ENERGY ANALYSIS AND NET ENERGY*

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For the last decade procedures for energy analysis developed earlier for ecosystems have been formalized for the general analysis of any system using a language of energy symbols that helps eliminate semantic problems, combines procedures of many sciences, and is useful in synthesis. The energy analysis diagrams are mathematical statements, representations of computer programs, and general systems presentations as well as means for quantitative energy evaluation. A listing of uses of the energy language is given in Table 1. Some basic symbols are given in Figure 1. More on these procedures are given elsewhere (1, 2, 3, 4, 5, 6). In Fig. 2 an example of energy analysis of a city is given by Zucchetto (7), who provides numerical evaluations of all pathways in Tables.

Given here is a summary of one aspect of the energy systems analysis which measures the energy contribution to the human economy. Diagramming and evaluating energy flows of pathways show the way many energy sources and free environmental inflows are contributing to the system of man and nature. One part of the procedure considers the contribution of each energy source separately. In this work some new energy principles were found important including the concept of energy quality concentration, which requires that energies of different form be compared only after their energy costs of transformation are included. Because it was clear last year that some advice reaching the national decision process was incorrect in regard to which sources were potentially large and which were using more energy than they were worth, we made an effort in July, 1974 to improve the national thinking with a series of presentations to agencies in Washington including a press conference.

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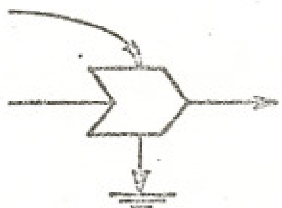
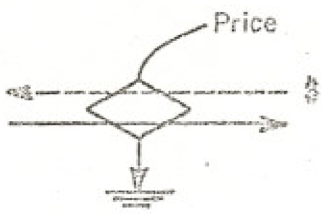
Fig. 1. Some of the symbols of energy circuit language.

Energy source (forcing function), source of external cause.

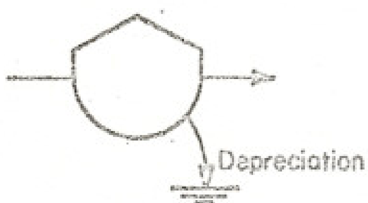
Heat sink, outflow of used energy.



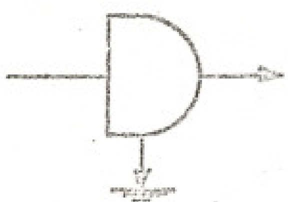
Energy interaction, one type of energy amplifies energy of a different quality (usually a multiplier).



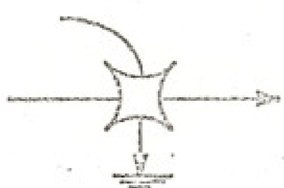
Economic transaction and price function.



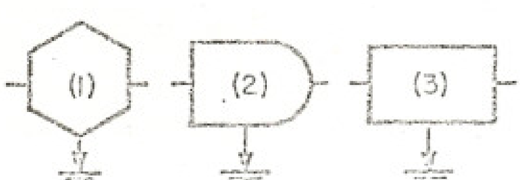
Storage (state variable).



Circulating energy transformer with Michaelie-Menton kinetics (diminishing returns transfer function).



On-off control work (digital actions).



Group symbols (1) autocatalytic self-maintenance units, (2) production units, and (3) general purpose box for miscellaneous subsystems.

