One theory for decline of some countries is that energy expensive efforts such as war were attempted during a time of already declining energy causing a collapse of central functions.

Declining energy necessarily requires a pullback, but it also decreases likelihood of war as countries become effectively further apart. Large cities are another activity of high energy and high quality energy that has to decrease as energy qualities and quantities decline. Cities that try to maintain full structure in declining energy can go bankrupt. Loans and banks are not workable in declining energy because interest requires growth. Such urban plans as fast centralized mass transit are not needed and cannot be paid for.

The great structures already built are of enormous value, which can serve until they have depreciated, but efforts at remodeling and better maintenance should concern the building industry in place of new construction. As cities become dilute, more vegetation, gardens, and trees will come back. Earth can be brought to cover concrete in some cases.

ENVIRONMENTAL PROTECTION

Environmental Protection as now being developed in the federal and state programs is basically wrong energetically. High quality energy (technology) is being used to get rid of high energy (wastes). Analysis of some representative cases such as cooling towers and tertiary treatment with technology have very bad investment ratios. A better approach is to couple man's wastes to interface ecosystems that can utilize the substances and energy values of the waste using solar energy through vegetation in place of valuable fuels through technology. Design of man and nature means using environmental energies well with high ratios relative to fossil fuel investments.

PRICING OF ENERGY

Some price control policies may have been helping the U.S. in a transformation from growth to steady state, even though they were implemented for different reasons. Holding down prices of natural gas and oil reserves discovered before 1973 caused these reserves to be held back. The ultimate effect would cause the U.S. to use foreign oils at higher price now, saving its own so as to grow less now, making a smoother transition and being more secure later.

CONCLUSION

The overall conclusion from energy analysis and modeling of the basis for U.S. life, is the conviction that we are in process of leveling growth with some further gradual decline in energy flow and level of activity to come.

The major national need is an announced recognition of the nature of the future to be expected by public leaders, followed by implementation of special plans for transition. One of these should be the organization of available lands for rural resettlement and intermediate energy agriculture that is labor intensive and more using of the solar energy. Although some research should continue on fusion and other types of alternative energies, the main effort should now go into the reality of the steady state.

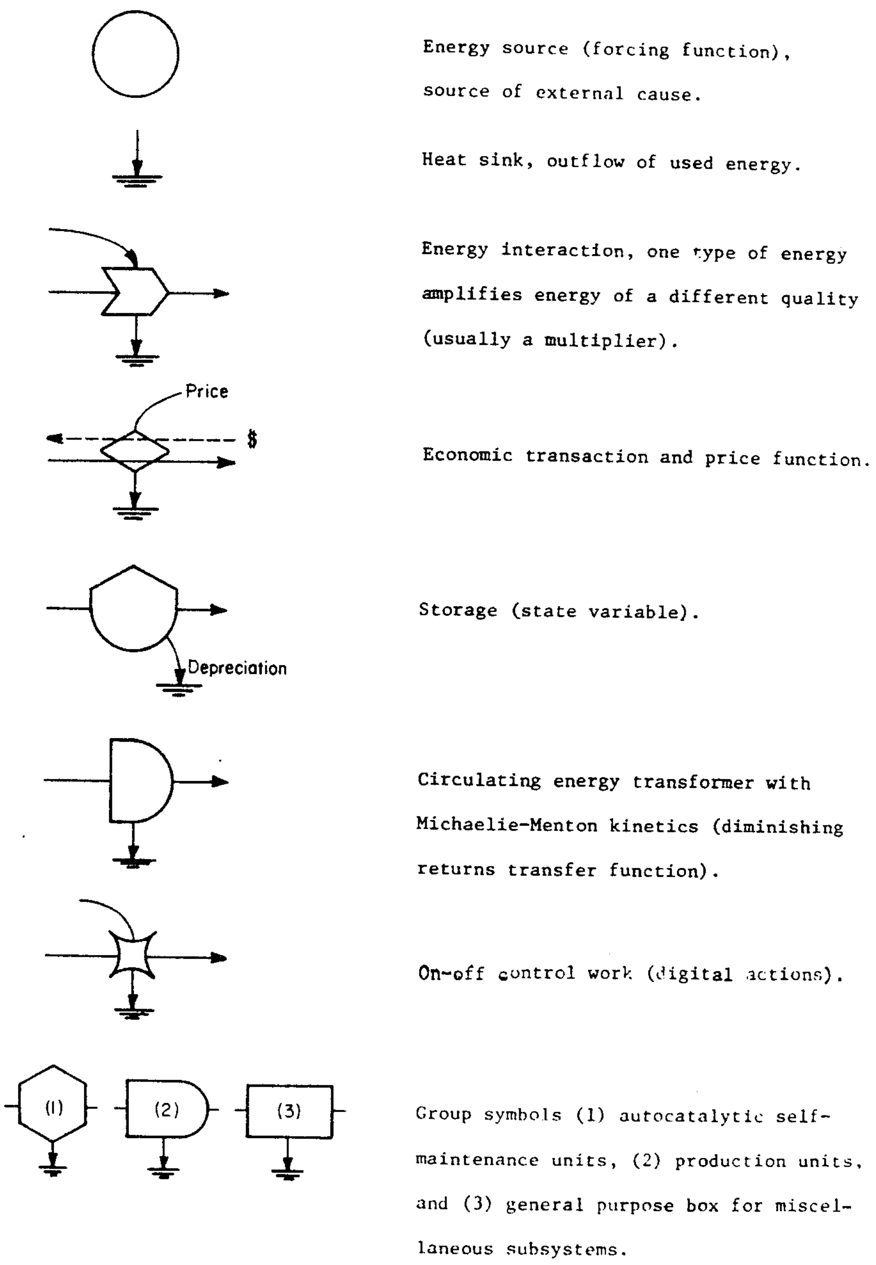


FIGURE 1.—Symbols used in energy analysis diagrams (7, 8).

FIGURE 2.—Overview energy model of world assets and prices (simulation by J. Alexander and Neil Sipe. Lines are pathways of energy flow. Circles are external driving functions bringing in sources of potential energy. Tank symbols are storages. The pointed arrow into ground is the heat sink symbol indicating flow of energy becoming unavailable with entropy increase as required of all processes and storages (depreciation). The pointed blocks with multipler (x) designation are interactions of energy flow of different quality generating productive output of high quality energy. Fossil fuels are shown as multipliers of free renewable energy of sun.

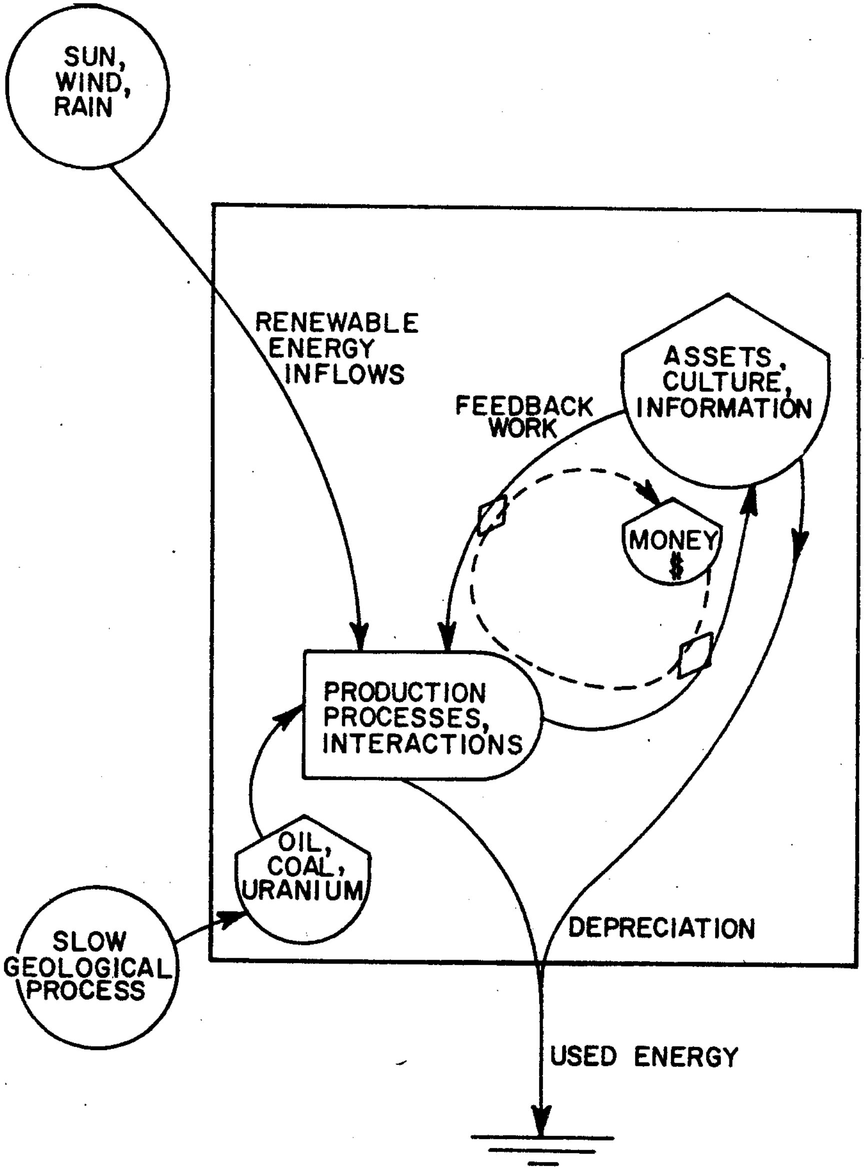
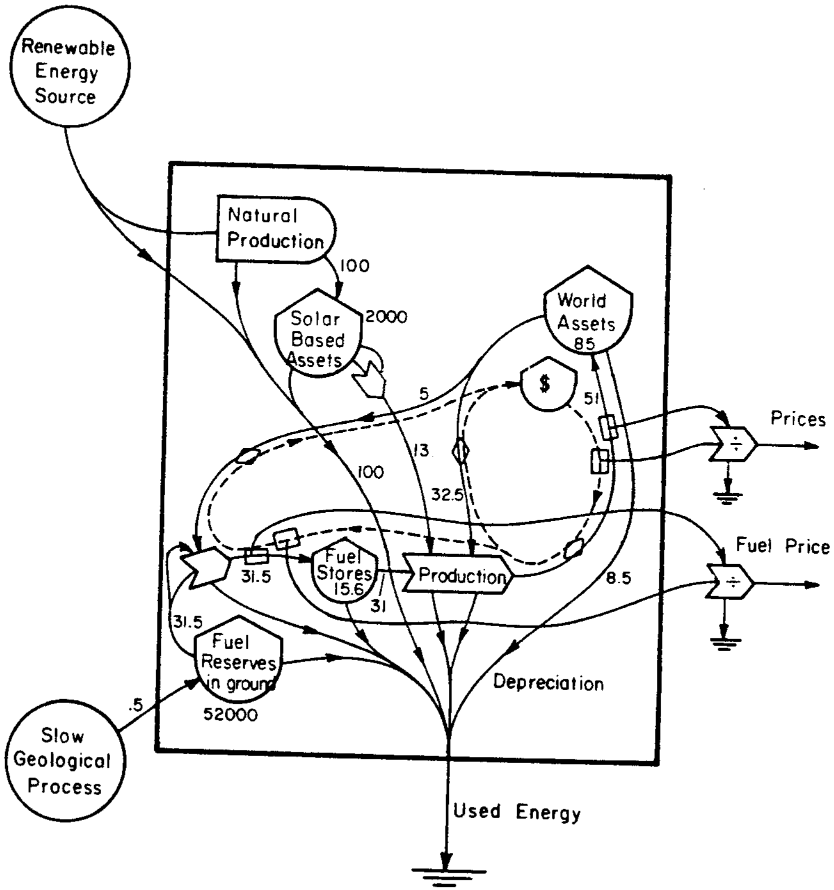
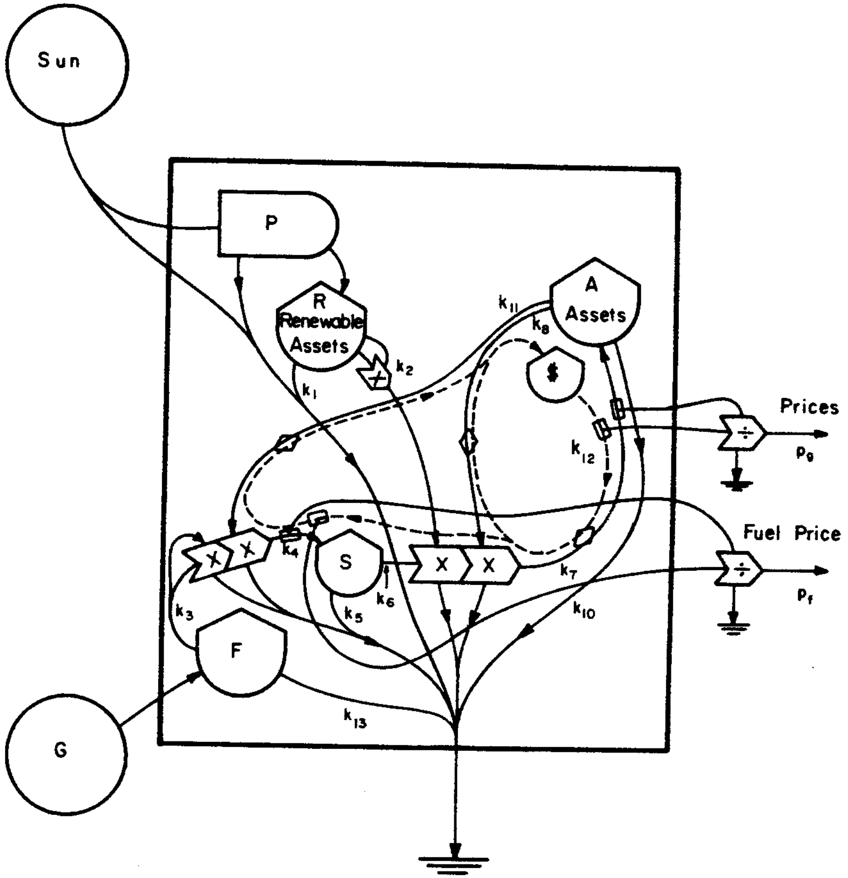


FIGURE 2a.—Assets, culture, and information are shown as a balance between production flow based on fuels interacting with renewable energy and losses due to depreciation.



