30

ENERGY ANALYSIS, ENERGY QUALITY, AND ENVIRONMENT

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Table of Contents

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Energy analysis is the modeling of systems accompanied by an evaluation of the energy flows inherent in the system. It includes a synthesis of parts into whole patterns where energy flow is used as the common unit of measure among parts. In practice, energy analysis starts with a diagram of important flows, structures, storages, and process interactions. Such a diagram is accompanied by numerical evaluation and appropriate tabular documentation. This evaluated energy diagram shows simultaneously energy balances, energy transformations, kinetics, material flows, information flows, and work transformations. From this basic energy diagram, various aggregate calculations and simulations can be carried out. These result in an evaluation of the role parts of the system play in maintaining the vitality of the whole. Energy analysis shows common characteristics among systems of different types and suggests new energy concepts.

The energy flows of one type required to support energy flows in another part of the system define the energy cost of that part, and the energy cost is often a measure of the potential value of the part to the system as a whole. The quality of energy is measured by the Calories of one type that can generate a Calorie of other types, and the ratio suggests which features of the system must have large amplifier effects to justify their accumulated energy cost.

As part of the basic science of energetics and systems, energy analysis diagrams have been used for a half century in many fields to show overall relationships and resources. In recent years, as fossil fuel supplies diminish, overall environmental energy analysis procedures have become of special interest for showing the energy basis of the economy of humanity. This is a description of some of the methods of energy analysis as used both to understand the energetics of man and the biosphere and to evaluate alternative choices in energy use. The paper is divided into four parts. The first section includes a description of the basic energy diagram and some of the theory which underlies data preparation. The second section discusses the concept of energy quality, its evaluation, and its significance as a value measure. The third section applies the concept of energy cost and energy quality to real world natural and economic systems. The final section applies these same concepts to some alternatives of special interest in energy policy-making today.

Preparing Energy Analysis Data

Data in several forms are required for a full energy analysis of the system of interest; these data are derived from an evaluation of the heat equivalents of energy flows. Certain theoretical factors which explain the observed patterns of energy flow in many systems aid in data preparation and in diagramming. In this section, the energy symbols used in diagramming are given first along with an example. Second, the evaluated energy flows (as heat equivalents) inherent in the example are given--a first law evaluation. Third, the maximum power theory, which may explain observed patterns of energy flow, is introduced. Fourth, some characteristic webs of energy flow which develop because of the maximum power theory are given. Finally, the concept of energy of equivalent quality is discussed via an energy cost diagram.

Energy Symbols and Diagrams

Although different symbols have been used by different authors diagramming systems for various purposes, the full potential of energy analysis requires that the symbols carry mathematical and energetic meaning simultaneously. For this, the energy analysis symbols in Fig. 1 are available as used and described in many books and papers since 1967 (1). An energy analysis diagram of Silver Springs, Florida, is given in Fig. 2 which shows the flows of energy of many types and in several forms. It indicates how these flows interact as they do work and shows all flows ultimately leaving the system as degraded heat. While Silver Springs is predominately a "natural" system, note that its economic component is included in Fig. 2. As the diagram indicates the work of the natural processes interfaces and attracts the flow of money in tourist-supported developments.

First Law Evaluation; First Law Diagram

The next step after diagramming the system is a numerical evaluation of the energy flows.

In Fig. 2 the average heat equivalents stored or flowing per time are written on the diagram giving the reader an overview of the pattern of external inflow of resources, the inside storages in structure, the processes, and the feedback control actions. Heat equivalents are the Calories of heat obtained from each form of energy if converted into heat. Since transfer into heat by definition and by the first law is 100%, heat equivalents are the common denominator of all flows. Even flows of material and information have energy accompanying them.

All inflowing Calories must be accounted for in storages or outflows. If the diagram like that in Fig. 2 is in steady state, inflows equal outflows. A heat equivalence diagram is a "first law diagram". There is generally no controversy in concepts about making a first law diagram, although there is ample room for error in getting the pathways and values correct and comprehensive.

Maximum Power Theories

Heat equivalence measures, or first law measures, provide no information about the potential value of the energy for performing some work function. Second law considerations, however, do. More precisely second law considerations in combination with a time measure of energy flow (which allows energy flow per unit time to be maximized) may, in fact, explain why systems develop certain standard organizational designs. The observed patterns of energy flow and transfer in many kinds of systems seem readily explained by the theory of maximum power. This theory, if general, may make possible the restructuring of science to view systems of many kinds as special cases of a few general patterns. The similarity in the design of systems helps the process of energy analysis, since energy diagrams can be drawn more easily when the basic plans for the shapes and configurations of pathways are suspected in advance.

Apparently first clearly stated by Alfred Lotka in 1922 (3), the maximum power principle states that systems which maximize their flows of energy survive in competition. Among the observed properties of real energy webs, which seem to be explained by this principle, are the characteristic patterns in Fig. 3. Here the potential energy in the source is transformed to a new kind of energy represented by the storage. Some of it is degraded in the process and some is transformed into a higher quality form with new characteristics. Some of this stored higher quality energy is fedback in loops to interact with and amplify the incoming flow of low quality energy from the source. Systems develop chains of these storage-feedback units forming discrete

F. 3

energy levels. The transformation of energy from low to high quality via webs of storage-feedback units is apparently what allows power to be maximized in the system.