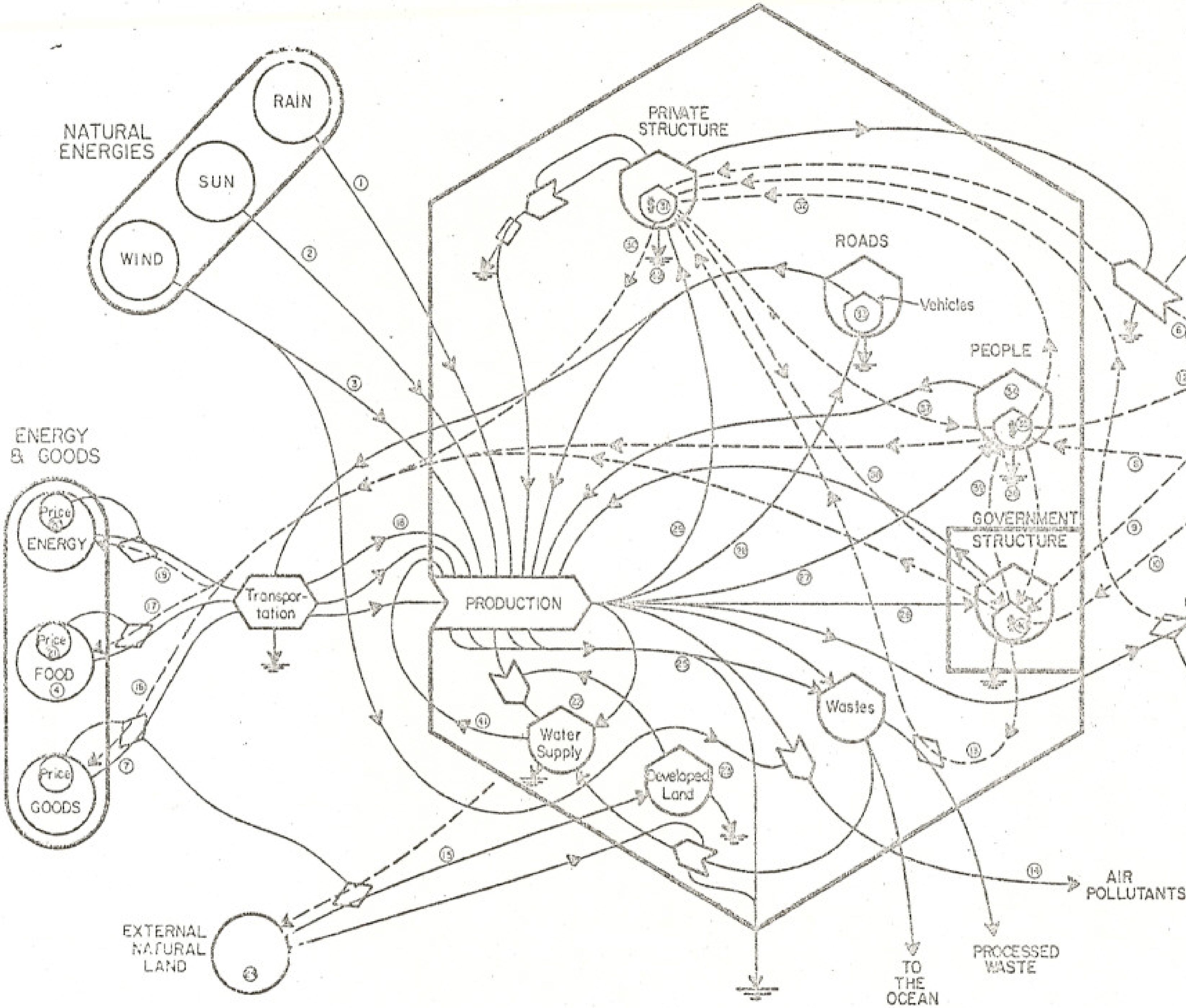


Fig. 2. Energy flow in Miami, Fl... Example of an energy analysis and synthesis from Zucchetto (6).

Table 1. Uses of Energy Language (4).

The following uses of energy language are suggested for modelling

(1) Analyzing models for comparative consideration of mechanisms. Some mechanisms in one field are recognized by those in another as familiar when they translate.

(2) Combining kinetics, dynamics, energetics, material balance, and economics in one method rather than writing separate equations.

(3) Combining the varied languages of several fields into one common language.

(4) Helping to insure that constraints of energy laws are included. This is done in the calculation of energy balance at each intersection or pathway.

(5) Providing a ready way to recognize emergent mechanisms resulting from combining units. For example, Michaelis-Menton effects emerge whenever a limited flow enters a multiplier.

(6) Providing a recognizable translation between the formulations of mathematics and science and the systems diagrams of Forrester, Koenig, and Payntor.

(7) Presenting differential, difference, logic, and integral equations in a form more readily carried in the mind in single unified form.

(8) Showing complex interactions for purposes of summarizing the impact of proposed environmental actions. See (6).

(9) Providing a ready way to portray average data in steady-state flows for purposes of computing missing data. Numbers placed on diagrams indicate visually the magnitudes of time constants, relative importance of flows, and the basis of coefficients in data.

(10) Providing the pathways for which total energy flows are calculated for energy cost benefit evaluations. The relative value of a pathway

is taken to be the energy flow which it causes.

(11) When diagrams are provided with computer names and addresses (analog or digital), the diagrams facilitate debugging of simulation programs.

(12) Programming of complex systems in great detail may be followed by successive redrawing with compartmentalization (aggregation) to develop simple models with some of the essence of all classes of components, while retaining the overall integrity of material and energy balance.

(13) The diagrams help to prevent the unintended double insertion of a mathematical term. For example, a Michaelis-Menton relationship may be desired in the model and it is added. Yet the network into which it is added may already have this relationship in the configuration of limited flows reaching multipliers. Thus the modeller adds it twice unknowingly. There may be no harm in this if the system has two. However, hardware is economized and cost is saved by not duplicating unnecessarily those units that are at a micro-level of organization, where inclusion will not change performances much.

(14) Comparison of a great variety of ecosystems suggests a pattern of structure, function, and processes common to all systems that endure. The pattern is one of obligatory storage and development of high-quality energy and information which is fed back to a controlling, pumping improvement of the energy gathering processes.

The sketch in Table 2 is a very simple generalized structure for overall models of ecosystems which have some of each kind of subsystem. The total generation of power flow is maximized by generating structure, energy, storages, information, and culture from which are fed back forces and amplifiers to pump in the maximum possible energy using all of the potential energy gained towards this. The criterion of competitive continuation and survival is the effective use of structures towards maintaining the energy basis.

(15) Diagramming as a common language may prevent the unnecessary duplicate development of the same concepts in different fields. For example, the kinetics of solar cells, chloroplasts, photochemical reactions, and some examples of diminishing returns in economics are all identical with the original enzyme substrate recycling model of Michaelis Menton in 1913.

(16) Diagramming in network form shows that many models, which have similar form in algebra or differential equation form, are entirely different phenomena, and this shows in network drawing.

(17) Diagramming with a group gathered around a blackboard has been found useful in drawing out from several persons their combined knowledge.

(18) Diagramming of systems that are the focus of semantic argument often clarifies issues and meaning. The diagrams of limiting factor kinetics given in this chapter may be an example.

(19) For learning and teaching the diagrams may help in visualizing the various relationships in the environment. For example, chemists and Biologists used to working with models in energy circuit language may learn physical oceanography without the mental divisions that comes from changing languages.

The understanding and responses were spotty. The public press picked the theme up briefly giving it the name "Net Energy." Our presentation to Senator Hatfield may have influenced the inclusion of net energy considerations in the law which caused this workshop to be held. A presentation to General Gribble of the Corp of Army Engineers may have led to their current interest in comparing energy cost benefit and money cost-benefit analyses in environmental and development project planning. In the year that followed several of the types of energy sources proposed as important for national operation have been examined with the energy analysis approach to estimating net energy. The general conclusions about the national energy situation written before the Arab embargo (8) have so far been confirmed, especially the way declining net energy causes higher inflation.

Our work was supported by the AEC now ERDA with contract # E-(40-1)-4398 and details are given in the contract reports. We have observed some efforts by others which we believe are erroneous because they do not convert energy flows of different type to their equivalent energy cost expressed in the same form of energy. The most important error is leaving out the very high quality energy flows inherent in expensive goods and services which have very high energy costs for their generation and maintenance.

To help eliminate the confusion a book for the general reader and usable in Junior College or Senior High School was prepared (5) and is in proof with McGraw Hill (Energy Basis of Man and Nature). It has chapters on net energy, the relationships of money and energy, and main energy sources of the United States considered with the equal quality energy analysis. The following is a summary of the current procedure for evaluating the net energy contribution of an energy source or an environmental interaction. We believe Calories are the preferred unit where decision makers and the general public are concerned, since this unit is more generally taught in elementary schools in connection with food nutrition.