Numbers in 10^{15} kcal/yr

FIGURE 2b.—Overview model in more detail. Energy storages and flows are written on the diagram in coal equivalents. See footnote (10) for sources of estimates.



$$\dot{R} = P - k_1 R - k_2 S R^2 A$$
$$\dot{F} = G - k_3 F^2 A - k_{13} F$$
$$\dot{S} = k_4 F^2 A - k_5 S - k_6 S R^2 A$$
$$\dot{A} = (k_7 - k_8) S R^2 A - k_{10} A - k_{11} F^2 A$$
$$p_g = k_{12}\$ / k_7 S R^2 A$$
$$p_f = \left(\frac{k_{11} A F^2}{k_{11} A F^2 + k_8 A R^2 S}\right) k_{12}\$ \Big/ k_4 A F^2$$

(2c) Kinetic aspects of the model with equations in standard form.

Simulation results of the system of equations in Fig. 2c using

energy reserves and flows in Fig 2b.

FIGURE 2c.—Kinetic aspects of the model with equations in standard form. Simulation results of the system of equations in Fig 2c using energy reserves and flows in Fig. 2b.

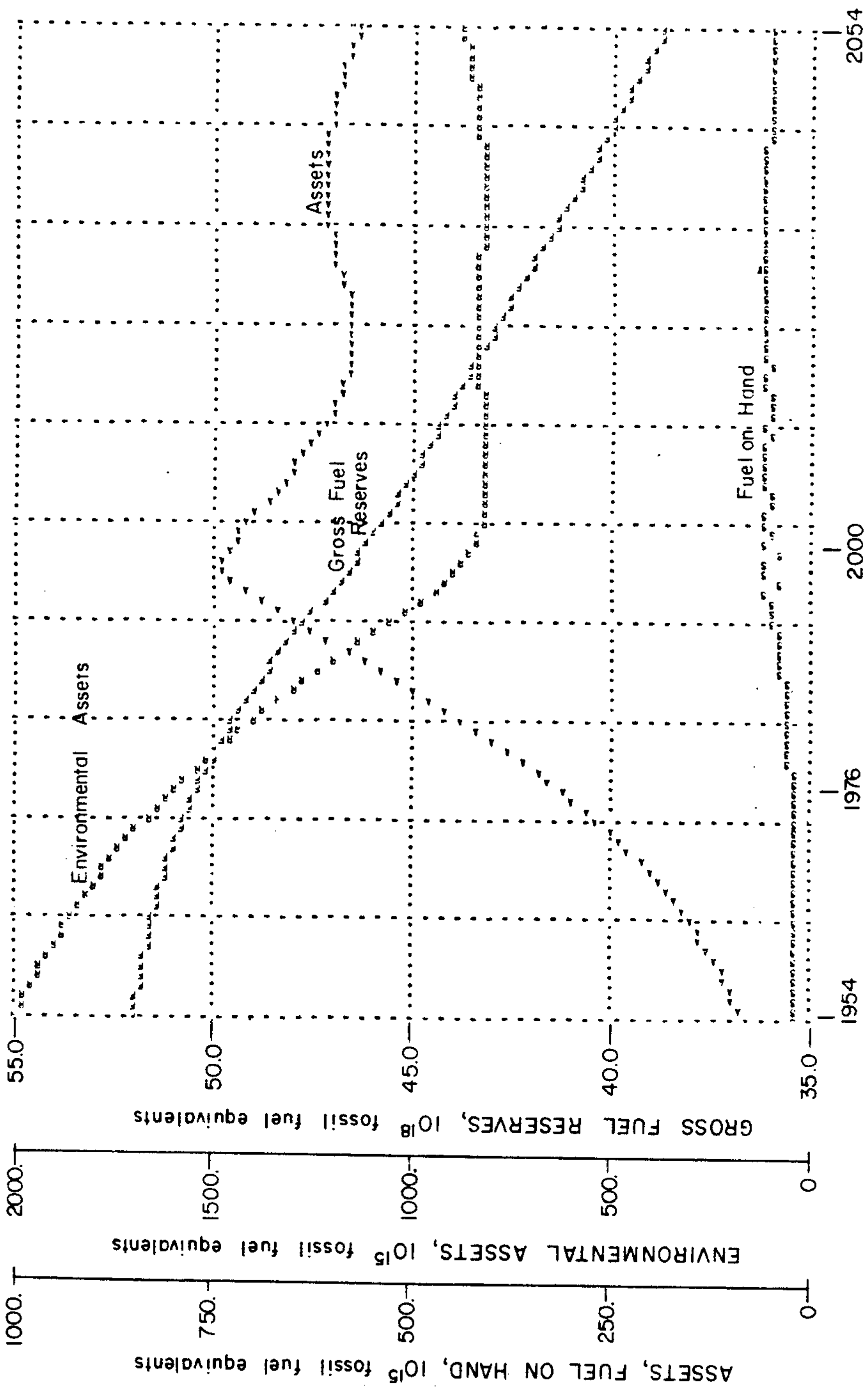
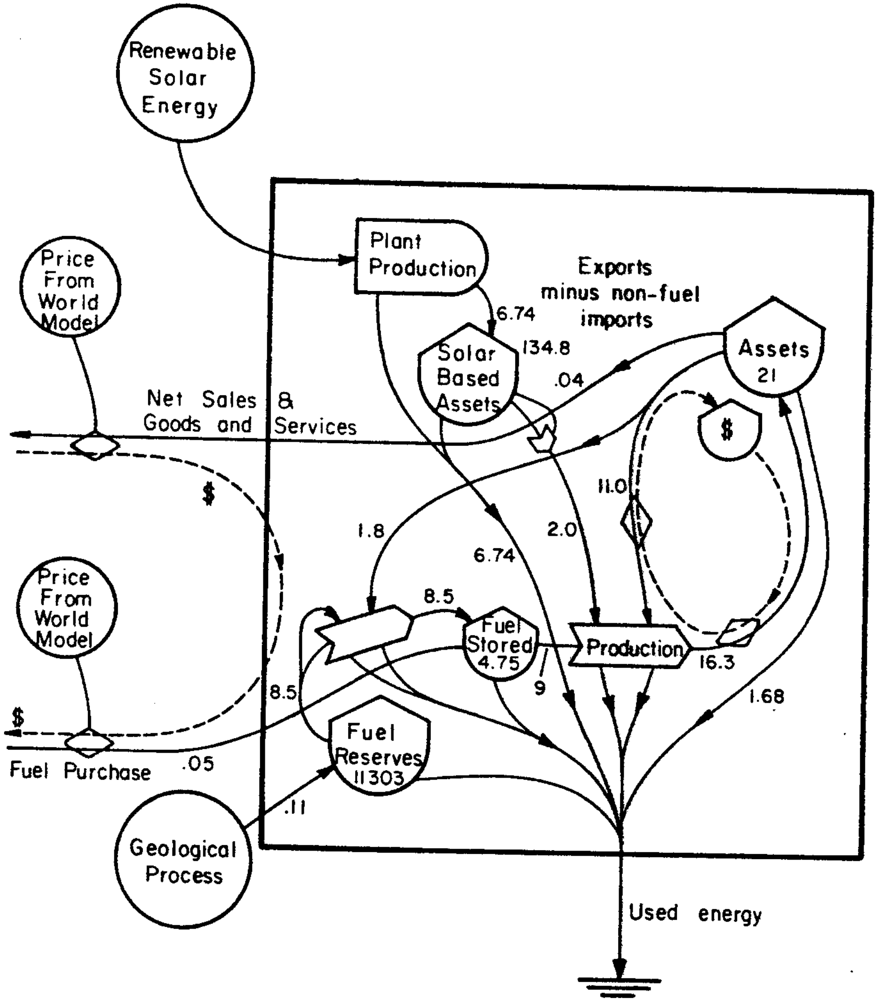
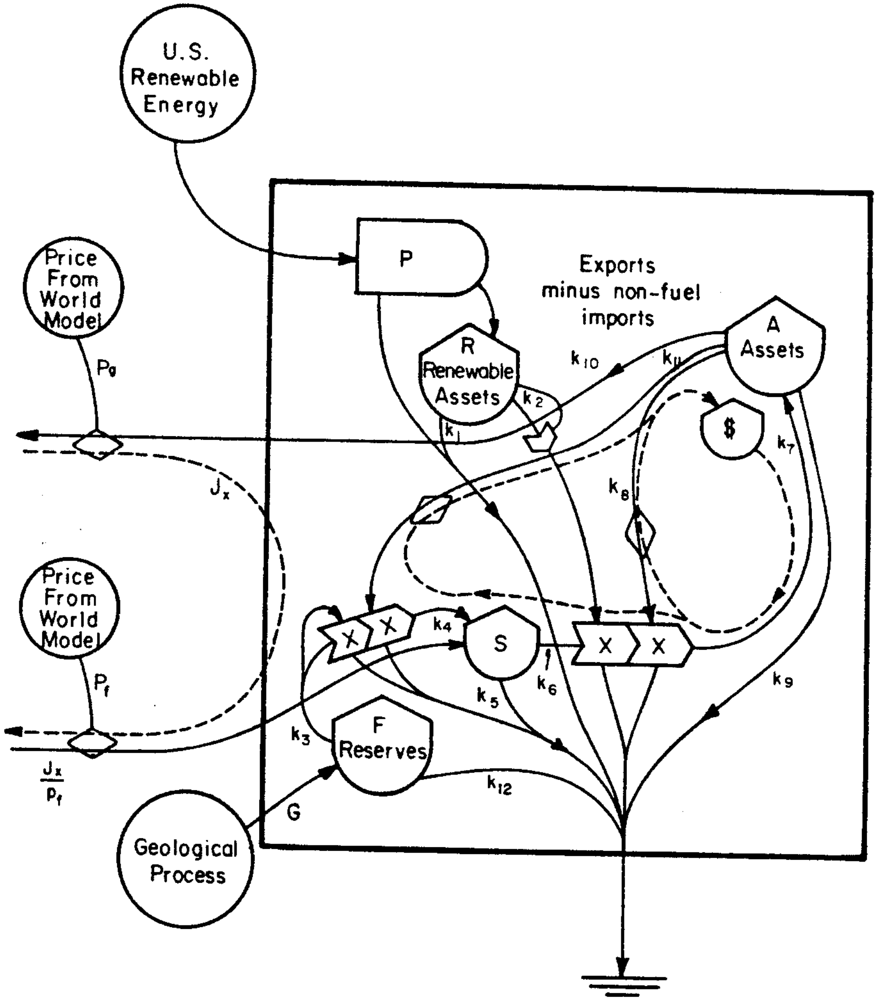


FIGURE 3.—Simulation of the model in Figure 2 starting in 1954.



Numbers in 10^{15} kcal/yr

FIGURE 4a.—Energy flow mini-model of the economy of the United States with prices controlling international exchange supplied from the world model in Fig. 1. System equations are translated from the diagram and written in their usual form. Details are given in footnote (11).



$$\dot{R} = P - k_1 R - k_2 S R^2 A$$
$$\dot{F} \quad G - k_3 F^2 A - k_{12} F$$
$$\dot{S} = k_4 F^2 A - k_5 S - k_6 S R^2 A + \frac{J_x}{p_f}$$
$$\dot{A} = (k_7 - k_8) S R^2 A - k_9 A - k_{10} A - k_{11} F^2 A$$
$$J_x = k_{10} A p_g$$

FIGURE 4b.—Model with equation.

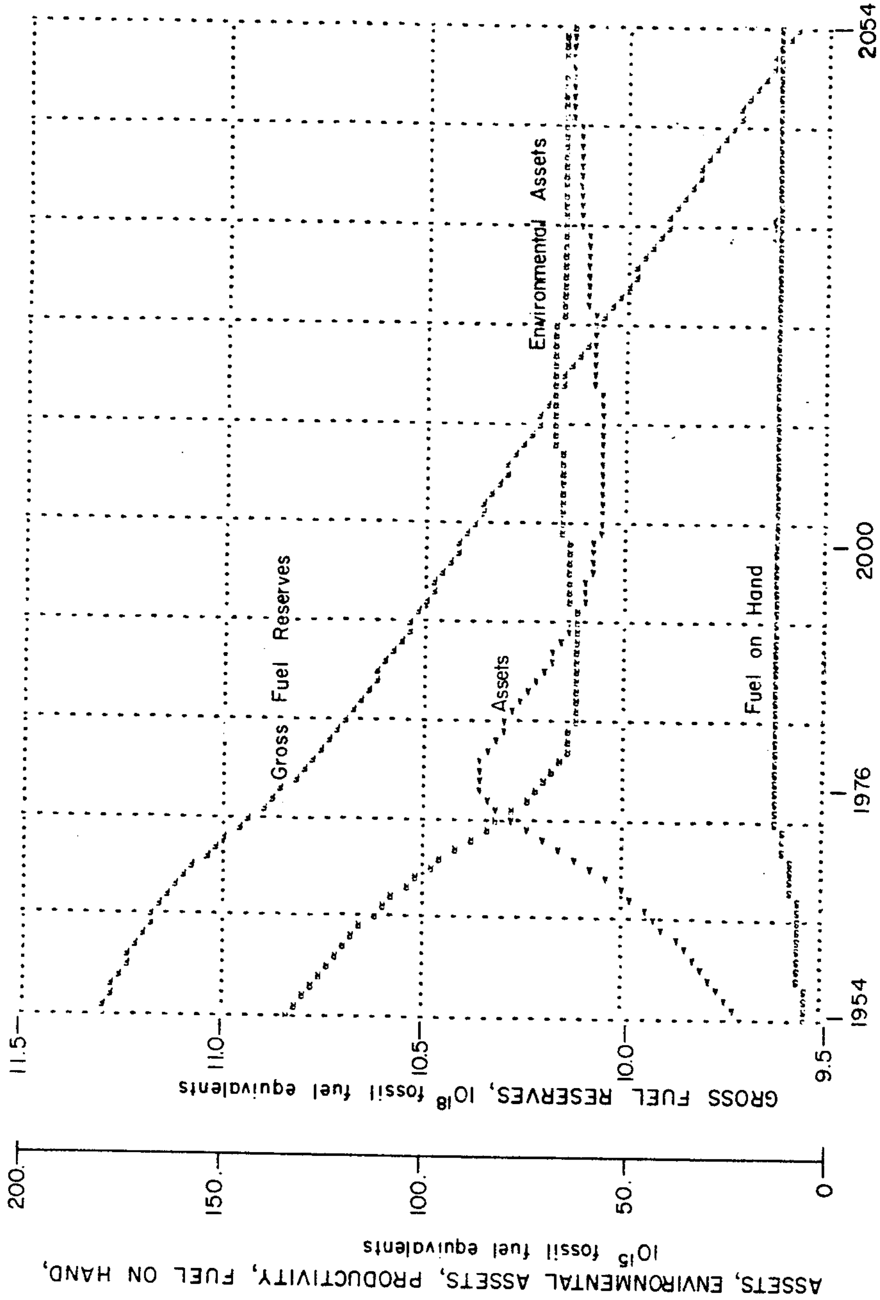


FIGURE 5.—Graph showing results of simulating the model given in Fig. 4b, with energy inflows and prices derived from the simulation in Fig. 3.