The objective procedures of energy analysis given here do not require acceptance of the generality of the maximum power principle. However, the possibility that all systems can be easily generalized with these energy principles is responsible for some of the excitement developing in this area of science. Details on the maximum power theories are given elsewhere (1).

Characteristic Webs

Fg. 4

Figure 4a shows this web of storage-feedback units found in real systems such as those of the biosphere and the economy of humanity. Note that the flow of energy from a primary source simultaneously generates diverging flows that converge back and interact again. Examining any one storage unit on the diagram suggests that several energy inputs are required to sustain that storage. However, tracing pathways back in the web shows that simultaneous diverging and reconverging pathways provide all inputs, each the by-products of the other. For minimum waste the flows can be adjusted so that no one of the necessary interacting pathways is any more limiting to the storage than another.

When the energy from the source or sources on the left diverge, converge, interact, and loop in the characteristic manner shown, potential energy is degraded and dispersed into the heat sink. It is no longer usable for work. As a result, the pathways on the right have relatively few heat equivalents, although their role as feedback controls may be just as important and essential as the flows with larger heat content on the left. The flows and structures on the right require the flows on the left, and vice versa.

Diagram of Cost Equivalents

After an energy web is drawn and the flows of heat equivalents are evaluated, the diagram shows the manner and extent to which the energy flows within the system depend on the sources of energy. Another copy of the energy diagram can be used to write energy costs on all the pathways. This becomes an energy cost diagram. Figure 4b is an example. It is the same as Fig. 4a but evaluated in energy units of equivalent quality rather than in heat equivalents. The energy cost in solar equivalents of each flow is written on the pathway. Since there is only one source for all flow pathways in this example, all pathways have the same numerical cost value. The values on an energy cost diagram are not additive. Pathways diverging from a production process each have the same cost equivalents. When they reconverge in an interaction process, the output is not the sum of the converging flows. The cost value is that of the flow originally responsible for the interacting flows. In this example, the sun's flow is the cost of all the derived renewable flows.

For several purposes of energy analysis, the equivalent cost diagram is a basic tool for determining which flows are important. In it all numbers are expressed in Calorie equivalents of the same type.

In examples where there are two different outside energy sources, the energy cost equivalents of two interacting flows may be greater than the cost in cases where all flows are mutual by products of one source. In that case, observed energy cost equivalents on the diagram may not be the thermodynamic minimum cost.

Evaluation and Significance of Energy Quality

The discussion above indicated that the heat equivalent of an energy flow does not reflect the energy cost required to sustain the flow. The energy cost of sustaining a flow or a storage is a measure of its energy quality. Many heat equivalents are lost to the heat sink when low quality energy is transformed to high quality energy. The more transformations that occur, the fewer heat equivalents that remain. But, as we have seen, the high quality energy with few heat equivalents is required via feedback to maintain the preceeding transformations. Needed is a means to evaluate this energy quality at each step. This section introduces a method for that evaluation and suggests that energy quality may be a measure of value.

Work and a Scale of Energy Quality Transformation

Maxwell defined work as energy transformation. Represented by Fig. 4a and observed in systems of all kinds are chains of energy transformation in which the Calories of heat equivalence are gradually converted into degraded heat of low quality while upgrading the remaining energy stepwise into higher and higher quality (Fig. 4). For example there are food chains like that in the Silver Springs diagram of Fig. 2. Similar chains occur in the energy transformations of the human industrial economy, in the chains of energy transfer in the earth's processes and the chains of biochemical action in cells, etc.

If a system based on one energy source has been maximized for power transformation with the least waste (as compared to alternative designs), then the ratio of two flows in a web diagram is the efficiency with which one type of energy flow is transformed into another. For example, in Fig. 4a the ratio of B to A is 0.1%. The reciprocal is the number of Calories of one type of energy required to generate another type. In this case, 1000 Calories of flow A are required to generate 1 Calorie of flow B. This energy quality ratio is defined as Q.

$$Q = \frac{\text{Calorie flux of type A}}{\text{Calorie flux of type B}} \quad \text{in Calories per Calorie}$$

If the type of energy which is the input is put in the numerator and the type of energy that results from the transformation is the denominator, then the energy quality ratios are greater than 1. The energy quality idea is simple in chains from single sources. It is simply the energy of one type required to develop energy of another type and is a cost measure of the relative value of two types of energy. The ratio of the two flows of energy in heat equivalents is the energy quality factor for that transformation. It is hypothesized that there is a minimum energy cost for a transformation at maximum power. That cost represents an inherent thermodynamic limit below which no improvement can be made. It is further reasoned that systems that have had a long period of evolution and survival under competition have approached these thermodynamic limits. Thus it is useful to develop tables of energy quality factors by evaluating energy analysis diagrams of long established systems. When there are two sources, energy quality is calculated by expressing one source in quality units of the other type, using energy quality factors relating the two types of energy as independently determined (4). The complex web of varied flows that develops is apparently necessary to maximizing each flow. Cost factors can be given in solar equivalents or in units of some other type of energy. Coal equivalents are often used. An analysis of a system which transforms the energy of the sun into wood and then into heat engines, indicated that 2000 Calories of sun are required to produce 1 Calorie of steam, a Q ratio of 2000 Cal/Cal. Do the geological processes which produce coal from sunlight do better?