Definition of Net Energy

Net energy is defined as the energy flow over and beyond that energy necessarily fed back to process that energy, where both flows are expressed in equivalents of the same energy quality. In Figure 3a the net energy is the energy flow N defined as the gross production flow P minus the feedback flow F where both P and F are expressed in units of the same type (such as fossil fuel equivalents). The quantity N is a way of describing the usefulness of the source. Most useful energy transformations involve upgrading part of the energy inflow, using some high quality feedback energy while degrading the rest. Net energy subtraction cannot be made without conversion of the energy flows of different quality into units of the same type using of energy cost factors for transforming less concentrated types to more concentrated types.

An example is given in Figure 3 in which rate of flow of Calories of heat equivalence are given first in b, and according to the first law Calories of energy inflowing equal those stored and outflowing. One cannot, however, make a net energy calculation with these heat equivalents because the quality of energy of F and P may be different, and their ultimate energy cost may be different. In Fig. 3 b before the energy quality conversion there seemed to be a net energy of (+20 Calories/time) but this would be an incorrect inference since 10 units of P would be required to make one of F. In Fig. 3c both F and P are expressed in Calories of the energy quality of F. Since F is now larger than P, there is a negative net energy (-7 Cal/time). The process would not go without a second source of energy.

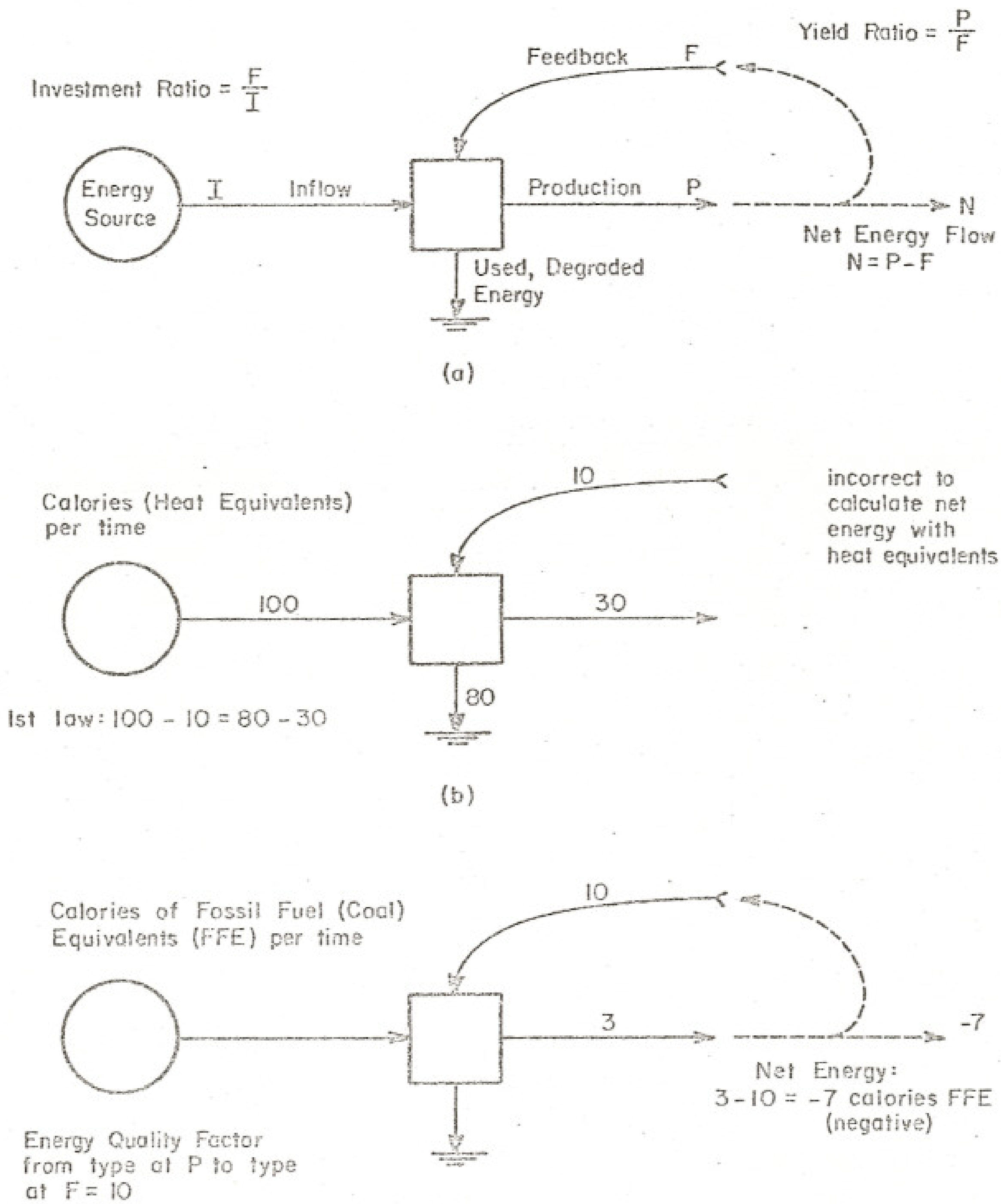


Fig. 3. Net energy calculations (a) definition of net energy and descriptive ratios; (b) example of energy transformations with high quality feedback; (c) example expressed in fossil fuel equivalents (same quality) so that net energy can be calculated.

Energy Quality Factors

Since energies must be converted into equivalents of the same type before they are added or subtracted, a table of energy transformation costs is required and some progress has been made in developing an approximate table. For a given energy transformation there is some conversion which is the best possible for the energy flow at maximum power. It is a general hypothesis that systems of nature and those of technology are selected for maximum power, rather than efficiency. Energy transformation costs were obtained by examining systems that were in operation under conditions of competition where there was a chance to maximize energy flow, eliminating waste, approaching the inherent maximum possible transformation. The energy transformation process is diagrammed and all hidden energy flows shown, evaluated and converted into energy equivalents of the same type in order to evaluate net energy and thus find transformation factors. Some of the factors estimated for conversion to fossil fuel equivalents are given in Table 2. Each was estimated from calculations of real systems. In Figure 4 is given one of the calculations. Solar energy was estimated to be 1/2000 of the value of fossil fuel delivered to point of use by a power plant (fossil fuel equivalents). In Fig. 5. electricity is 3.7 times more costly than coal. Net energy calculations and determinations of energy transformation costs are done with the same data diagram.