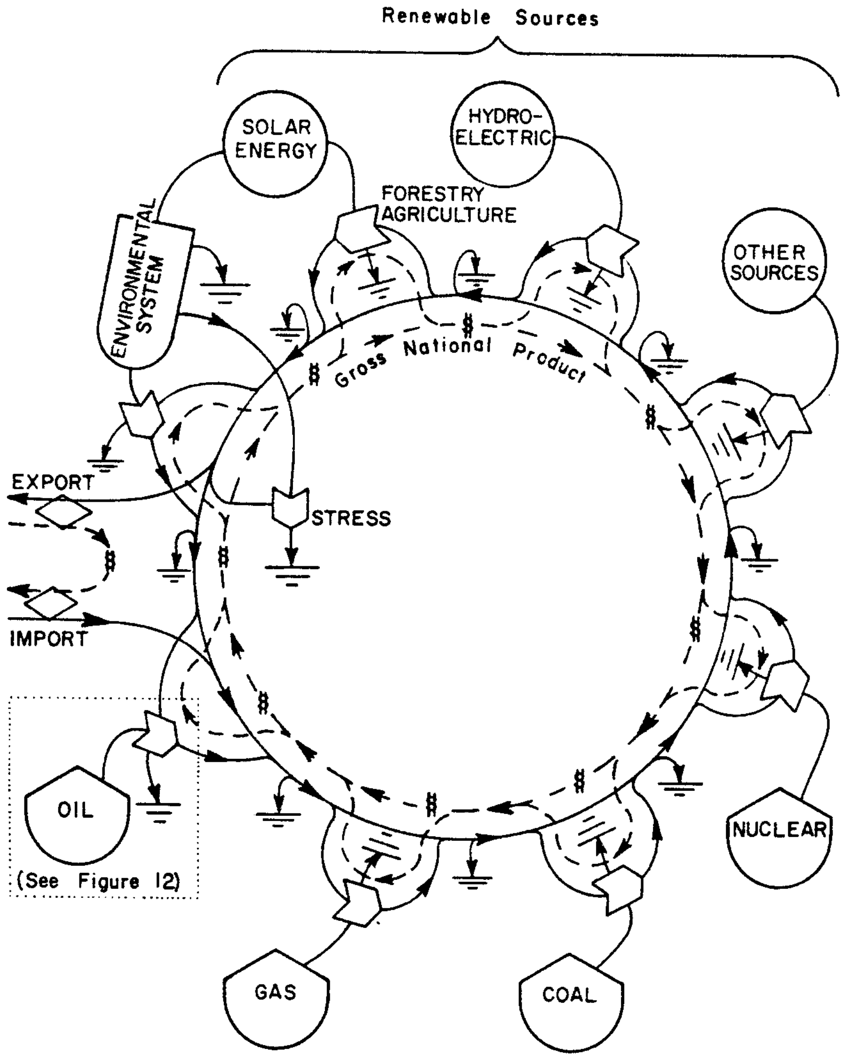


FIGURE 6.—An energy model of the United States for examining the sectors concerned with inflows of external energy. Energy circulates counter clockwise and money clockwise.

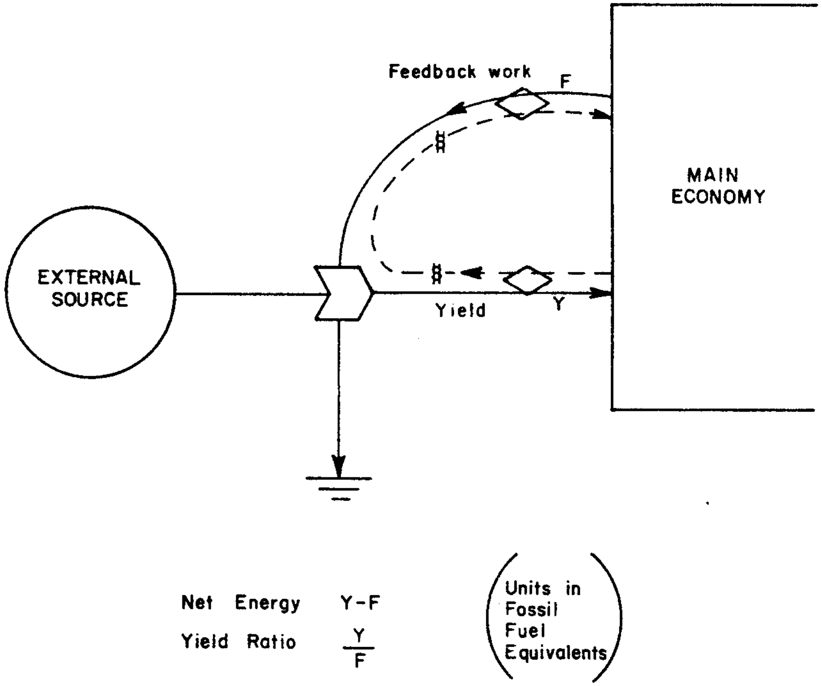


FIGURE 7.—Energy flows where a feedback from the main economy (F) interacts and facilitates an inflow of energy from an external source. The feedback F includes some energy of Y that has made the cycle through the economy and is returned. A good primary source is one that has a relatively small return relative to the yield.

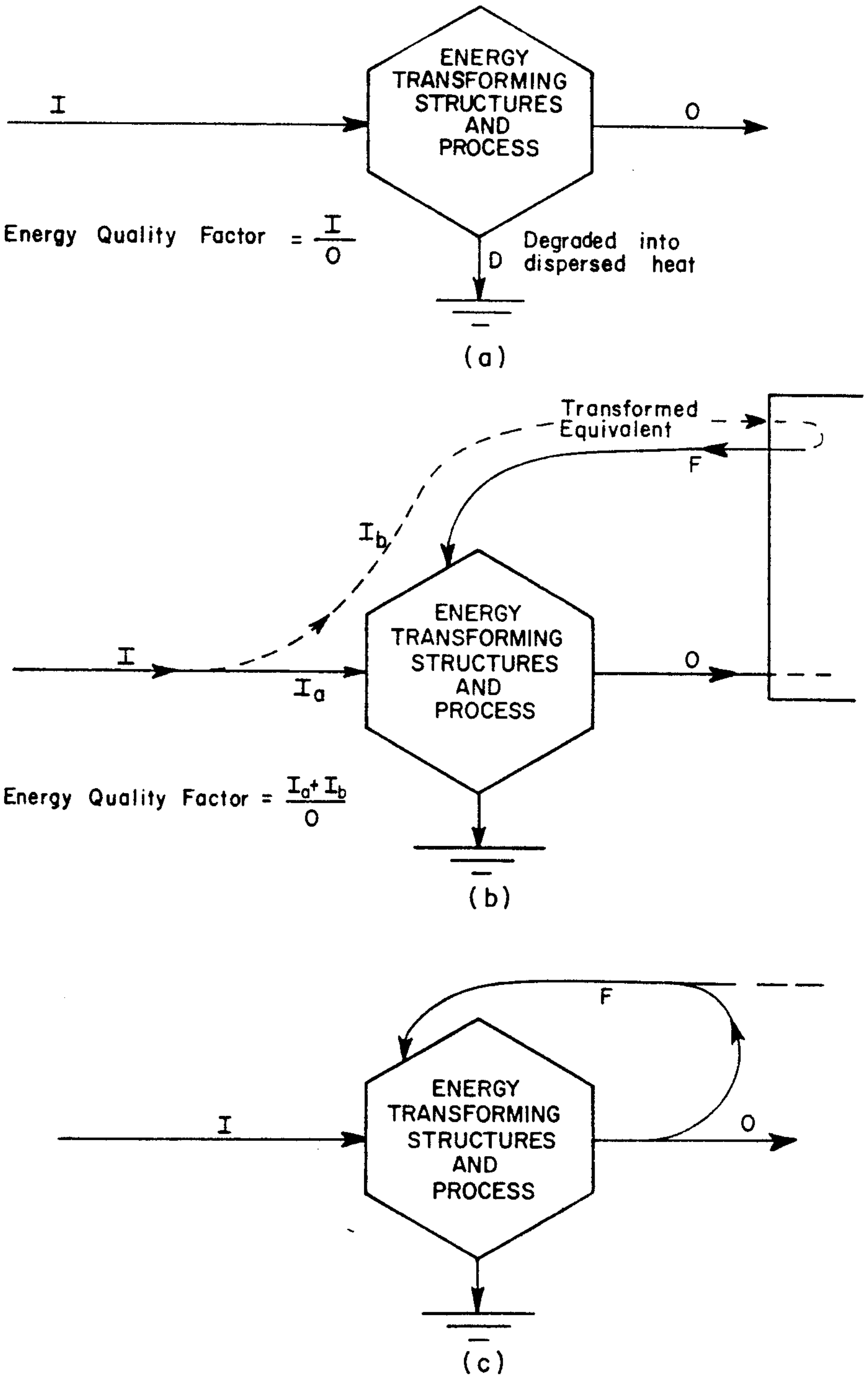
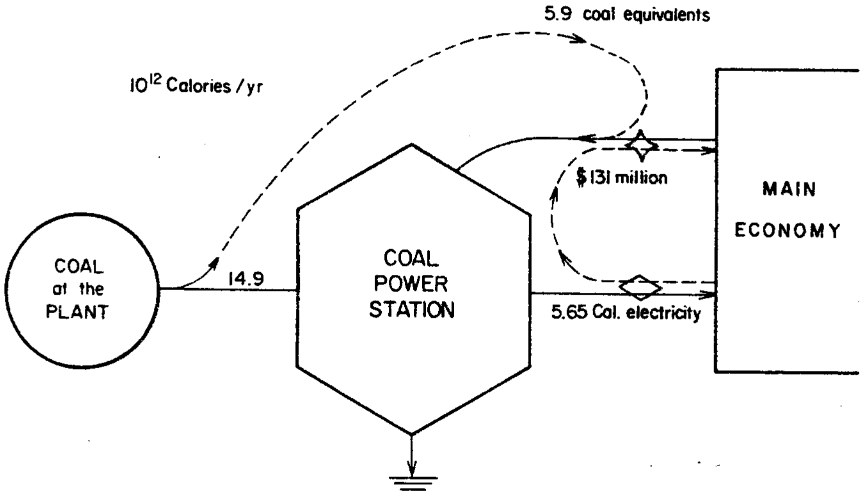


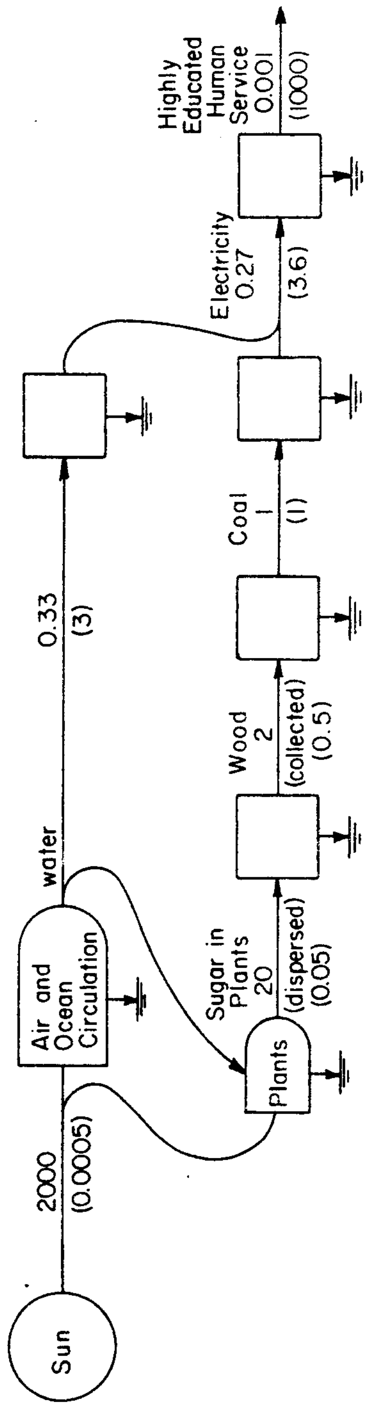
FIGURE 8.—Definition of energy quality factor. By definition the ratio is applied only for real, successfully competing systems believed to be operating competi-

tively at maximum power. (8a) Oversimplified concept without feedback. (8b) Real systems have feedbacks (F) from higher quality. The energy quality factor in obtained by expressing F in equivalent energy units of the input (I_b). (8c) Alternative way of estimating energy quality factor—expresses energy of the feedback in equivalent unit of output and subtracts to get net yield.