Diagram of Energy Quality Ratios

Having drawn a first law diagram and a cost equivalence diagram, numbers for a diagram of energy quality ratios (Q) are obtained by taking the ratio of the cost equivalents to the heat equivalents (as in the example of Fig. 4c). This diagram shows the solar Calorie cost of each Calorie of other type of energy flow. As one moves further downstream from the energy source, the energy quality ratio increases. Sometimes a table of cost equivalents is used to evaluate the diagram of energy quality factors which is then used with the first law diagram to calculate the diagram of cost equivalents.

Cost and Potential Effect

Procedures thus far have shown how to calculate the energy cost of sustaining some component of a system. But how can the effect of that component on the rest of the system (via its feedback pathways) be evaluated? In other words, what is the value of the pathway to the system? The maximum power theory suggests that the energy cost of a component determines how its feedback flow will interact upstream. For the long selected system, energy costs may have been minimized and energy amplifier effects are similar. In that case, energy cost measures energy effect and, therefore, is a measure of the energy value of the component to the system. In other words, the ultimate potential value of an energy flow is equal to its minimal energy cost, and it may be safe to assume that systems which have existed for long time periods have minimized their energy costs. Furthermore, maximum power theory as well as observed system structures suggests that the development of a web of energy flows which produces many kinds of energy at the same time is the most efficient way to transform energy to higher quality.

For new, developing systems such as some new energy technologies, energy costs may not be minimized as yet. In those cases, present energy costs may exceed their effect. From the maximum power principle, however, it may be postulated that any unit that does not feed back with an amplifier effect that is at least as great as its energy cost may be a liability and will tend to be eliminated.

When humans manipulate the energy flows in the economy, they affect the manner in which feedback flows interact with and amplify the upstream processes. Flows of energy which have high potential value (because of their high inherent energy costs) should be saved for uses with high amplifier effects.

Many new technological mechanisms for energy transformation arranged by man seem simple at first glance. But an energy diagram of those mechanisms (which forces one to identify the sources of energy) indicates that large amounts of high quality energy from a complex web of natural and economic interactions sustains the new mechanism. The new mechanisms may use more energy than natural processes. For example, Kemp (13) analyzed desalination plants and found that the production of 1 calorie of chemical free energy of fresh water required 3.1 calories in energy cost expressed as coal equivalents. This is about 6000 calories of energy cost in solar equivalents and is higher than natural desalination by the sun in world weather processes (3215 cal/cal as given in Table 1).

Paradox of the High Energy Cost of Flows of Low Calorie Content

Implicit in this discussion is the fact that the energy cost of maintaining a flow or component increases as the heat calories that flow contains decrease. It is postulated that this concept is general because it is a property of all real energy webs observed. In energy diagrams, such as that given in Fig. 4, the less a flow at the right seems to involve heat equivalent energy, the more heat equivalent energy there is behind it making that flow possible. Flows of valuable materials, information, human service, etc. seem to be low in energy whereas the energy flow that makes them possible may be very large.

Webs of Energy Flow in Nature and in the Economy

This section applies the concepts developed thus far to some examples of real world energy webs. By applying the concepts of energy cost, energy quality, and energy effect as well as the possibility that systems organize themselves into webs which maximize power, a great deal of insight into how real world systems function is possible. First consider the earth's surface and its biosphere where the energy web is mainly based on solar energy. Second, consider energy webs controlled by humans with economic components.

Solar Based Energy Web of the Biosphere and Earth's Surface

Usually the flows of energy in the biosphere are considered in parts as dictated by such discipline boundaries as meteorology, oceanography, and geology. But energy flows across discipline boundaries in the real world. The real world biosphere system operates as a web with all parts working in unison. Fig. 5 represents an attempt to diagram the many kinds of energy transformations and feedbacks that take place in the biosphere as it develops the wind, waves, and rain and its land cycles, chemical transformations and biological productivities. In the process of diagramming the biosphere model, many controversial questions were raised. Before all the pathways can be evaluated with confidence, some of these questions will need detailed analysis and some

5

require advances in science. Current calculations in heat equivalents are given in Table 2 and on Fig. 5 (a first law diagram). Part of Table 1 was assembled from the ratios found.

The point is that energy analysis models are one way of stating hypotheses for further testing. For example, according to older theories, the uplift of land in mountain building receives energy from the residual temperature gradient between the deep earth and the surface (note the flow from residual deep heat to continents in Fig. 5). An alternative theory, which emerged as Fig. 5 was being developed, is that there is enough energy from the sun going into crustal work to drive most of the uplift cycle. Note (Fig. 5) that energy from the sun becomes part of uplift processes through the hydrological cycle, through chemical potential energy deposited in sediments from photosynthesis and other biosphere activities, and from the heat from radioactive substances that are concentrated into the surface cycle by differential photosynthetic, sedimentary, and geothermal activity.

The heat emerging from the earth as potential energy is about 1.27 calories per square meter per day (12). For a temperature gradient of 300°C (from 600°C to 300°C over a depth of 35 km) the Carnot efficiency with which work could be done is 50%. Such a system, if operating at maximum power, might do mechanical work with 25% efficiency and produce 0.32 calories per square meter per day as mechanical work. Figure 5 shows more than this much work in rivers. The photosynthetic production buried in sediments is large enough to account for a good part of the emerging heat.

Energy Webs Controlled by Humans

Where pathways in a web are controlled by humans, money circulates in closed loops and flows as a counter current to the flow of energy (see Figs. 4d and 6). How and under what circumstances are the money flows and the energy flows related?