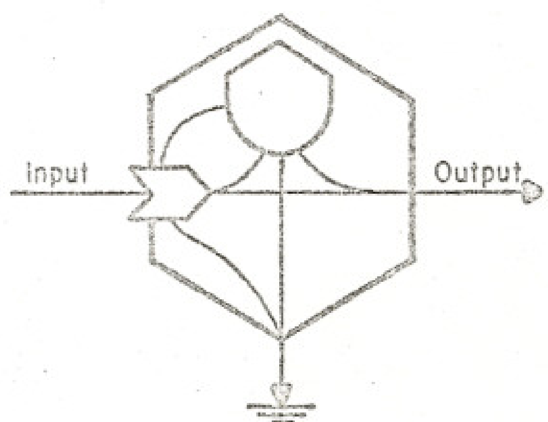
Money and Energy

Money circulates in closed circles as a counter current to the flow of energy which passes in the same closed loops in opposite direction as shown in Fig. 6a. Money goes in exchange for work within the closed loops but it does not flow along the paths to the energy sources or the energy interactions of the environment. Thus money cannot be used to evaluate

TABLE 2

Straight Chain Conversions Factors Between Energy Quality Where All Units Are in Kilocalories. Read across for equivalent.

	Sun	Gross Sugar	Wood	Coal	Electrical	Dollar Flow
Solar Equivalents	1	0.01	.001	.0005	.00014	2.0×10^{-8}
Sugar Equivalents	100	1	.01	.005	.0014	2.0×10^{-6}
Wood Equivalents	1000	10	1	.5	.14	2.0×10^{-5}
Coal Equivalents	2000	20	2	1	.28	4.0×10^{-5}
Electrical Equivalents	7200	72	7.2	3.6	1	1.437×10^{-4}
Dollar Equivalents	50×10^{6} ($33 m^2$)	500,000	50,000	25,000	6,960	1



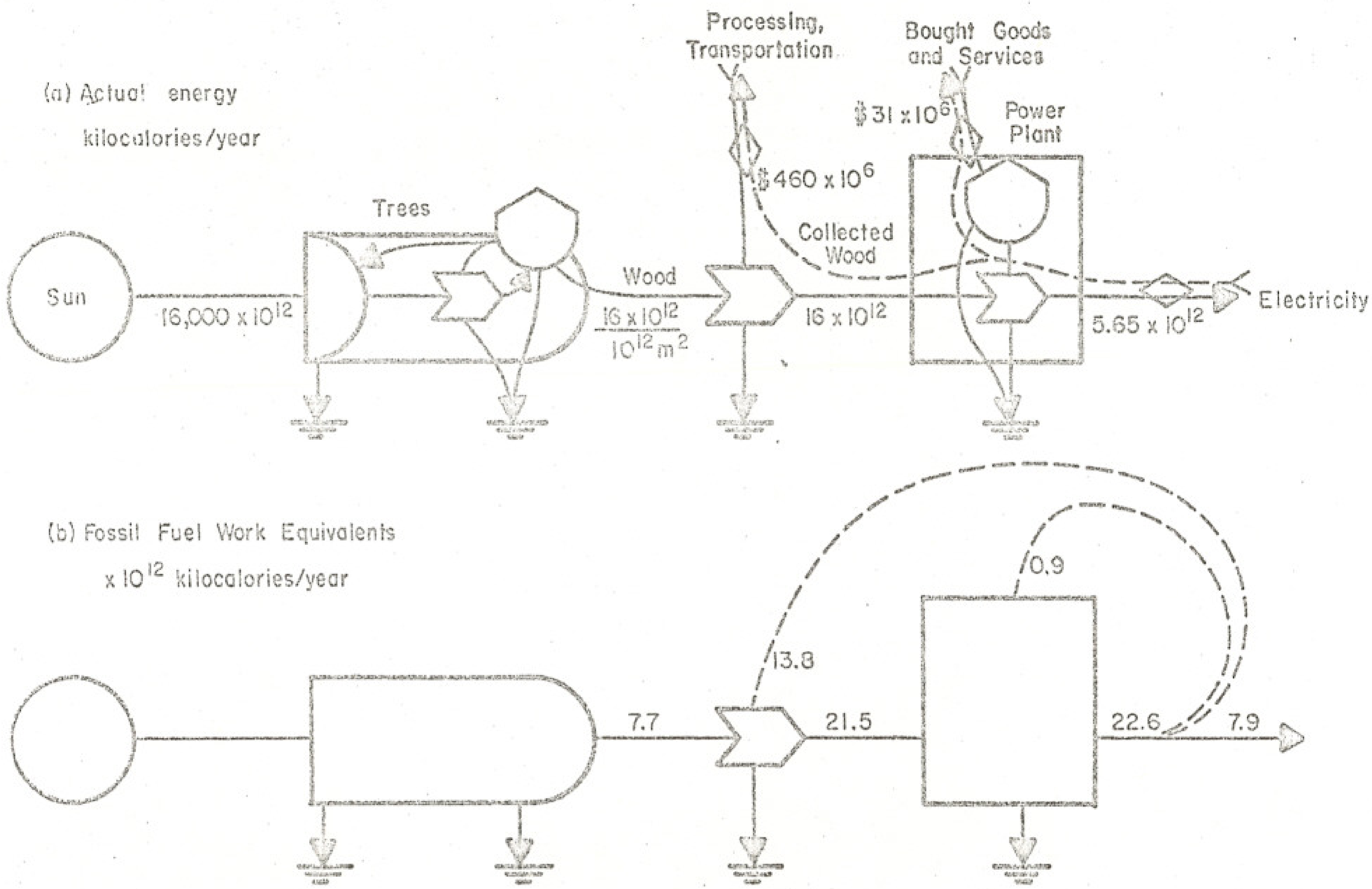


Fig. 4 Diagrams for estimating energy conversion from sun to photosynthetic gross production to net production of wood to power plant production of electricity from burning wood. (a) diagram showing calorie flows of several energy types and flows of money. (b) same diagram with fossil fuel equivalents applied by back-converting from electricity.