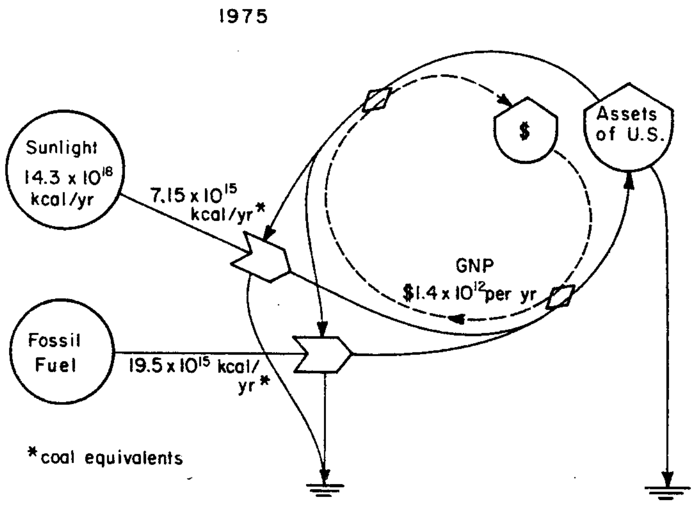
$$\frac{I}{O} = \frac{14.9 + 5.9}{5.65} = 3.7$$

FIGURE 9.—Example of energy quality calculation; coal electric power generator. Details are in footnote (15). Energy quality factor is 3.7 Cal. coal per Calorie electricity.



Numbers above line are calories heat equivalent.
Numbers in parentheses are calories fossil fuel equivalents.

FIGURE 10.—Energy quality factors arranged in a chain.



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

FIGURE 11.—Diagram indicating the flow of gross national product and the energy flows from fossil fuels and from natural renewable environmental sources. These flows are used to calculate the ratio of Kilocalories of coal equivalents to the dollar. The ratio is used to estimate the energy flows that are responsible for money flows in the general economy (16).

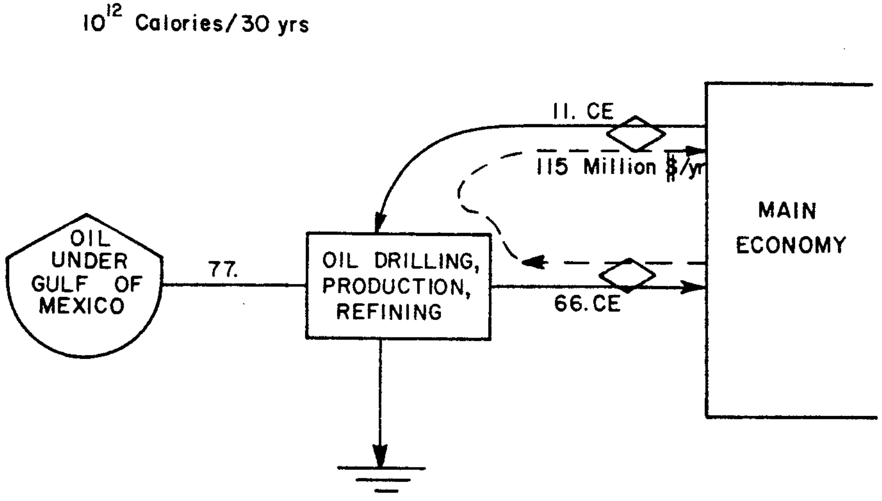


FIGURE 12.—Net energy summary of oil from a cluster of wells in the Gulf of Mexico in 100 ft. water in 1969. Details are in footnote (17). Yield ratio is 6.0.

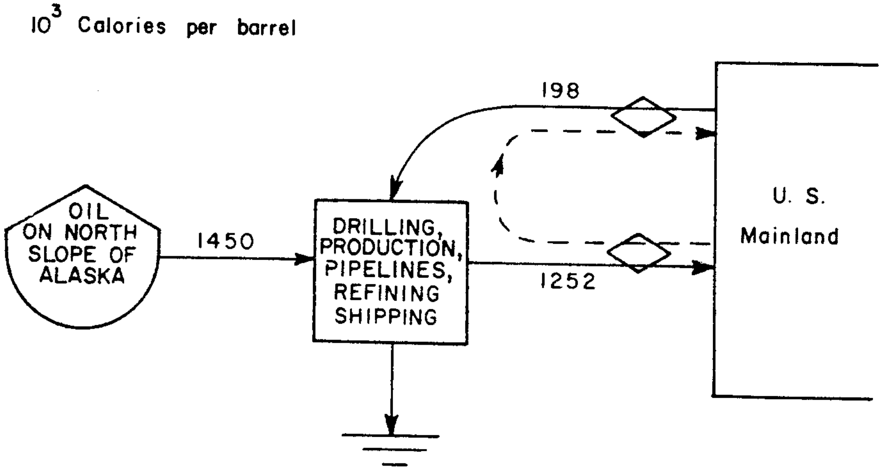


FIGURE 13.—Net energy estimate of Alaskan oil to be delivered to U.S. west coast. Details are in footnote (18). Yield ratio is 6.3.

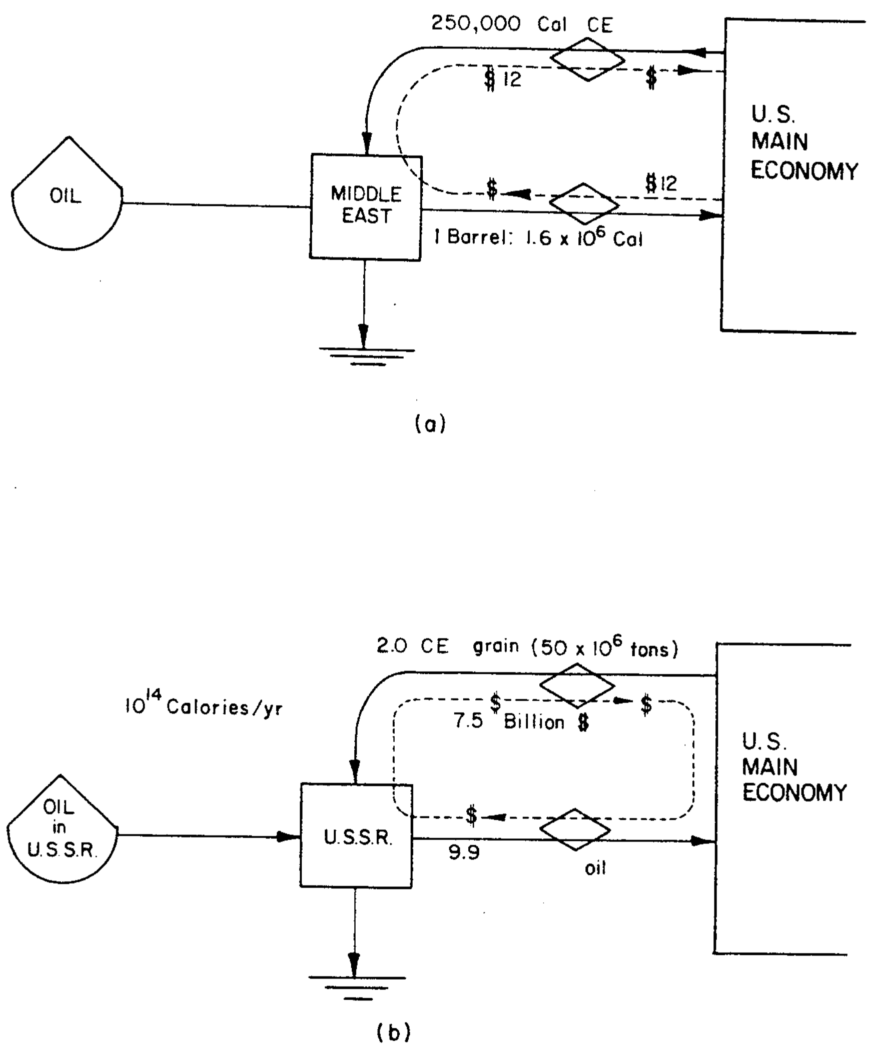


FIGURE 14.—Net energy summary of oil obtained in foreign exchange (14a) purchased with 1975 prices from foreign sources. Details are in footnote (19). After refining yield is 1.42×10^6 CE and yield ratio is 5.7. (14b) Net energy from sale of grain at 1975 prices. Details are in footnote (20). After refining yield is 8.78×10^{14} CE and yield ratio is 4.4.

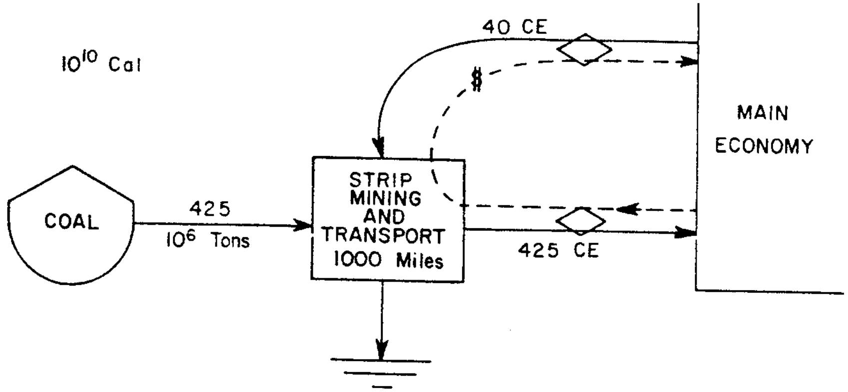


FIGURE 15.—Net energy summary of typical strip mining of western coal mining followed by transportation 1,000 miles. Yield ratio is 10.6. (Ballentine). Details are in footnote (21).

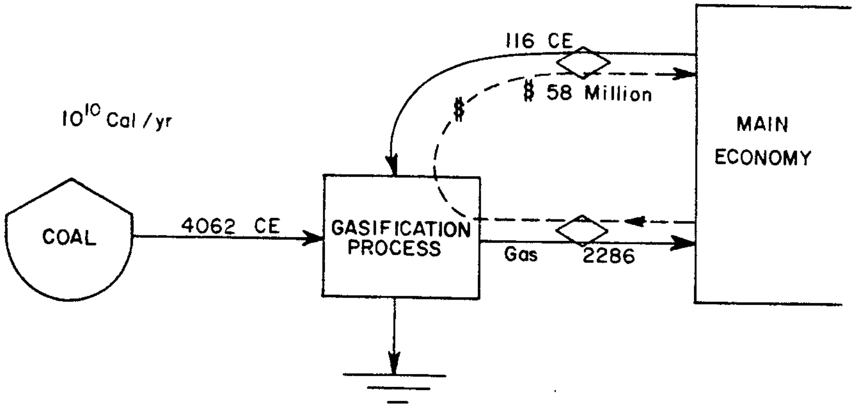
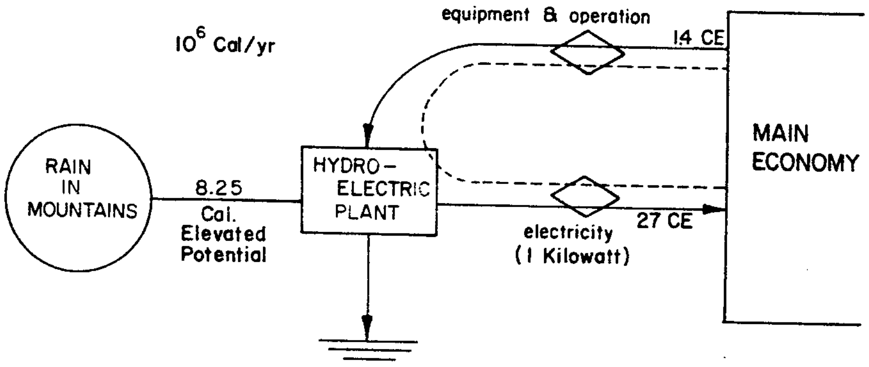


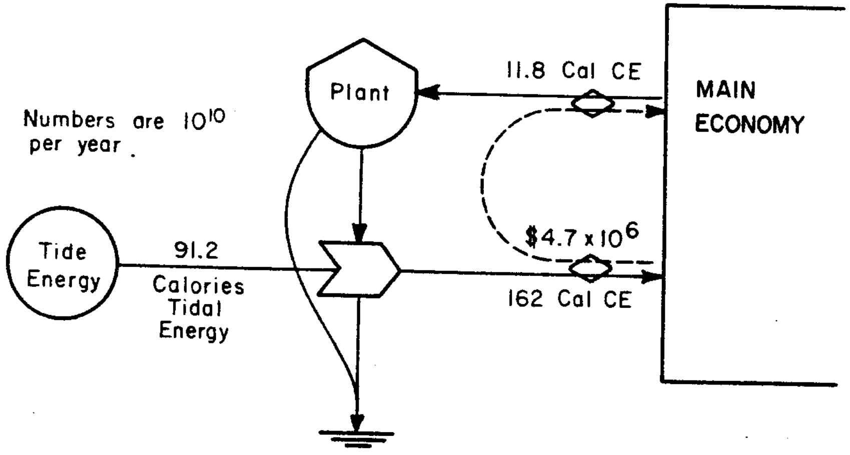
FIGURE 16.—Conversion of mined coal to high energy gas resembling natural gas. Details are in footnote (22).



$$\text{Energy Quality Factor} = \frac{8.25}{27-1.4} = 0.32$$

FIGURE 17.—Net energy summary of typical hydroelectric power. Details are in footnote (23). Yield ratio is 19.