In order to examine the relationship of energy and money, we consider four cases: the relationship (i) at the point where energy obtained externally enters a system, (ii) within a circulating money-energy loop internal to a system, (iii) in the overall U.S. economic system, and (iv) in circulating money-energy loops at the end of the system web (the terminal or most down-stream point in the system).

Consider Fig. 6 in examining the point where energy enters the system. Money (the dotted lines on Fig. 6) circulates around the feedback loops involving humans but not around the pathways of the environmental systems nor does it flow out of the system toward the sun or fuels in the ground. Clearly, the amount of work (energy effect) that goes with the circulating flow of money depends on those external inflows from the sun and fuels. But the money flow, at the point where external energy flows into the system, buys only the work that is being fed back from the economy that processes the energy. At that point, money does not reflect the eventual effect of the external energy. Therefore, the money flow at that point is not proportional to the amount of energy entering from the external source.

Second, consider the relationship of money to energy within a loop internal to the system. How do economic price mechanisms affect these internal energy flows? By eliminating limiting factors, the price mechanisms of an open market tend to facilitate the maximum flow of power through the whole network. For example, when a commodity becomes scarce and the price rises, more money (and thus more energy) flows through that pathway from upstream; that is, more money flows through the pathway in which the shortage occurs. The result is elimination of the shortage. When a commodity is scarce, obtaining some of that commodity results in more energy effect than under non-scarce conditions (because obtaining the commodity opens a bottleneck of flows). Thus, that commodity is temporarily more valuable and justifies more energy cost. It is well established in economics that money flows into a pathway in response to the marginal effect of that pathway as a limiting factor. More money flows toward the commodity that is limiting output than toward any other commodity involved in producing the output at that time. It appears then that money flows are proportional to energy costs when energy costs and energy effects are equal. Fig. 4 represents such a case. However, in the more usual examples of the present time where the economy is in a transient state and is heavily subsidized by fossil fuels, some energy flows are being used with less energy effect than their energy cost. In these cases, money flow and energy costs are not proportional. Separate money and energy diagrams identify such cases. To show the full facts of systems of energy and economics, a separate diagram of money flow should be included with the first three already mentioned (Fig. 4d).

Third, consider the case of the U.S. economic system. The overall money circulation (real GNP) can be related to the overall rate of energy inflow as a Calorie to dollar ratio. This ratio changes with time and measures overall inflation. The ratio of energy inflow to dollar of GNP decreases with inflation. While one can calculate an energy to dollar ratio where the energy counted is only that of concentrated fuels, a more meaningful ratio includes all sources, solar energy as well as fossil fuels. As indicated by Fig. 6 and others, the money flows depend on solar energy (as it is processed by the environment) as well as on concentrated fuels. Several questions were raised at the symposium about the possibility of double counting where the ratio of GNP to total energy flow is used to estimate the approximate energy contributions of goods, services, labor, and other inputs to a sector. These questions are addressed in a note (14).

The final case is that of the money-energy relationship at the end or termination of the web. In a system like that of Fig. 6, the high quality pathways at the end of the web (the far right on the diagram) contain a flow of energy which is the convergence of most of the energy interactions. These terminal flows may have nearly the same ratio of energy (in cost equivalents) to dollars as the overall system does. Given data on the flow of dollars in these terminal high quality loops, an estimate of the energy flow (in energy cost equivalents) can be obtained by multiplying by the energy flow/dollar flow ratio for that year.

Among the high quality loops at the high quality end of a web are the feedbacks of human service. These have very high energy quality factors and high amplifier control actions at their work interactions. Energy to dollar ratios are appropriate for estimating the energy cost involved in these feedbacks. The Energy Quality of a medical doctor's service may be as high as 4 x 10^{12} solar Calories per Calorie.

Considerable controversy exists as to what part of the energy support of humans as consumers is a regular necessary part of the support of the feedback. Maximum power theory and experience in analyzing systems suggests caution in dismissing as unimportant any part of a working and competing system. Because of its high quality and thus high energy cost, human service is the major part of any energy analysis and cannot be omitted.

Evaluating Alternatives

After energy diagrams are prepared and energy quality factors estimated, special calculations can be made to suggest which features of a system or proposed system are energetically important. Examples of such calculations are given in this section for some cases of special interest in energy-environmental policymaking.

Evaluating Net Energy

Net energy is the difference between the yield of energy and the feedback required in a process, where both flows are expressed in Calorie equivalents of the same type. A net energy calculation is made to evaluate a single source to determine how important its contribution is. Figure 7 is an example. As in procedures previously described, heat equivalents of the flows are determined first. Then, using tables of quality factors, solar or coal cost equivalents are estimated and written on the diagram. The difference between yield and feedback is the net energy (Y-F). Fig. 7

To interpret the importance of the source to the economy, the ratio of the yield to feedback is calculated. High ratios mean that the source can support the development of more activity in the economy downstream to the right. When the yield ratio is small, there is little energy to support activity other than that which supplies the necessary feedback. A system with only one source which has developed a steady state has no net energy since it feeds back energy of equal cost to that delivered (as illustrated by Fig. 4b). Where there are several sources and/or where there is growth with feedbacks not yet fully developed, analysis of a single source (as shown in Fig. 8) can indicate the role of that source in supporting more economic development. A whole system which is in steady state has no net energy; it feeds all of its work from net energy sources back to amplify interactions, subsidizing other sources, and maximizing power (as illustrated by Fig. 6). Fig. 8

The U.S. is running now on many sources with yield ratios of about 6 units yield for 1 fed back.* Sources with higher yield ratios than this are good primary sources and contribute more to the economy. Sources with a lower ratio are being partially sibsidized by the main economy, since they yield less per unit received back than their competitors.