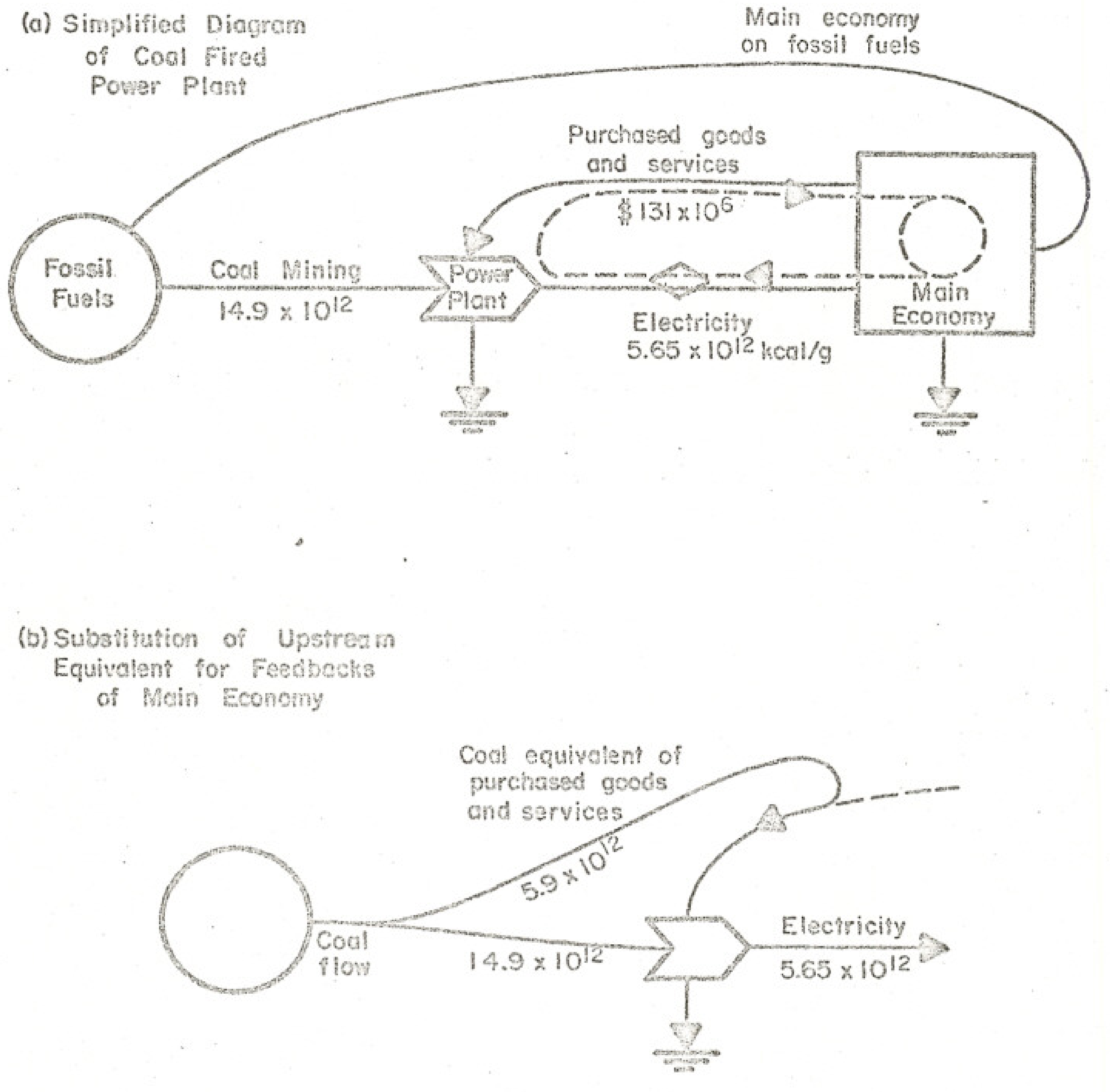


Fig. 5 Energy diagram for a coal filled electric power plant 1000 megawatt capacity, 75 load factor, 3 cents per kilowatt hour, 38% efficiency of heat conversion to electricity. (a) energy flows (b) fossil fuel equivalents substituted for purchased goods and services to obtain a straight chain equivalent. Energy quality factor is input divided by output = 3.7.