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 18.—Net energy summary of a tidal power example with 20 ft. tide. Details are in footnote (24).

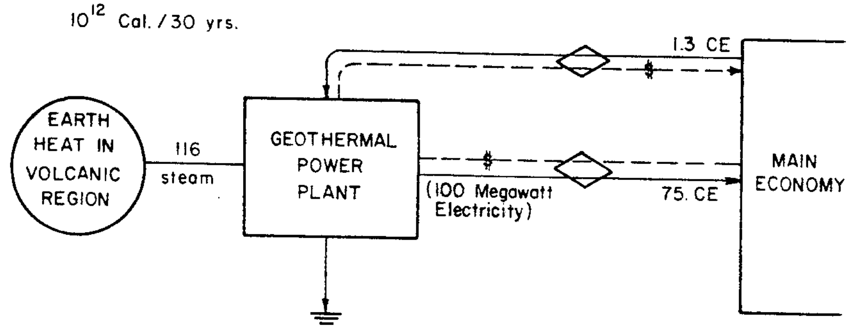


FIGURE 19.—Net energy summary of geothermal power plants. From Gilliland (25). Yield ratio is 57.4.

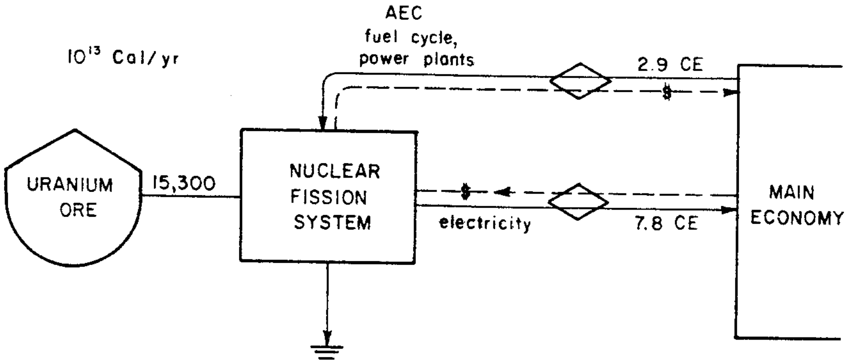


FIGURE 20.—Net energy summary of fission nuclear powerplants. Details are in footnote (26). Yield ratio is 2.7 (109 x 10^{13} Cal/yr is for U–235 fission energy in conventional reactors. If the potential energy content of U–238 is included, which can only be released by breeder reactors, the value becomes 15,300 x 10^{13} Cal/yr).

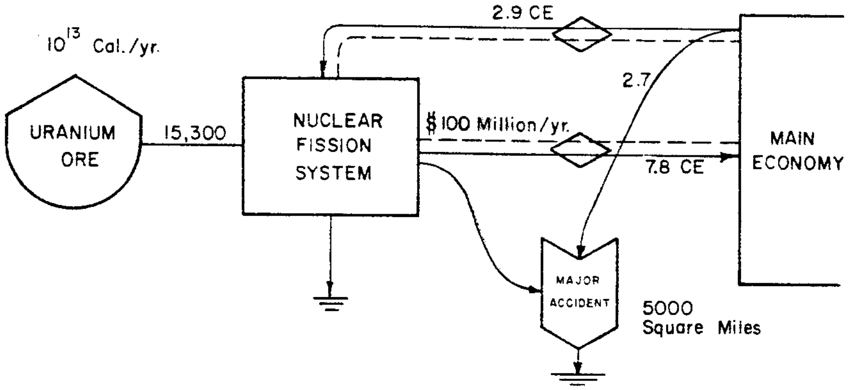
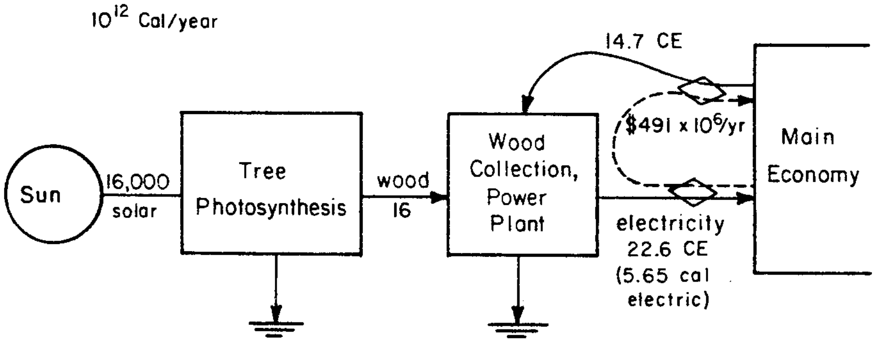
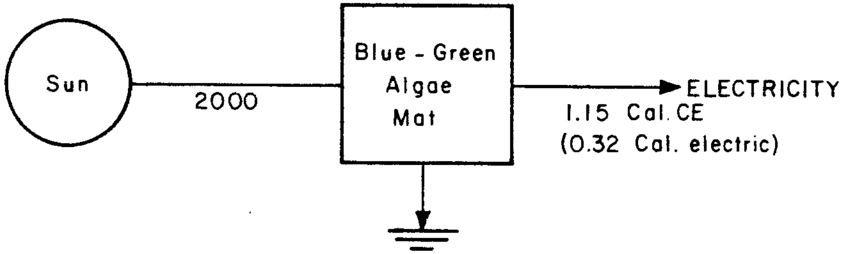


FIGURE 21.—Net energy summary of nuclear power with the costs of an accident included. Details are in footnote (27). Yield ratio is 1.4 (109 x 10^{13} Cal/yr is for U–235 fission energy in conventional reactors. If the potential energy content of U–238 is included, which can only be released by breeder reactors, the value becomes 15,300 x 10^{13} Cal/yr). Whether the breeder process considered as a whole will be net energy is not known.



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

FIGURE 22a.—Net energy summary of net energy yield of solar energy when concentrated through plant photosynthesis, to wood to powerplants; details are in footnote (28).



$$\text{Energy Quality Factor} = \frac{2000}{1.15} = 1740$$

FIGURE 22b.—Blue green algal mat; details are in footnote (29).

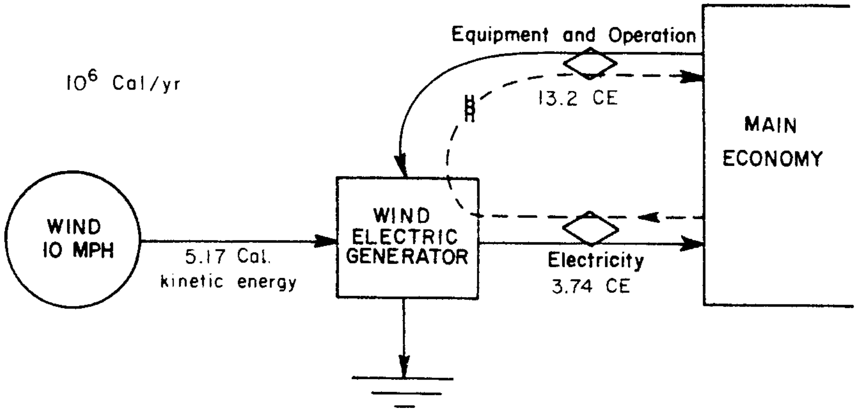


FIGURE 23.—Net energy summary of wind generated electricity. Details are in footnote (30).

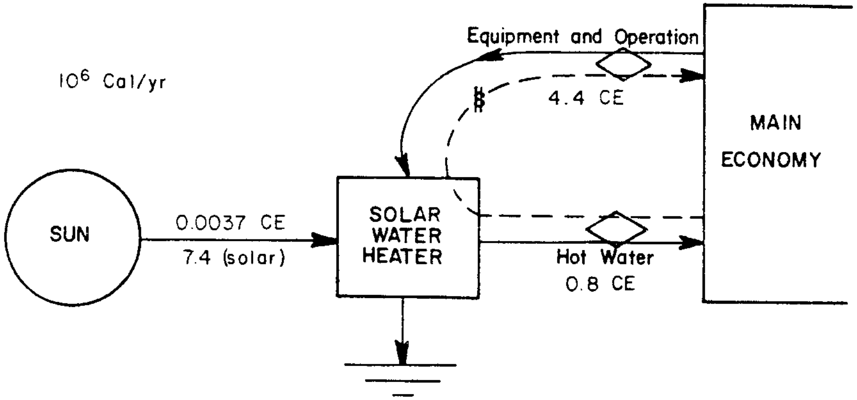


FIGURE 24.—Net energy summary of solar heating using an energy analysis of a commercial solar water heater by Brown and Zucchetto. Details are in footnote (31).

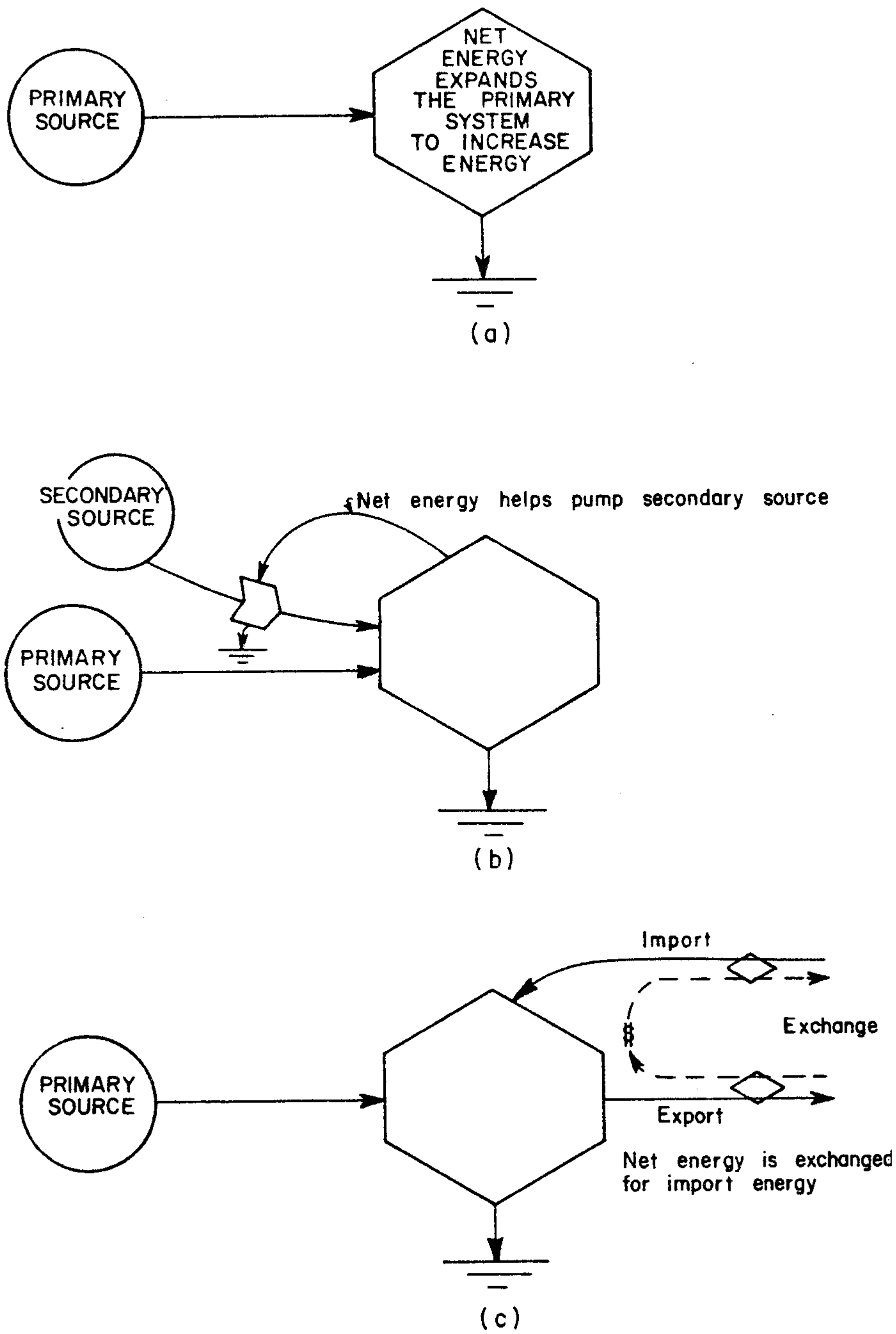
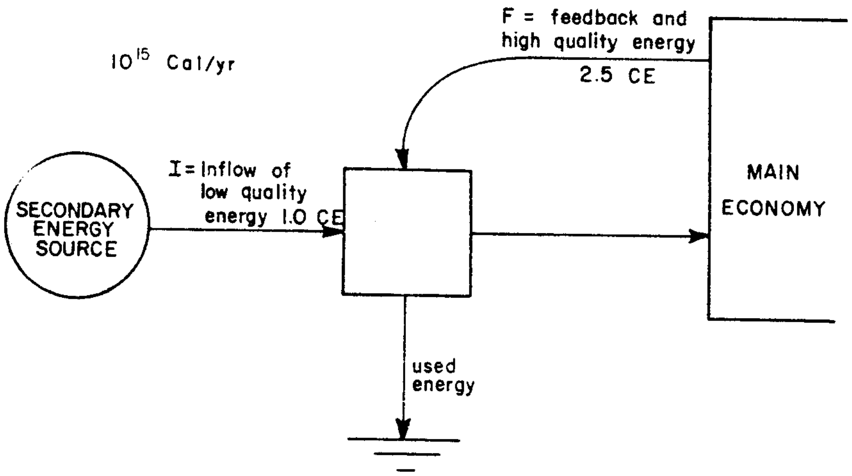


FIGURE 25.—Three alternative uses of net energy generated by primary energy sources. (25a) to expand present system so as to gain more energy from primary source (growth); (25b) to subsidize a secondary source that may not yield net energy alone; and (25c) to exchange for additional energy with outside areas.



$$\text{Energy Investment Ratio} = \frac{F}{I} = \frac{2.5}{1.0}$$

FIGURE 26.—Diagram defining the investment ratio with values for the United States. Feedback of high quality energy is shown pumping an inflow of low quality energy from a secondary source. Numbers are coal equivalents. See footnote (32).