As was indicated earlier the amount of circulating money associated with the production of an energy source does not indicate the energy contribution of that external source. It only affects the overall energy to dollar ratio later. A source need not be a good one (competitive) or have net energy to be economic.

Evaluating Secondary Sources

A secondary source is one that does not yield net energy although it does bring in additional energy to the system

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*In calculating the net energy and yield ratios of primary energy sources using the method described here, the energy costs include those associated with concentrated fuels, labor, and solar energy as it is processed by the environment. All of these are necessary inputs and are present in the feedback loops which allow the source to be develop. All must be evaluated in equivalent energy cost units prior to summing. ed from the outside. A secondary source receives more energy in feedback than it draws from the environment, where both are expressed in Calorie cost equivalents of the same type. However, secondary sources are a major, necessary part of systems that have an excess of high quality energy from one or more primary sources. High quality energy does not generate effects commensurate with its energy costs unless it can interact with large quantities of low quality energy such as sunlight. For example, energy in rivers and fossil fuels must be used in interaction with landscapes and solar energy to generate as much work as these sources cost. The more the high quality energy can be spread out to interact with the solar energy the greater amplifier action it may have. Examples are irrigation, tourism, forestry, and fisheries. All of these depend on high quality fossil fuel sources which feedback, interact, and amplify the solar energy required for crop production, forestry, fisheries, and tourism. But as these systems are now operated, solar energy is a secondary source and the high quality fossil fuels are their primary energy source.

Evaluation of the secondary source interaction with high quality feedback is done in the example given in Fig. 8 Heat equivalents are evaluated first. Then cost equivalents of the same quality are evaluated. Then an investment ratio is calculated. The investment ratio is the ratio of feedback to the flow of new resource, where both are expressed in Calories of the same quality. A source is competitive when high quantities of new external energy are brought in per unit of feedback energy invested to make the process possible. In the U.S. as a whole, a usual ratio of feedback to inflow is 2.5 to 1 (both in energy units of the same quality), 2.5 Calories of energy invested via feedback for each 1 Calorie that investment brings in externally. Ratios lower than this are economic; ratios higher than this tend to be less competitive.

Evaluating Consumer Feedbacks

Some of the higher quality feedback loops of systems, such as human medical and governmental service, feedback their work with little direct interaction with external energy sources. Their contribution to maximizing power in the system is in providing special mechanisms, materials, parts, controls, and information. Evaluating their contribution involves comparison of their energy cost with their energy effect. Energy costs can be obtained from the basic energy diagrams showing the energy flows required to develop feedback. The effect, however, can be determined only by disconnecting the pathway and observing the energy flows with and without the feedback interaction. Often these numbers are found by comparing similar systems which differ in having the concerned pathway. Often simulation models are used. This concept of consumer feedback with consequent amplifier action on the whole system can be illustrated by three examples, one involving no humans and two where humans are essential.

A tropical forest plantation of Cadam trees in Puerto Rico has a productive net yield of photosynthesis 20 g/m^2/day (80 Calories/m^2/day wood equivalents) as a monoculture without many consumers (5). In contrast, a fully developed ecosystem nearby (with fully developed consumers feeding back in an organized manner) showed an increase in this basic primary production. An increase of 7 g/m^2/day (28 Calories/m^2/day), most of which was used by the consumers without any net energy, was measured. The system with consumers contained more energy flow (power) than the same system without consumers. Most of the web of producer-consumer interaction was required to maximize power.

In systems involving human consumers, many think of human consumption as the terminal purpose of an economy. In contrast, human consumers really act as units which feedback services necessary for maximizing power under competition. Agriculture and space heating provide two examples.

Only in primitive subsistence agriculture was crop production a primary energy source that yielded net energy. In subsistence agriculture, yield ratios are about 2 to 1. By the time human activities are coupled back into the system, the yield ratio is closer to 1 to 1. Most industrial agriculture now receives more energy (in the form of fossil fuels) back from the economy than it yields (all energies measured in cost equivalents). Thus industrial agriculture is now a secondary source of energy. It is characterized by ratios of feedback to inflow energy of 2-10 to 1 (yield ratios of 0.1 - 0.5 to 1). When agriculture (or other similar solar technologies) are carried out in tiny areas such as greenhouses, ratios of feedback energy to inflow energy are very high, 1000 to 1 or more (both in Calorie equivalents of the same quality), or yield ratios of 0.001 to 1 or less. Since they take far more energy from the economy than they contribute, such operations are not sources of energy. Rather, these operations are consumer devices that use solar energy to aid the flow of some other kind of energy. For example, greenhouse vegetables could be necessary for the health of human beings on a desert island; the amplifier action would be that of the health differential and the energy cost would be justified because of its effect on human health. The energy effect is to increase the power flow of the entire system (because the human population is healthier and can interact and do more work in other parts of the system).