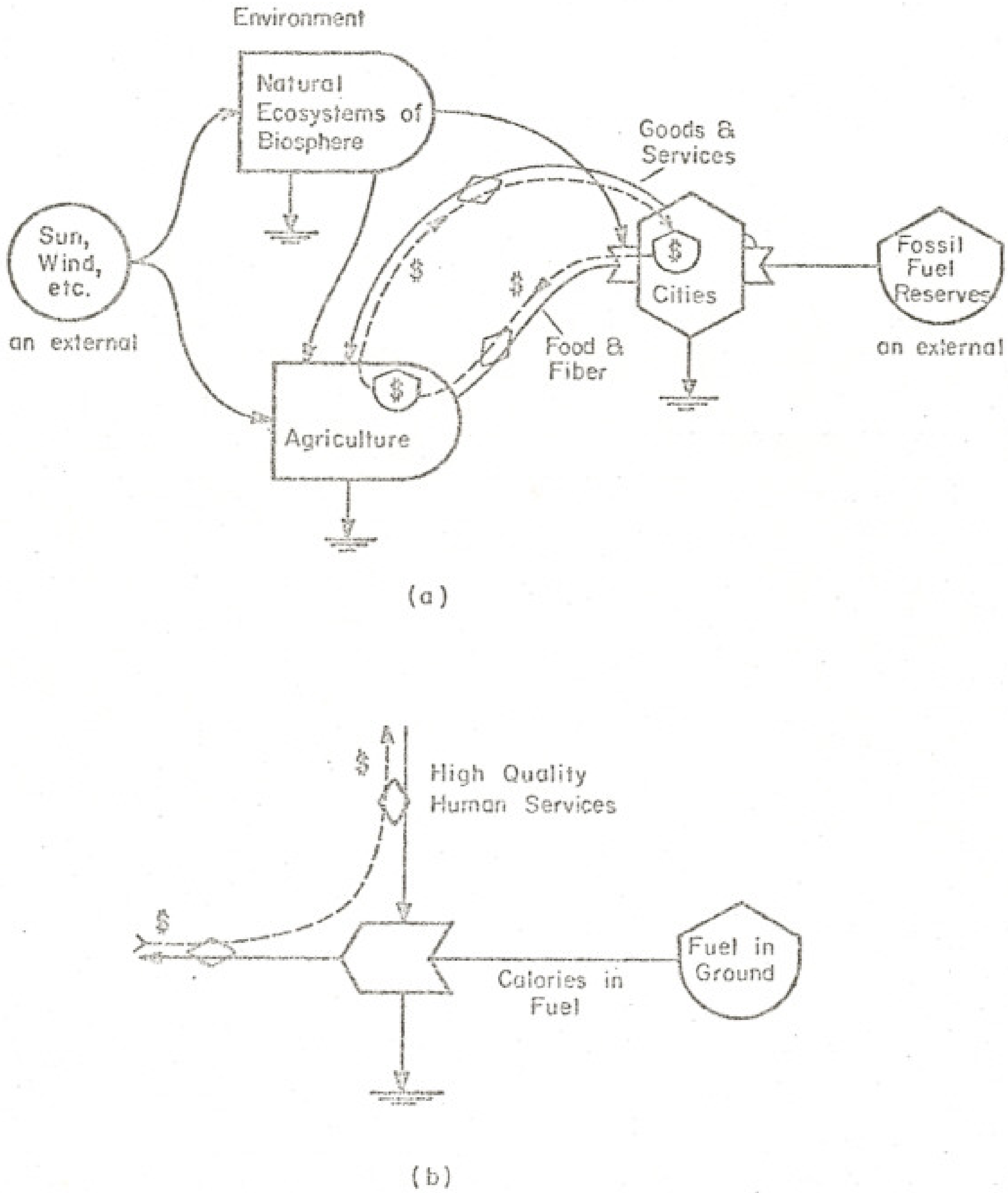


Fig. 6. Relationship of money to energy. (a) dollar flow only within loops controlled by humans; (b) two energy sources in processing fuel but only one recognized by money.

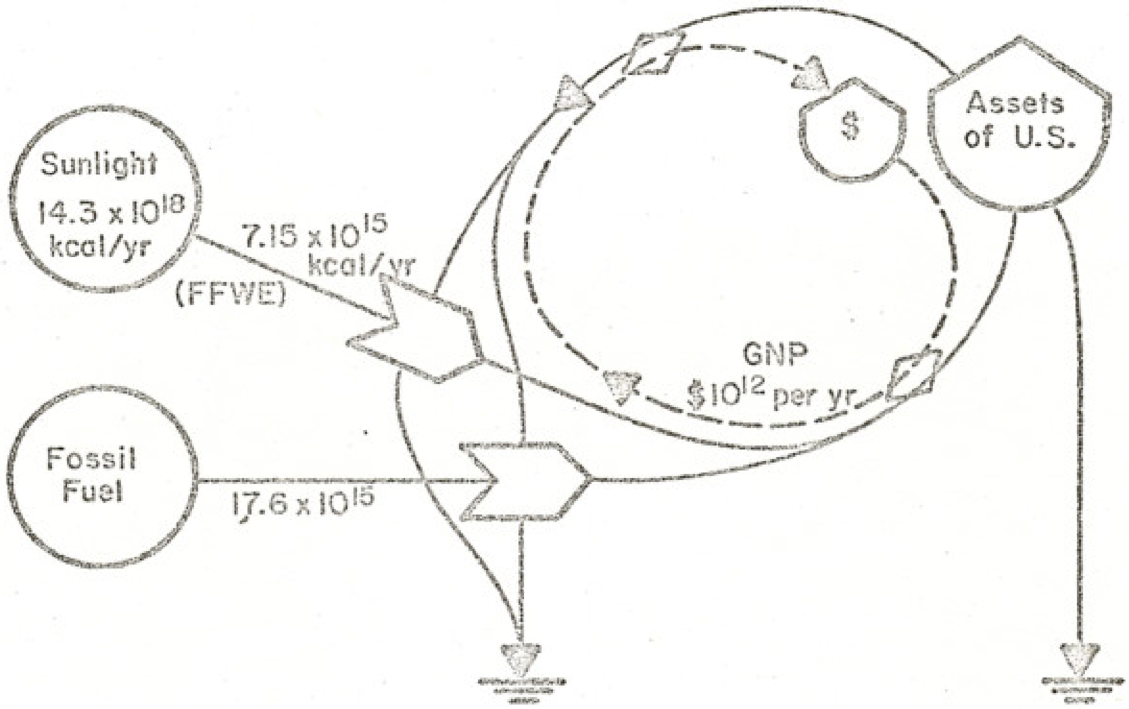
either energy sources or environmental impacts. Energy analysis is required. For example in evaluating the energy inflow from a purchased oil inflow in Fig. 6b one has to add two numbers, one the calories of oil that came out of the ground not paid for (no one paid the ground) plus the energy involved by people and machines in bringing the oil to point of use. Money covers only the latter. There is no set relationship of the money to the energy inflowing from external sources. This varies from year to year. The ratio of money to heat equivalent units flowing varies everywhere in the system, but within a closed loop the energy flow expressed in equivalents of same quality tends to be more constant.

Use of Money Flows to Partition Energy Costs of High Quality Goods, Services, and Equipment

Although energy flows rather than money are evaluated in order to include all externals, we may use money flow data as an indirect way of estimating those energy flows that feedback from the high quality, complex part of our economy.

We may use the ratio of total energy flow to total money flow to estimate the approximate energy costs of high quality goods, services, and equipment costs. These flows are so far down the energy chain of quality and so complex in their web of interactions that tracing energies directly would be difficult.

Figure 7 shows the total money and total energy flows estimated for the United States for 1973. The energy flow includes the fossil fuels and also the solar-based energies (including sun, wind, and rain). The ratio of the money flow to energy flow was about 25,000 Kilocalories of fossil fuel equivalent to the dollar. For mixed goods and services that draw on the complex economy as a whole in an average manner, we may use



$$\frac{\text{Total Energy Flow}}{\text{GNP}} = \frac{25. \times 10^{15} \text{ kcal/yr}}{10^{12} \text{ \$/yr}} = 25{,}000 \text{ kcal/\$}$$

Fig. 7 Diagram for estimating money - energy conversions in U.S. economy environmental systems in 1970.

this energy to dollar ratio to convert dollar data to energy contribution. Often the hidden energies ultimately required to develop the goods, services, and equipment turn out to be among the largest energy inputs.