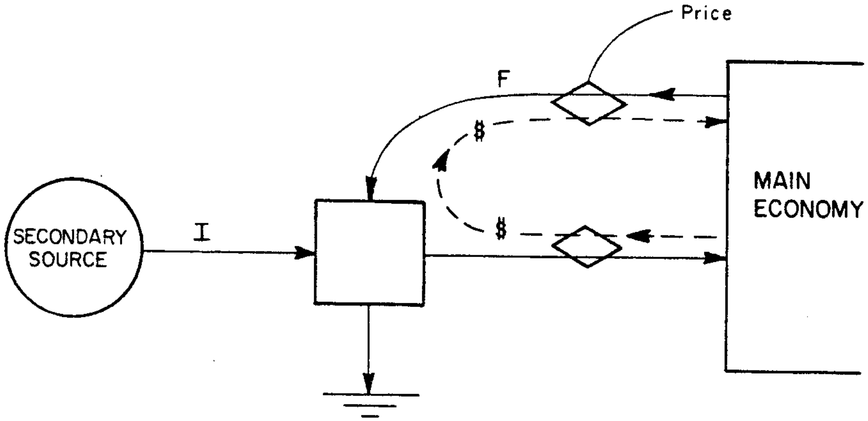


FIGURE 27.—Money flows that are associated with energy investment in a secondary source. A secondary source is economic when the contribution of the free external secondary energy I is larger than for competitors, when F/I is less than 2.5.

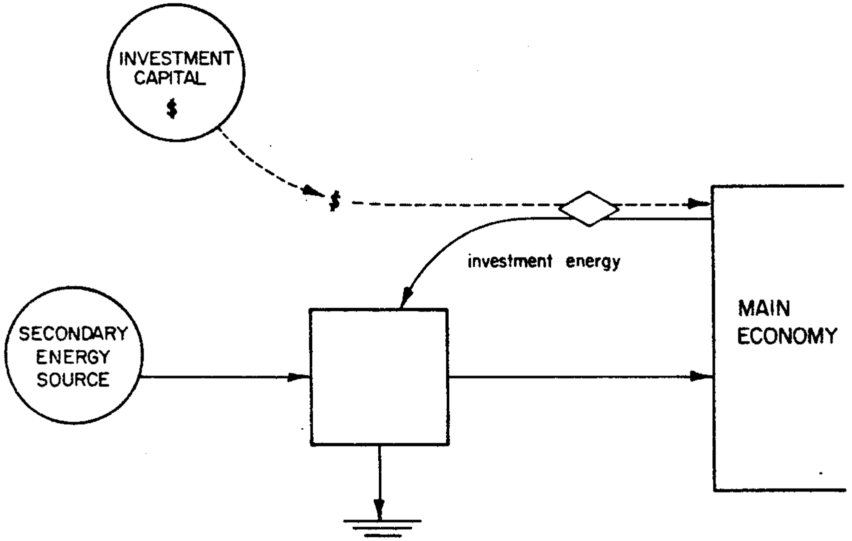
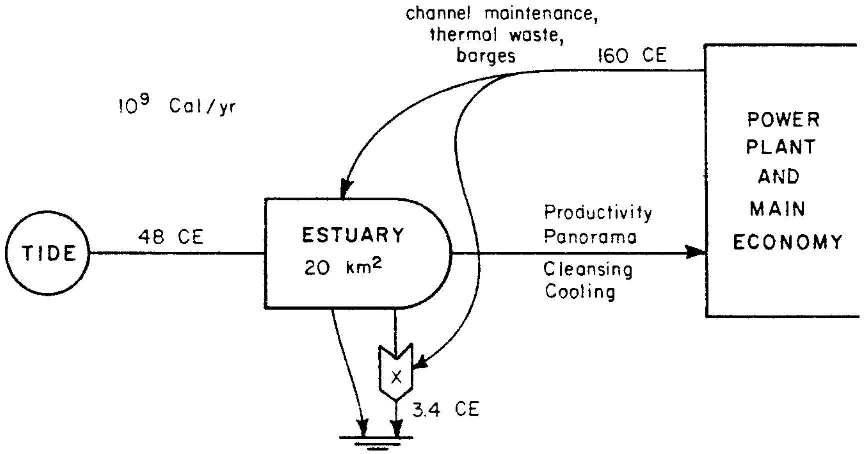


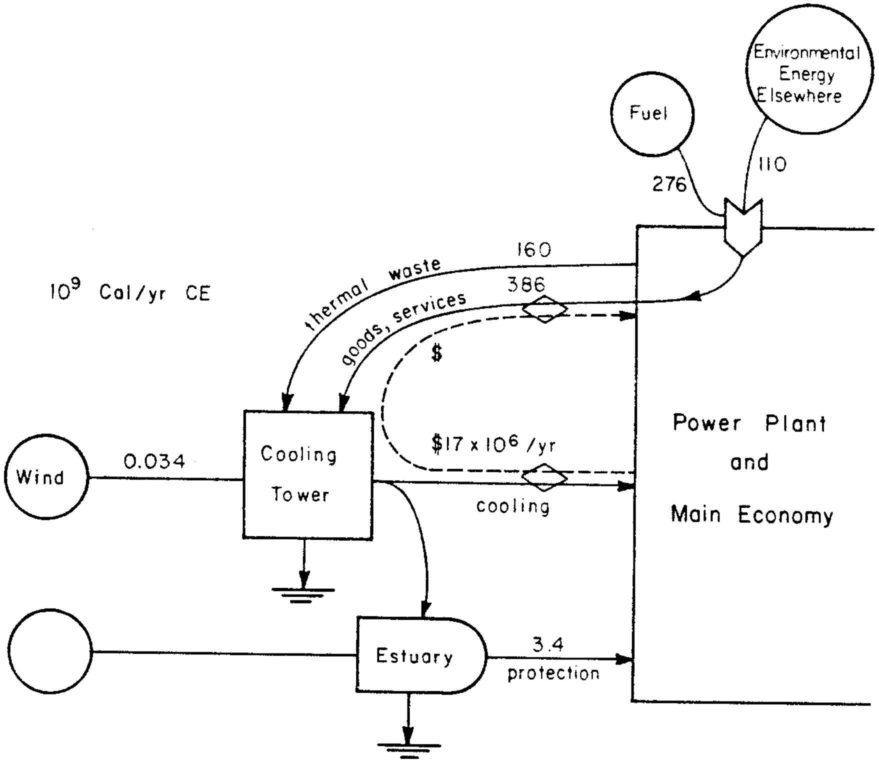
FIGURE 28.—Capital investment initiates feedback energy which starts flow of energy and money as in Fig. 27.

FIGURE 29.—Comparison of thermal cooling of an estuarine power plant.



(a.)

FIGURE 29a.—Energy analysis of power plant and environment at Crystal River, Fla. Estuarine cooling; investment ratio is 3.6. See footnote (34).



(b.)

FIGURE 29b.—Cooling tower in place of estuarine cooling. Investment ratio is 160. See footnote (35).

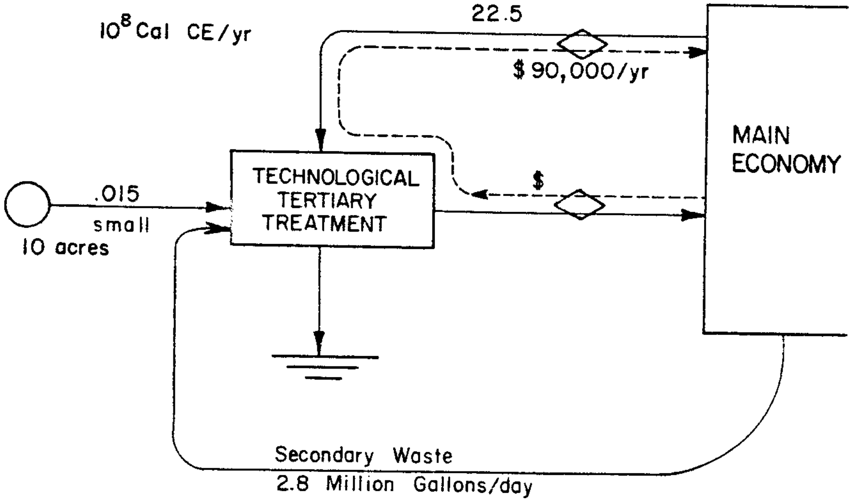


FIGURE 30.—Energy analysis summary of tertiary treatment by technological means. See footnote (36).

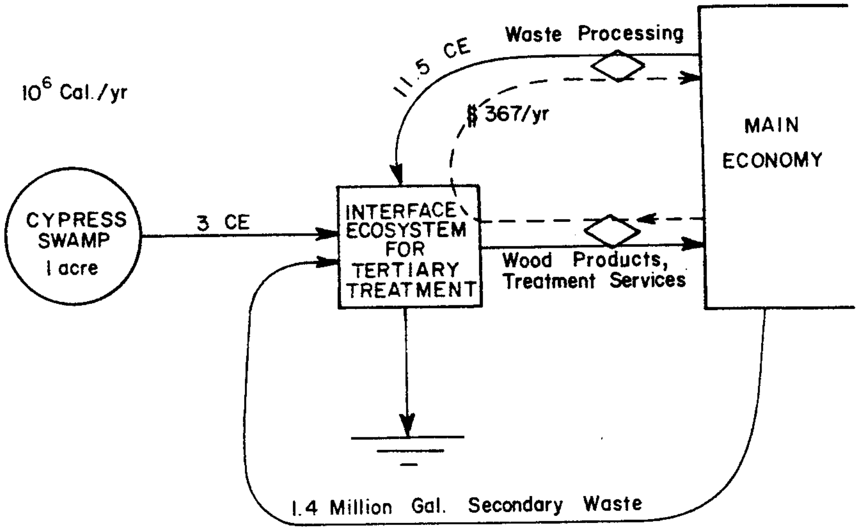


FIGURE 31.—Energy analysis summary of tertiary waste recycling that uses cypress swamp interface ecosystems in Florida. See footnote (37).

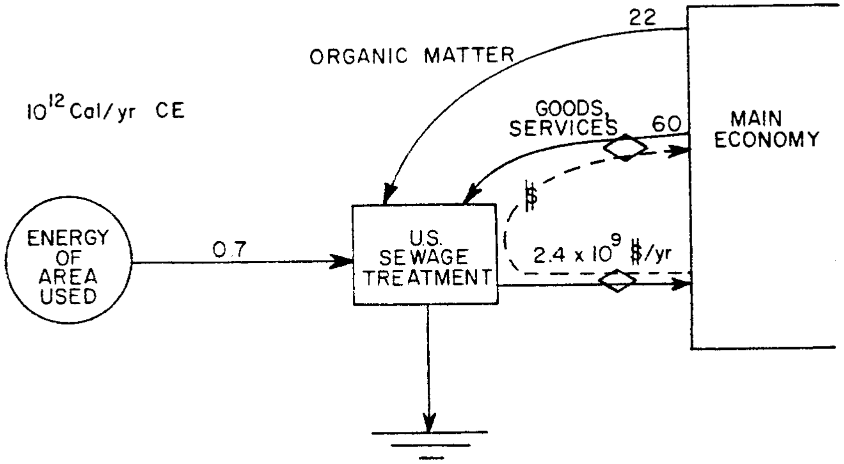


FIGURE 32.—Energy flows in primary and secondary sewage treatment in the United States. See footnote (38).

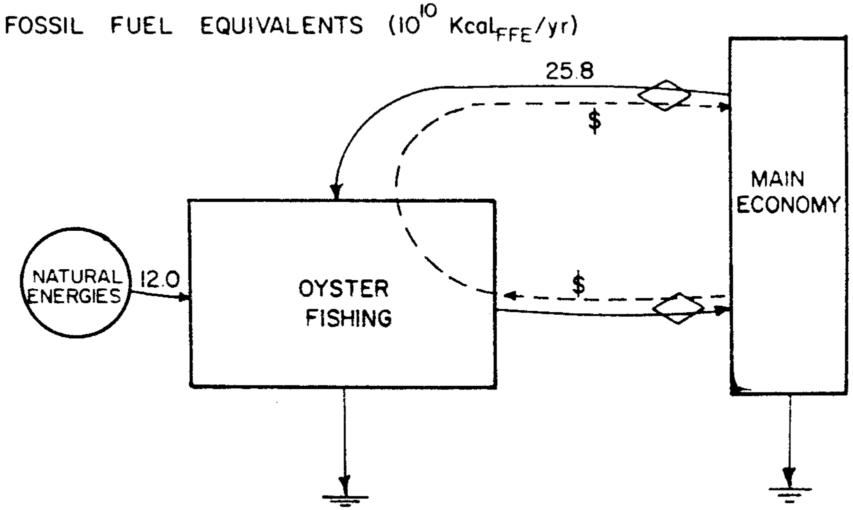


FIGURE 33.—Energy analysis summary of oyster harvest at Apalachicola, Florida. Boynton. See footnote (39).