Neither a gas water heater nor a solar water heater yields net energy. A gas water heater takes 11 Calories to generate 1 Calorie of hot water. An evaluation of solar water heaters as an energy conservation action (in comparison to natural gas heaters) suggests a savings ratio of 4 Calories per Calorie; the system does still not yield net energy. However, space heating is clearly required for human productivity. It should be viewed as a consumer device which is energy costly, but which is also energy effective via all of the feedback pathways involving human productivity.

In summary, excess energy goes to consumers who feedback with an amplifier effect and make the whole system more effective. Undoubtedly in times of expanding energy, a system, which is already ahead of others in competition for power, generates net energy that goes to consumers but does not immediately feedback to amplify some other flow in the system. The maximum power theory suggests that such unlooped consumer flows are fairly random, but are creative, and after later selection, effective feedback interactions develop. As energy excess decreases and growth slows, those feedbacks with greatest effect will survive; unlooped consumer flows will not. In order to plan for times of decreasing net energy, it is important that we begin evaluating the energy cost and energy effect of the multitude of consumer feedback loops existing in our economy.

Evaluating Energy Conservation Alternatives

Measures proposed to conserve energy can be evaluated on a Calorie per Calorie basis. The feedback of conservation service such as providing housing insulation or improving car efficiencies can be evaluated in Calorie cost. Calorie savings can then be compared to the Calories fedback in the savings effort (where both are expressed in energy equivalents of the same quality). If the ratio of savings to feedback is greater than one there is a net energy contribution. The feedback is usually one of high quality goods and services, and data are usually expressed in dollars. The U.S. Federal Energy Administration has sometimes used the ratio of dollars spent to energy saved. This ratio is about the same as the ratio of energy spent to energy saved, since feedback of high quality goods and services can be evaluated with an energy to dollar ratio.

Evaluating Environmental Impact

The use of energy diagrams and energy analysis for evaluating environmental impact has led to some exciting, if controversial, insights into the appropriate use of environmental control technologies. Environmental control techniques are energy costly. The maximum power principle suggests that their energy effect in maintaining human health (e.g. a flue gas desulfurization system) and in maintaining environmental flows or fisheries (e.g. tertiary sewage treatment plants and cooling towers) ought to be at least equal to their energy cost and should involve external solar energy where possible. The investment ratios of these systems (e.g. the ratio of energy invested in a tertiary sewage treatment plant to the energy flow that investment involves in solar energy interaction) ought to be as low as possible. Our analyses at the University of Florida indicate that some advanced technologies have very high investment ratios. In these cases, the energy flow in the environment that is maintained or even amplified by the technology is too small to justify so much economic investment. Technologies with high investment ratios are poor users of the conservation dollar.

A better fit of humanity and nature is obtained by coupling the wastes of the economic system to the natural systems through interface ecosystems which can make more use of solar energy. Fig. 9 shows a general format for evaluating such energy interactions with the environment. An example is the recycling of treated sewage into cypress swamps as was carried out in our Florida experiments (Fig. 10). Compare the investment ratios of two alternatives for handling secondary sewage. A tertiary sewage treatment plant might be invoked to remove the nutrients from the effluent prior to its release into a river. The investment ratio for that alternative is 100 to 1 or more. At least 100 Calories of energy are invested in the treatment plant for each Calorie of productivity in the coastal zone involved in the process (all Calories equivalent in quality). The alternative evaluated in the Florida experiment called for cycling the secondary treated sewage directly into a cypress swamp. The wastes were absorbed or transformed and valuable wood growth accelerated. The energy investment in the system (D in Fig. 9) was 11.5 x 10^6 Calories (coal cost equivalents) per year per acre and represented mainly the cost of pipes and pumps. The energy flow from the swamp (expressed in coal cost equivalents) was 3 x 10^6 Calories per acre per year (B in Fig. 9). The investment ratio (the ratio of D to B in Fig. 9) is 3.8 to 1, a vast improvement over the 100 to 1 ratio involved in a tertiary sewage treatment plant.

Fig. 9

Fig. 10

Furthermore, the mining and manufacturing processes required to assemble raw materials into a treatment plant depend themselves on environmental energy flows. We have seen over and over again through these energy diagrams that the economic processes with which money is associated rarely take place in the absence of environmental processes (based on solar energy). The economic processes both interact with and depend on the environmental ones (e.g. manufacturing depends on the wind to dilute and disperse its air pollutants). The processes of mining and manufacturing utilize and load the cleansing capacities of these environmental flows. For 100 units of energy invested in the tertiary sewage treatment plant about one third is environmental loading elsewhere. (The U.S. energy budget matches 2.5 coal equivalents of fuel energy with one coal equivalent of renewable environmental energy). In the case of the treatment plant, utilization of 33 units (100 x 1/3) is more than the 1.3 units (3.8 x 1/3) required for the recycling system. In addition to being poor investments, the distinct possibility exists that advanced environmental control technologies actually cause more environmental degradation than they alleviate.

Summary

Energy analysis is the basic science of energetics of open systems, which considers laws and principles by which energy flow generates designs of structure and process. A language of energy symbol diagrams helps develop models and organize data for analysis and synthesis. Understanding the contributions of external energy sources and internal mechanisms is aided by preparing diagrams: (i) a first law diagram of heat equivalent flows, (ii) a diagram with energy costs expressed in Calories of the same quality, (iii) a diagram with energy quality factors as related to sunlight or coal and (iv) a diagram with money flows. Energy analysis studies are generating new concepts of energetics, systems organization, power spectra, and the energy basis of economics.