Examples of net energy evaluations are given in Figure 8-11. The final figures shown in these diagrams are fossil fuel equivalents.

Yield Ratio

In addition to showing the net energy, data from the evaluated energy diagrams provide special perspective on how useful the energy contribution is to the economy. Many situations may be represented by the diagram in Fig. 11 with free energies from the environment interacting with feedback of goods and services facilitated by economic investment. It is not enough to say that a source has net energy. It must provide as much energy as alternative sources. The ratio of the production yield (P) to the feedback energy (F) is defined here as the yield ratio. To be competitive primary energy sources need to yield 8 Calories of fossil fuel equivalent for each invested back as feedback. This is the yield to the U.S. of purchasing Arab oil or mining coal in the west.

Investment Ratio for Evaluating Usefulness of Energy Sources Which Have Negative Net Energies

According to the maximum power principle systems designs are formed that maximize total power. Systems may increase their total power by using their rich primary energy sources to subsidize secondary processes that would not by themselves yield as much energy. Thus atomic energy was heavily subsidized by fossil fuels during much of its history of development. If it contributes as much as alternatives, an energy source may be useful even if it yields no net energy alone. To be an economic contributor it

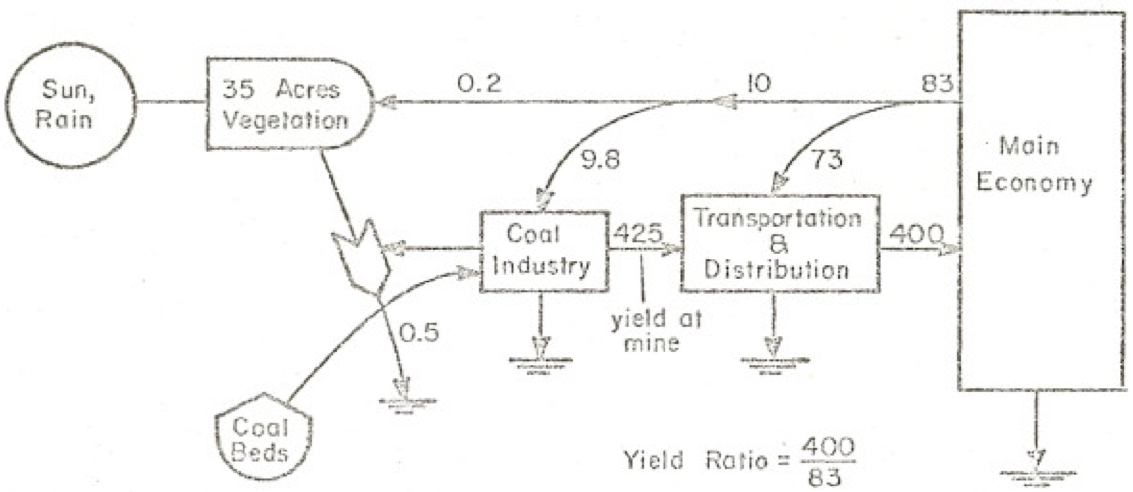


Fig. 8. Net energy analysis of coal (T. Ballentine). Numbers are fossil fuel equivalents.

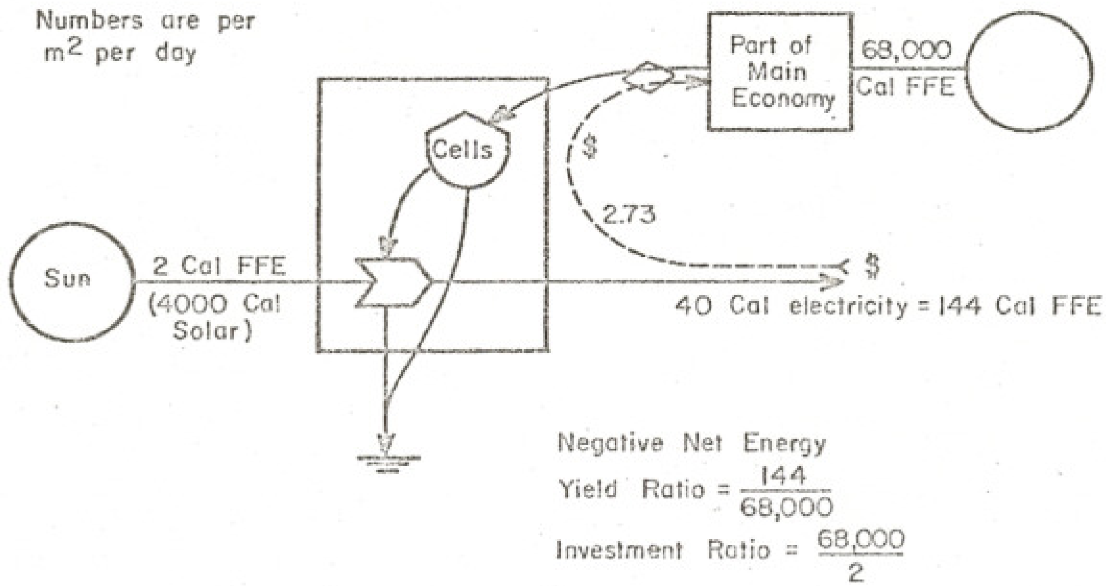


Fig. 9. Net energy analysis of solar cells. Numbers are fossil fuel equivalents.