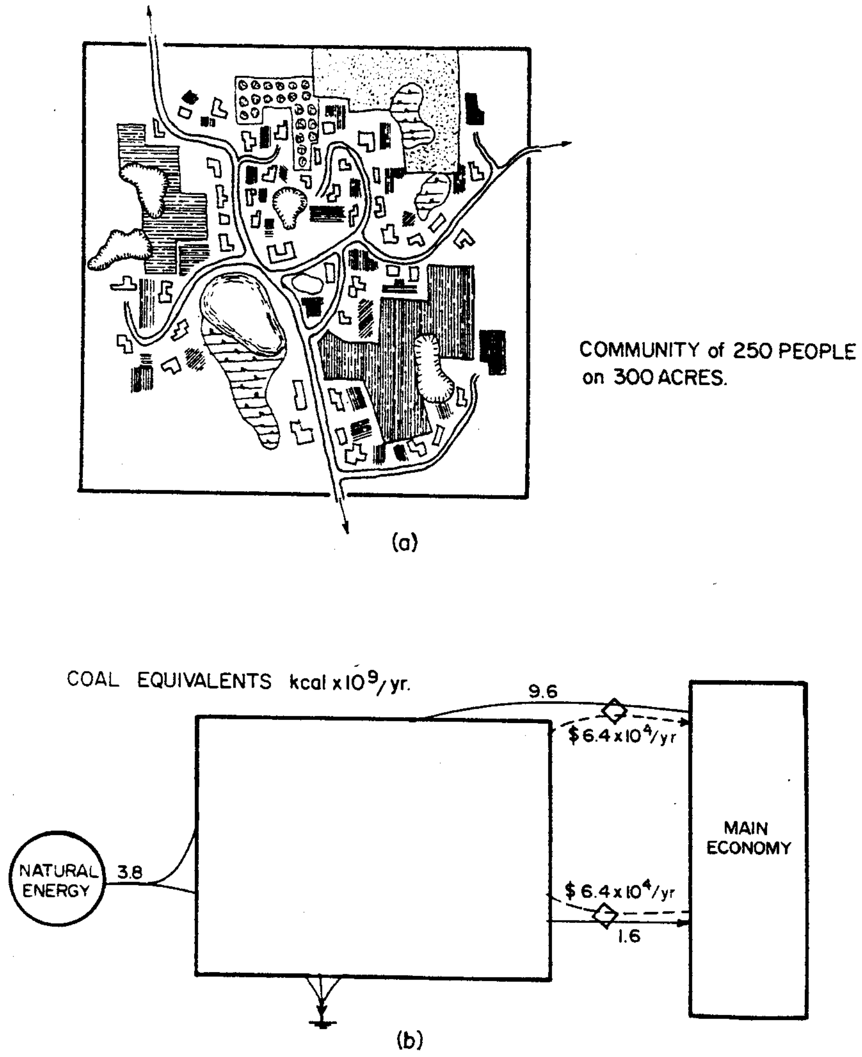


FIGURE 34.—A development with dilute housing and vegetation with an investment ratio that is competitive (2.5).
(a) Diagram of representative layout.
(b) Energy diagram.

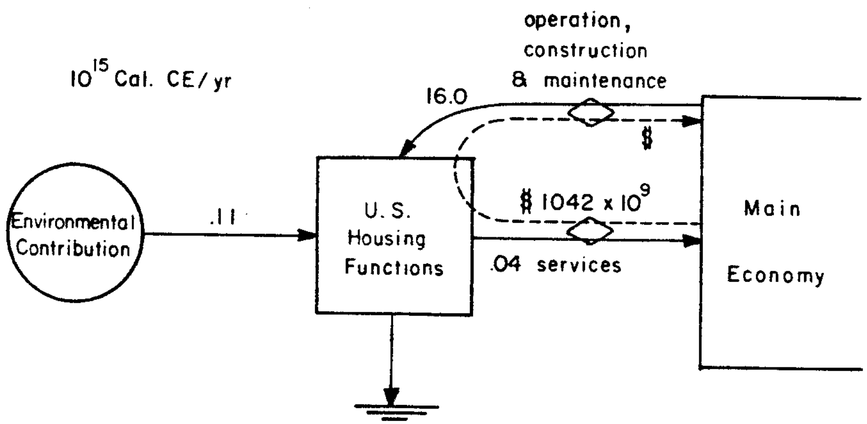
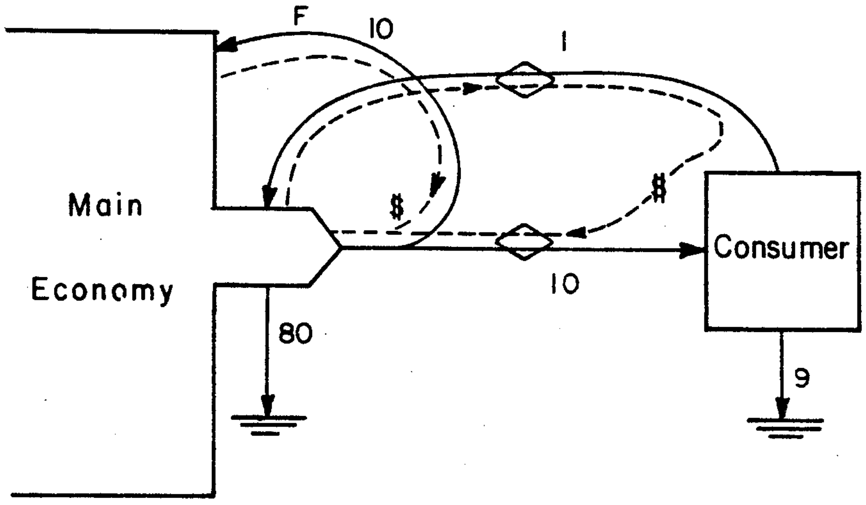


FIGURE 35.—Energy analysis summary of U.S. housing. See footnote (40).



Amplifier factor of feedback: x10

FIGURE 36.—Energy pattern for sectors of the economy which are entirely internal, that is they have a closed loop with some other sector of the economy. See footnote (41).

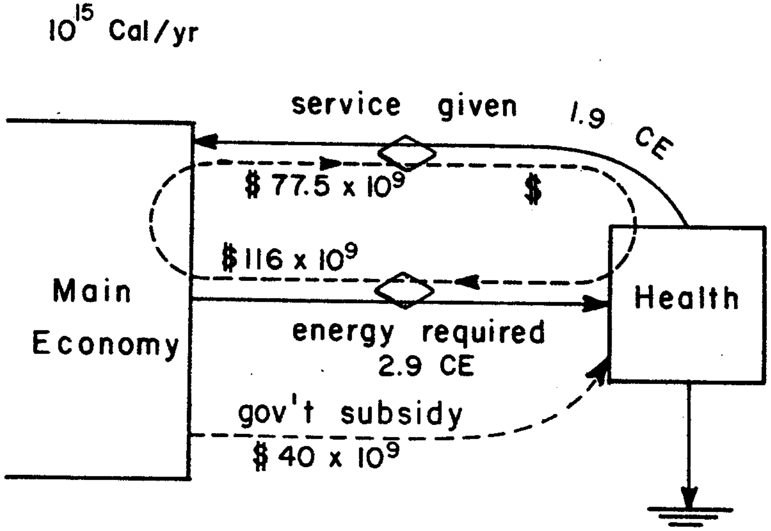


FIGURE 37.—Energy analysis summary of U.S. health related systems. See footnote (42).

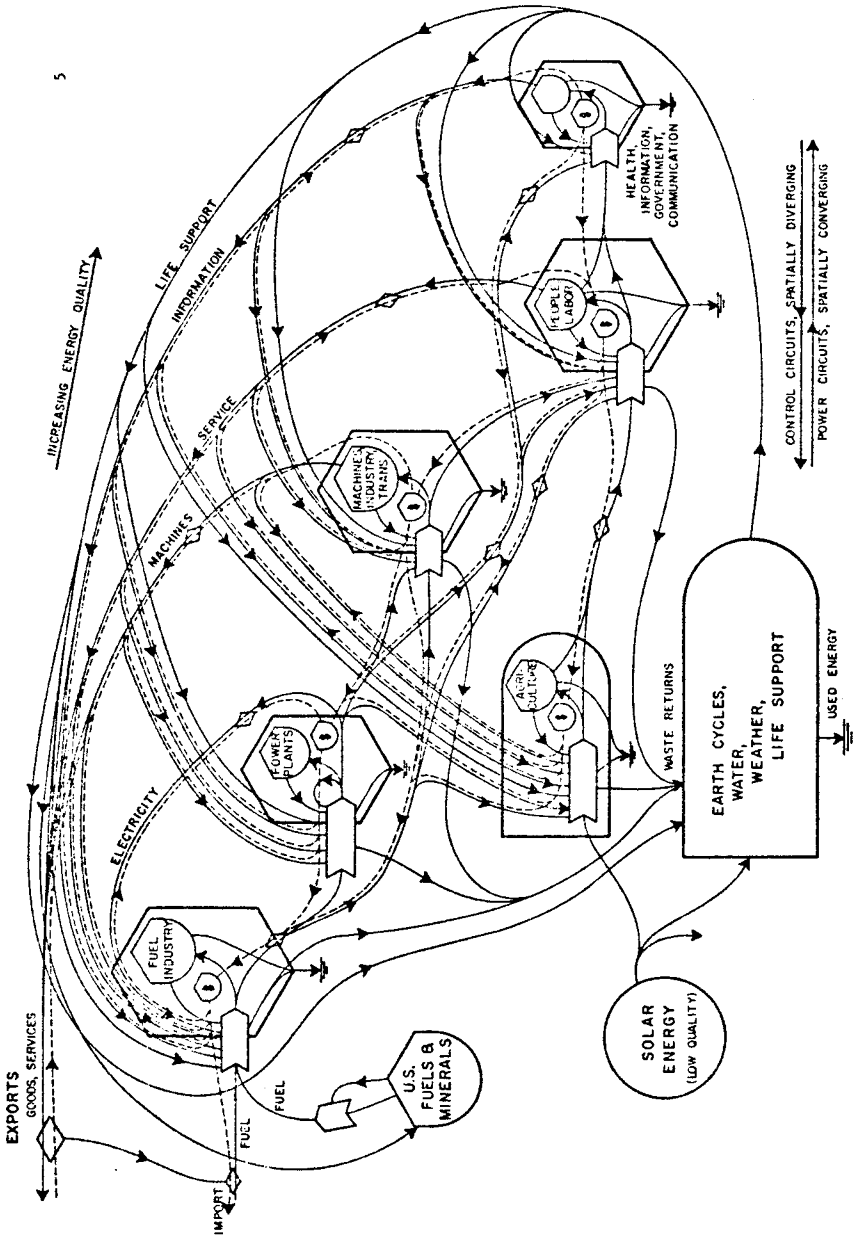


FIGURE 38.—Energy model of the United States. Money flow is indicated by dashed lines that circulate in counter current to work in loops controlled by people.

IX. FOOTNOTES AND REFERENCES

Only the first four authors are responsible for the text. Others made contributions and calculations in various sections. Work was supported by ERDA Contract En(40-1)-4398 with Univ. of Florida.

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(5) Roots of our work in net energy come from the old concept of net productivity in ecology which we apply to energy chains generally. Net energy analysis was applied to questions of agriculture in 1967 by Odum (6) and elaborated in book form in 1971 (7). A new book has chapters on net energy and energy resources of the United States (8). A general summary with examples from geothermal energy was given by M. Gilliland (9) former student who completed her dissertation at Gainesville.

(6) Odum, H. T. 1967. Energetics of World Food Production. pp. 55–94 *in* The World Food Problem. Vol. III. A report to President's Science Advisory Committee. White House, Washington, D.C.

(7) Odum, H. T. 1971. Environment, Power and Society. John Wiley, N.Y. 336 pp.

(8) Odum, H. T. and E. C. Odum. 1976. Energy Basis of Man and Nature. McGraw-Hill, 297 pp.

(9) Gilliland, M. 1975. Energy analysis and public policy. Science. 189:1051–1956.

(10) Sources of data for world model:

Symbol	Value	Explanation, Source
P	100×10^{15}	Flow of solar energy into the world calculation based on incident sunlight on the world.
R	$2{,}000\times10^{15}$	Storage of solar energy in such items as soil, organic matter and trees. Calculation based upon a 20 yr storage of P.
K_1	100×10^{15}	Flow of depreciation of solar based assets. A 5 percent per year assumed rate.
K_2	13×10^{15}	Flow of natural energy into world economy.
F	$52{,}000\times10^{15}$	Storage of ultimately recoverable fossil fuel reserves. U.S. House of Representatives, "Energy Facts," p. 12.
K_3, K_4	31.5×10^{15}	Flow of fossil fuels into world storage.
S	15.6×10^{15}	Storage of fossil fuels for a 6-mo period. Maximum storage capacity is a a 1-yr supply.
K_5	15×10^{15}	Flow of depreciation of stored fossil fuels. A 1 percent per year loss is lost due to spillage.
1MP	---------------	
K_6	31×10^{15}	Flow of fossil fuels into world economy.
K_7	51×10^{15}	Flow of goods into world economy.
K_8	32.5×10^{15}	Flow of labor, supplies and capital into fossil fuel production and production of goods.
K_{10}	8.5×10^{15}	Flow of depreciation of world assets. A 10 percent per year rate is used.
A	85×10^{15}	Storage of world assets.

(11) Sources of data for U.S. model:

Symbol	Value	Explanation, Source
P	6.74×10^{15}	Flow of solar energy into the United States. Calculation based on incident sunlight on the land area of United States.
R	134.8×10^{15}	Storage of solar energy in such items as soil, organic matter, trees. Calculation based upon a 20 yr storage of P.
K_1	6.74×10^{15}	Flow of depreciation of solar based assets. A 5 percent per year rate is assumed.
K_2	2×10^{15}	Flow of natural energy into U.S. economy.
F	$11{,}303\times10^{15}$	Storage of ultimately recoverable fossil fuel reserves. U.S. House of Representatives, "Energy facts," p. 12.
K_3, K_4	8.5×10^{15}	Flow of domestic fossil fuels into storage. U.S. Statistical Abstract, p. 531.
S	4.75×10^{15}	Storage of domestic and foreign fossil fuels for a 6-mo period. Maximum storage capacity is a 1-yr supply.
K_5	0.047×10^{15}	Flow of depreciation of stored fossil fuels. A 1 percent per year loss is lost due to spillage.
1MP	0.05×10^{15}	Flow of import of fossil fuels. The amount is calculated by assuming that the money received from exports is used to purchase fuel.
K_6	9×10^{15}	Flow of domestic and foreign fossil fuels into the U.S. economy.
K_7	16.3×10^{15}	Flow of goods into U.S. economy.
K_8	$\times10^{15}$	Flow of labor, supplies, and capital into and production of goods.
K_9	1.68×10^{15}	Flow of depreciation of U.S. assets. An 8 percent per year rate is used. U.S. Statistical Abstract, p. 385.
A	21×10^{15}	Storage of U.S. assets. U.S. Statistical Abstract, p. 46.
K_{10}	0.04×10^{15}	Flow of exports from United States. A 5 percent per year export rate is used. This rate was derived from U.S. Statistical Abstract, p. 812.
K_{11}	1.8×10^{15}	Flow of labor, supplies, and capital into fossil fuel production.