Practical application of energy analysis includes calculations of net energy to evaluate primary sources, calculations of an energy investment ratio to evaluate secondary sources, calculation of energy savings ratios to evaluate energy conservation ideas, and calculation of energy effectiveness ratios to evaluate which consumer roles are competitive.

Because of its generality, energy analysis may be useful as a point of departure in general education of students learning the unity of the world system of humanity, economics, and environment.

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14. Double Counting Questions: Figure 8 shows the flows of energy and money in the general economy. It includes free environmental energies and external fuels from deposits which are also free since their external pathway is not accompanied by money. All Calories must be in cost equivalents (not heat equivalents). The rough proportion is used to estimate the energy feedback (F):

$$\frac{\text{Energy feedback (F)}}{\text{Total energy (T) including environmental inputs}} = \frac{\text{Money flow in Loop (L)}}{\text{Total GNP}}$$

In the example shown this is:

$$\frac{F}{25 \times 10^{15}\text{kcal/yr}} = \frac{0.14 \times 10^{10}\$/\text{yr}}{1.4 \times 10^{12}\$/\text{yr}}$$

$$\cdot\ F = 2.5 \times 10^{15}\text{Kcal/yr}$$

Because some of the energy of sources goes into the economy and back to the sector as goods and services, one must correct for double counting for some purposes. When diagrammed with energy circuit and money flows as shown in

Figure 8 there is no question about what is meant and no question about what is the correct answer to the net energy questions.

If the question is: how much of the energy of the main economy is feeding back with feedback F, the answer is 2.5 x 10^{15}Kcal per year of which 40% was originally from the source S, since source S with 10 x 10^{15} Calories is 40 percent of the total of 25 x 10^{15}. If the question is what is the net energy contribution of source S., then one subtracts F from P. In the example 10 - 2.5 = 7.5 x 10^{15}Kcal net energy in fossil fuel equivalents. The yield ratio P/F is 10/2.5 or 4/1. In this example the sector is a net producer supporting other sectors.

Suppose the question asked is, "What are the ultimate energy sources for the sector?" In Figure 8, to obtain the total energy basis of the sector one should add the inflow from source (S) to 60% of the feedback (F), since this is the amount of F that is from entirely different sources.

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Table 1. Energy cost equivalents.

Type of energy		Table footnote	Solar Calories per Calorie
Solar energy at earth surface		1	1.
Tropical moist air		2	3.3
Winds		3	315.
Gross photosynthesis		4	920.
Coal		5	2027.
Tide		6	3400.
Water	World rain chemical free energy	8	3215.
	Rain potential over land, 875 m	9	3870.
	Potential organized in rivers	10	10,950.
	Chemical potential energy over land	11	15,320.
Electricity		12	7200.
Human service in world		13	257,000.
Human service in U.S.A.		14	418,000.
Work of land uplift		15	9.2×10^{11}

1. One by definition. 2. Ratio of 4600 to 1400 in Table 2. 3. Ratio of 4600 to 14.6 from Table 2. 4. Ratio of 4600 Cal/m ^{2}/day to gross production estimate for earth of 5.0 Cal/m^2/day (9). 5. 16,000 x 10^{12} Cal solar energy estimated to produce 5.65 Calories of electricity in a wood power plant. Coal equivalents are 3.6 x electrical (see footnote 12) equal 22.6 coal equivalents; 14.7 coal equivalents were used in necessary feedback of woods services and work of collecting wood. See reference (4). 6. Energy analysis of tidal electric plant at La Rance, France, expressing flows in coal equivalents (CE) in Fig. 7. Solar equivalents of coal taken as 2000 Cal/Cal CE as in footnote number 4. 8. Ratio of solar energy (4600 Cal) to chemical free energy in rain (1.43 Cal/m^2/day). Total rain of world,

Footnotes to Table 1 (continued)

520,000 km^3/yr (9); 5.1 x 10^{-4} Cal/g of rain from footnote 6 in Table 2. Calculation like that in footnote 6 of Table 2. 9. Ratio of 4600 Cal solar energy to 1.19 Cal rain energy overland per m^2 per day, calculated as in footnote 5 of table 2 except continental rain used: 105,000 km^2/yr (9). 10. Ratio of 4600 to 0.42 in Table 2. 11. Ratio of 4600 to 0.30 in Table 2. 12. Ratio of Calories of coal input to electric power plant to Calories of electrical output. Input includes coal used as fuel and coal equivalents of dollars spent on goods, services, and materials. See reference (4). 13. Ratio of 5140 Cal/m^2 /day (4600 plus 540, the solar equivalent of world fuel consumption) to 0.020 Cal/m^2/day in Table 2. 14. Ratio of U.S. Solar equivalents (1.26 x 10^{17} Cal/day) to human Calories (3.0 x 10^{11} Cal/day). Solar equivalents are sum of U.S.solar energy (solar energy overland: (1.2 x 10^6Cal/m^2/yr) (9.4 x 10^{12} m^2) = 10.6 x 10^8 Cal/yr plus solar equivalent of fuel consumption (2000 x 17.6 x 10^{15} Cal/yr.) Human Calories are product of 2500 Cal/person/day and 120 million people = 3 x 10^{11} Cal/day. 15. Ratio of 4600 Cal to 5.0 x 10^{-9} Cal in Table 2.