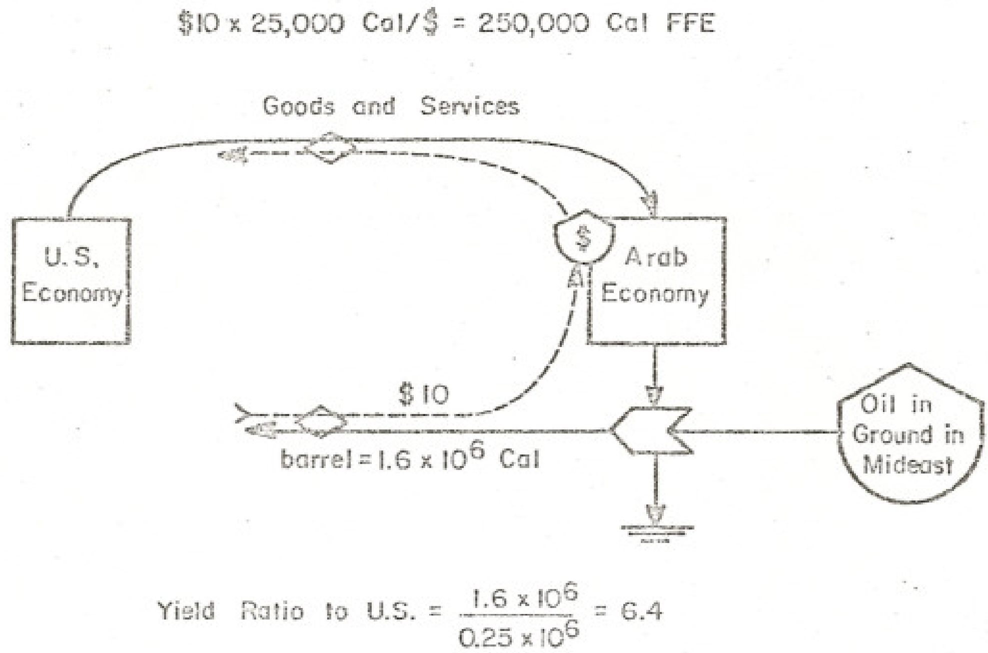
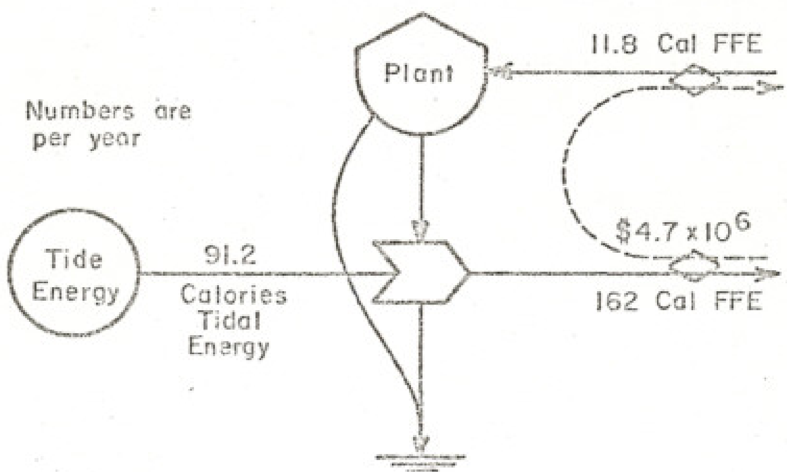


Fig. 10. Net energy analysis of oil purchased from abroad.

La Rance, France



Energy Quality Factor = $\frac{150}{91}$ = 1.7 Cal FFE/Cal. Tide

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

Net Energy = 162 - 11.8 = 150×10^{10} Cal FFE

Fig. 11. Net energy of tidal energy at Rance, France.

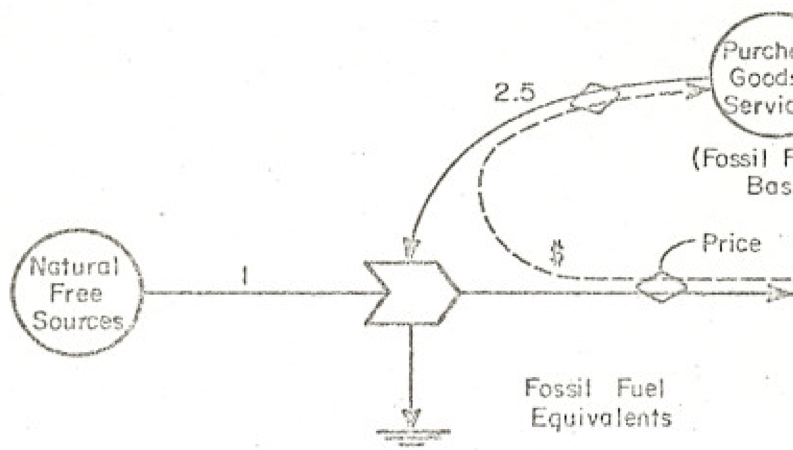


Fig. 12. Yield ratio for economic competition in the U.S. in 1974.

must provide as much new energy per unit energy invested as competitors.

For evaluating such sources the ratio of F to I (Figure 3 or Figure 12) is useful; we call it an investment ratio. If too much high quality energy F is fedback being matched by only a small energy from outside (I), it is a poor investment compared to alternatives with a lower investment ratio. The average ratio in the United States is about 2.5 Calories of fossil fuel equivalent feedback of complex goods, services to 1 Calories of free environmental based energy (solar for example) expressed in fossil fuel equilvalents. Sources with ratios of 2.5 or less may be considered as secondary energy sources and may be used to contribute to the economy.

Net Energy Depends on Point of Computation

Long known in production ecology is the property of net energy that its value may be greatest close to the source of energy and decline as one goes further down the web of energy into the system. If one considers a whole contained system without export and at a steady state there may be no net energy, since all is used for structure and complexity which feeds back to make the system effective and competitive. The net energy depends on the place the line is drawn for making the computation. Many difficulties about net energy come from different choices in point of calculation. However, as long as there is a full energy analysis diagram, semantic problems disappear.

Summary

Energy analysis for purpose of estimating net energy contributions is done by diagramming all flows of energy including goods, services, materials, environmental interactions, and money flows. Next, aggregated diagrams are evaluated for heat equivalents. Next heat equivalents are converted into fossil fuel equivalents using energy quality factors. Net energy, yield ratio and investment ratios are calculated at a defined point relative to the sources of interest. Value of an energy flow as a primary source is compared to a yield ratio for foreign purchase of 8/1; value of an energy flow as a secondary source is compared with an investment ratio of 2.5/1. Full understanding of the value of energy flows requires the whole energy system to be shown with their environmental interactions, feedbacks of amplifications of one flow affecting another and all sources.

Postscript

Just after the conference a general summary of net energy analysis by a former student from our Gainesville group was published in Science including a net energy analysis of two geothermal energy power plants (9).

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