Details of values used in U.S. Model in Fig. 4a.

For purposes of calculating coefficients, the zero rate of change of the period of cresting in 1974 was used to balance an assumed depreciation rate of 10% and an input of 5000 x 10^9 fossil fuel equivalents of productivity. The productivity was based on sum of fuel usage and fossil fuel equivalents of solar energy. Foreign fuels usage was calculated as the fuel bought by the money generated by export sales. Export sales were calculated in proportion to assets. Prices were generated from the ratio of money to energy flow in the world model.

(12) Hubbard, M. K. 1971. Energy Resources. pp. 89–116 *in* Environment. ed. by W. W. Murdoch. Sinauer Associates. Stamford, Conn. 440 pp.

(13) Cooke, E. 1975. The depletion of Geologic Resources. Technology Review. 77:2–15.

(14) Forrester, J. 1971. World Dynamics. Wright-Allen Press. Cambridge, Mass.

(15) Coal fired electric power plant with 1000 megawatt capacity; 75% load factor; income to pay for purchased goods and services at 3¢ per kilowatt hour; 38% efficiency of heat conversion to electricity when goods and services are not included.

(16) Calories of solar energy are divided by energy quality factor of 2000 (See Fig. 22a) to estimate the natural, solar-based energy that helps the economy without receiving money. Insolation taken as 1.5 x 10^6 Kilocalories per m^2 per year; area of the United States; x 9.52 x $10^{12} m^2$. As a first approximation all fossil fuels were regarded as coal equivalents.

(17) Based on case history of Gulf of Mexico oil production in; the following reference: Weaver, L. K., H. F. Pierce, and C. J. Jirik, 1972. Composition of offshore U.S. petroleum industry and estimated costs of producing petroleum in the Gulf of Mexico, Govt. Printing Office 168 pp. 350 million barrels yield 53.1 barrels in 30 years; 1.45 million Calories per barrel: $115 million earned at 1969 prices multiplied by 24,800 Calories per dollar plus 10% of fuel yield used in feedback for refining and transportation.

(18) 1.45 million Calories per barrel; 11.3% lost in refining, including CE of 5000 acres of displaced productivity and other losses; $.81 per barrel in operating costs; $0.02 per barrel in environmental costs; dollar inputs multiplied by 21,600 kilocalories per dollar. Feedback includes energy equivalents on dollar costs plus

fuel used in refining. Refining was 11.3% including 6% fuel; .3% goods and services and 5% displaced environmental productivity of refining area.

(19) 1.6 x 10^6 kilocalories per barrel; energy equivalent of goods and services exchanged for $12 per barrel was estimated at 21,000 kilocalories per dollar.

(20) Money exchange: Oil exchange estimated from money flow ($150 per metric ton times 50 million metric tons) and price of $12/barrel; multiplied by 1.6 million Calories per barrel. Energy in grain: 4 Calories per gram dry weight, 10^6 grams/ton; times 50 million metric tons and energy quality factor for grain to coal equivalents taken as 1.0 based on Pimentel. Pimentel, D., L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Sholes, and R. J. Whitman. 1973. Food Production and the Energy Crisis. Science. 182:443–449.

(21) Estimated by Ballentine in reference: Ballentine, T. 1976. A Net Energy Analysis of Surface Mined Coal from the Northern Great Plains. Thesis, Masters of Engineering. Department of Environmental Engineering Sciences, University of Florida, Gainesville. 161 pp. Transportation estimated at $0.007 per ton per mile. Total feedback energy was estimated from total money costs including prorated capital costs of $1.4 million and land reclamation costs of $7000/$10^6$ tons coal mined. Energy value of ecosystems destroyed and photosynthesis foregone were small due to low productivity of the short grass prairie communities found in the area of coal mining.

(22) Figures from reference: Ballentine, See footnote (21). 288 million cubic feet per day artificial gas like natural has yielded from 4062 x 10^{10} Calories coal per year.

(28) Estimated by Don Young for 1 Kilowatt 100 feet height of water elevation; Energy equivalent of feedback by multiplying by 25,000 Cal/$ cost of electricity as 0.64¢ per kilowatt. Coal equivalents of a kilowatt hour obtained by multiplying by heat calories per kilowatt and then by 3.6 Calories of coal equivalent per calorie of electricity as estimated from Fig. 9. Efficiency of conversion of Calories of elevated water to calories of electricity; 90%, not counting the cost of equipment and operation.

(24) Estimated by M. Kemp using reference: Lawton, F. L. 1972. Tidal power in Bay of Funday and economics of tidal power. *in* Tidal Power ed. by T. J. Gray and O. K. Gashus, Plenum Press, N.Y. Energy input calculated with 705 tidal rises per year and 7 m. tidal height area of tidal pool 2.2 x 10^{11}cm^2 at La Rance, France. Energy feedback estimated by multiplying 24,000 Cal/$ 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 electrical based on Fig. 9.

(25) Summary of energy analysis by Gilliland. See footnote (9) based on 100 megawatt dry steam turbine electric plant Geysers, California.

(26) Estimates by C. Kylstra and Ki Han in reference: Klystra, C. and Ki Han. 1975. Energy analysis of the U.S. Nuclear Power System. pp. 138–200 in Energy Models for Environment Power and Society. Report to Energy Research and Development Administration contract E–(40–1)–4398.

Estimated as though nuclear energy were in steady state with heat equivalents of Uranium converted to electricity. Coal equivalents of electricity was 3.6 as in Figure 9. Feedback to support non-defense part of the atomic energy commission was estimated as 15.2 x 10^{12} Calories per year, feedback to maintain fuel cycles was 10.75 x 10^{12}, and feedback to maintain, repair and operate steady state power plants was 2.8 x 10^{12} Calories per year, for a total of 29 x 10^{12} Calories for all feedbacks.

(27) Estimated as in footnote 26 except the land diverted or removed from production because of a major accident estimated as 5000 square miles and multiplied by reasonable rate of gross productivity and divided by 20 Calories coal equivalents per Calories of sugar dispersed in the environment.

(28) Efficiency of net production of wood estimated as 0.1% of solar energy. 1000 megawatt plant at 75% load generates 5.67 x 10^{12} Kilocalories per year electrical. Wood conversion to electrical Calories estimated as 28%. Wood collected from forest and delivered estimated as $28.70 per cord and 2.87 million Kilocalories per cord. Costs of power plant estimated by V. W. Uhl as 3.1 million dollars per year coal equivalents 3.6 times a calorie of electricity.

(29) Electrical power at optimum loading with platinum electrodes drawing power from natural blue green algal map placed in glass tubes. Coal equivalents taken as 3.6 Calories of electrical Calories. See reference: Armstrong, N. and H. T. Odum. 1963. A Photoelectric Ecosystem. Science 143: 256–258.

(30) Wind powered generator costs $440/year, is 20% efficient in generating 1200 kilowatt hours with average wind speed of 10 miles per hour.

(31) Energy analysis by S. Brown and J. Zucchetto. Area of collector, 4.46 m^2; 1.72 x 10^6 Calories/m^2/yr. Depreciation 10% per year (cost of $1070 in capital investment spread over 10 years) 4.3 million Kilocalories of hot water produced per year at 29 deg C. temperature elevation. Coal equivalents estimated by multiplying heat released by Carnot ratio (39/312).

(32) Solar energy of the United States divided by 2000 to obtain 7.15 x 10^{15}. Feedback is estimated as fossil fuel energy 18 x 10^{15} kilocalories in 1972. Ratio is about 2.5.

(33) Sources of investment ratios:

North Florida area estimated by M. Kemp in reference: M. Kemp. 1975. Energy evaluation of cooling alternatives and regional impact of power plant at Crystal River, Florida, pp. 49–166 in Power Plants and estuaries at Crystal River, Florida. Report to Florida Power Corporation on Contract GEC–159 918–200–188.19, Systems Ecology Group, Dept. of Environmental Engineering Sciences, University of Florida. Miami, Florida in reference:

Zucchetto, J. 1975. Energy Basis for Miami, Florida and Other Urban Systems. Ph. D. Dissertation, Dept. of Environmental Engineering Sciences, Univ. of Fla. Gainesville 248 pp.

High Energy Agriculture in reference in footnote: DeBellevue. E. Energy Basis for an Agricultural Region: Hendry County, Florida. Thesis for Master of Science. Dept. of Environmental Engineering Sciences. University of Florida, Gainesville. 215 pp. High Density City Building: Solar energy, 4000 kilocalories per square meter per day divided by quality factor 2000; Fossil fuel consumption about 4000 kilocalories per square meter per day coal equivalents; example New York City.

(34) Area of estuary receiving impact, 20 square kilometers times High quality tidal energy absorbed is 2.49 x 10^{12} Calories absorbed in 1.77 x 10^8m^2 as given by M. Kemp on page 447 in reference: Odum, H. T., W. M. Kemp, W. H. B. Smith, H. N. McKellar, D. L. Young, M. E. Lehman, M. L. Homer, L. H. Gunderson, F. Ramsey, and A. D. Merriam. 1975. Power Plants and Estuaries at Crystal River, Florida. Final Report to Florida Power Corporation on Contract GEC–159–918–200–188.19 with University of Florida, Gainesville. 540 pp. Tidal energy per square meter was multiplied by area impacted and by energy quality factor 1.7 Calories coal per Calorie tidal energy (derived from Figure 18) to obtain 48 x 10^9 CE/yr. Feedback impact from the Power Plant is the residual heat and stirring estimated by M. Kemp on page 453 using Carnot ratio of thermal waste for 8 degrees centigrade temperature gradient and discharge of 7.1 million cubic meters per day. Damage to estuary (3.4 x 10^9 CE/yr.) was measured as loss of half of productivity of inner bay metabolism, screen wash mortality, and entrainment mortality, each estimated with appropriate energy quality factor.

(35) Calculations of estuarine impact from reference given in footnote (34); 17 million dollars per year cooling tower multiplied by 20,000 Calories per dollar to obtain energy use in goods and services. Energy input in thermal waste and estuarine damage alleviated by cooling tower are the same as in footnote (34). Wind (5 miles per hour) energy absorbed in a square mile interacting with tower was estimated from kinetic energy and eddy exchange downward and multiplied by energy quality factor 0.13. Calories per Calorie wind energy total feedback energy (546=160+386) is divided in its source into natural and purchased energies ultimately based on fuel according to the U.S. investment ratio, 2.5.

(36) Calculations by W. Mitsch in reference:

Mitsch, W. 1975. Systems analysis of nutrient disposal in cypress wetlands and lake ecosystems in Florida. Ph. D. Dissertation, Dept. of Environmental Engineering Sciences. University of Florida. Solar energy contribution is the diverted energy of land on which the treatment plant is placed (10 acres and solar energy estimated as 15×10^6 Calories per m^2/yr). Feedback energy cost estimated from annual cost (490,000) times 25,000 Calories per dollar.

(37) Energy from cypress swamp estimated as 1.5×10^6 Calories solar energy per square meter per year divided by 2000 energy quality factor to convert sunlight to coal equivalents; Costs of processing secondary wastes to cypress swamp in experiment at Gainesville in project of the Rockefeller Foundation and the RANN division of National Science Foundation is $367/acre/year; multiplied by 25,000 Calories per dollar the feedback in coal equivalents is obtained.

(38) Calculation by M. Kemp using $1.4 \times 10^5 m^2$ area of land in primary and secondary treatment plants times solar insolation, and divided by energy quality factor for sunlight; organic matter determined from BOD and suspended solids removed in primary and secondary treatment and divided by 2 to obtain coal equivalents. Feedback of goods and services estimated from money flow using 25,000 Calories per dollar.

(39) Boynton, W. R. 1975. Energy of a coastal region, Franklin County and Apalachicola Bay, Florida. Ph. D. Dissertation, Dept. of Environmental Engineering Sciences, University of Florida, Gainesville, Fla. Natural energies were calculated from are of bay, sunlight and energy quality factor of sunlight (2000). High quality feedback energy was obtained from fuels added to expenditures using 25,000 Calories per dollar and including goods and services in the fishery, planting of shell, retail costs and goods and services in final purchase and retail consumption.

(40) Environmental contribution was estimated from average size of lot, the number of houses, the solar energy per area and the solar energy quality factor. Feedback energies were estimated from the annual expenditure on operation, construction, and maintenance multiplied by 25,000 Calories per dollar. Services were calculated in Kcals of human metabolism by multiplying total labor force by 200,000 Kcal per working day by 260 days.

(41) Heat equivalent calories are shown. The consumer upgrades energy producing 1 unit of high quality energy which feeds back and multiplies so as to stimulate as much effect on the main economy in units of intermediate quality (10) as was used by the consumer (10). It is reasoned that consumers whose effect is less than their drain will weaken their own energy support system and be eliminated when the system is under sharp energy competition.

(42) Money flow in Health (10.1% of GNP) multiplied by 25,000 Calories per dollar to get 2.9 CE involved in support. Service given estimated similarly from $77.5 million dollars paid for service.