Table 2. Estimates for environmental energy flows of the biosphere in order of quality. See Fig. 5.

Type of energy	Table footnote	Heat equivalents Calories/m^2/day
Solar energy not including albedo	1	4600.
Solar energy reaching surface including heat reradiation from sky	1	9000.
Evapotranspirational energy flux	1	1400.
Ozone absorption process	2	896.
Wind and storms	3	14.6
Photosynthetic productivity	4	5.0
Potential energy of rivers against gravity over continents	5	0.42
Potential energy of rain purity compared to sea water over land	6	0.30
Tide	7	0.119
Human labor	8	0.020
Volcanic activity	9	0.0119
World fuel consumption	10	0.265
Gravitational work of land uplift	11	5.0×10^{-9}
Seismic activity	12	2.0×10^{-14}

1. Sellars reference (10). 2. 13% of insolation, Ryabchikov (9). 3. Hubbard (8). 4. reference (9).

5. River runoff, 37,000 km^3/yr; average elevation, 875 m (9)

$[\ (10^{2}\ \text{cm/m})\ (3.7 \times 10^{4}\ \text{km}^{3}/\text{yr})\ (10^{15}\ \text{cm}^{3}\text{km}^{2})\ (875\ \text{km}).\ (1\ \text{g/cm}^{3})$

$(10^{3}\ \text{cm/sec}^{2})\ (2.38 \times 10^{-11}\ \text{Cal/erg})\ ]\ \div\ [\ (365\ \text{days/yr})$

$(5.1 \times 10^{-14}\ \text{m}^{2}\ \text{area of earth})\ ]$.

Footnotes to Table 2 (continued)

6. Calories free energy per gram of water = RT ln (100/97.5)

$$\frac{(2\text{ Cal/deg.-mole})\ (300\text{ deg.})\ (0.0154)}{(18\text{ g/mole})\ (1000\text{ g-cal./Cal.})} = 5.1 \times 10^{-4}\text{Cal./g}$$

Continental rain, 109,000 km^3 (9).

$[(109{,}000\text{ km}^3)(10^{15}\text{cm}^3/\text{km}^3)(1\text{ g/cm}^3)(5.1 \times 10^{-4}\text{Cal/g})] \div$

$[(5.1 \times 10^{14}\text{m}^2/\text{earth})\ (365\text{ days/yr})] = .30\text{ Cal./m}^2/\text{yr.}$

7. .0058 watts/m^2 (8); unlike other flows, tide is not from sunlight.

8. $$\frac{(4 \times 10^9\text{people})\ (2500\text{ Cal./person/day})}{(5.1 \times 10^{14}\text{m}^2/\text{earth})} = 0.02\text{ Cal/m}^2/\text{day}$$

9. .00058 watts (8).

10. 1970 3 x U.S. consumption

$$\frac{50 \times 10^{15}\text{Cal/yr}}{(5.1 \times 10^{14}\text{m}^2/\text{earth})\ (365\text{ days})} = 0.265$$

11. 3.6 cm uplift per 1000 years (7); 29% of earth surface continental (9)

$[(10^3\text{cm/sec}^2)\ (3.6\text{ cm})\ (.29\text{ continental})\ (3.6\text{ cm})\ (2\text{ g/}$

$\text{cm}^3)\ (2.38 \times 10^{-11}\text{Cal/erg})\ (10^4\ \text{cm}^2/\text{m}^2)\ ] \quad \div$

$[(365\text{ days/yr})\ (1000\text{ yrs})\ ]$

12. (1500 x 10^{20}ergs/yr (11)

$$\frac{(1500 \times 10^{20})\ (2.38 \times 10^{-11}\text{Cal./erg})}{(5.1 \times 10^{14}\text{m}^2/\text{earth})\ (365\text{ days/yr})} = 2 \times 10^{-14}.$$

Legends for Figures

Fig. 1. Energy analysis symbols.

Fig. 2. Silver Springs, Florida, example of an energy analysis diagram evaluated with numerical values of heat equivalents to form a first law diagram (2).

Fig. 3. Typical sub-unit observed in all systems. Note storage, depreciation, feedback, and production (transformation work) process.

Fig. 4. Typical form of energy web observed. (a) heat equivalent numbers included to form a first law diagram; (b) with solar cost equivalents written on pathways; (c) with solar energy quality factors written on pathways; these numbers were obtained by dividing those in Fig. 4a by those in Fig. 4b; (d) dollar flow.

Fig. 5. Aggregated energy flow model of the main processes of the earth's surface and the biosphere. See Table 1 for numbers.

Fig. 6. Energy flow in an aggregated economic model that shows the relationship of human service as high quality feedback in the U.S. Personal income, farm area and fuel use for 1974 (U.S. Statistical Abstract).

Fig. 7. Example of net energy evaluation of a single source. Tidal energy converted to electricity. Both electricity and feedbacks of goods and services are converted to cost equivalents of the same type (fossil fuels as used in heat engines abbreviated FFE).

Fig. 8. An example of evaluation of an economic sector and source.

Fig. 9. Summary of energy flows of the environment attracting additional energies of investment and economic development. Cost equivalents are evaluated at A or B and related to actual or potential energy flows attracted at D.

Fig. 10. Example of using a cypress swamp as an interface ecosystem to recycle wastes and maintain a high ratio of useful solar energy to purchased goods and services from the economy (6).

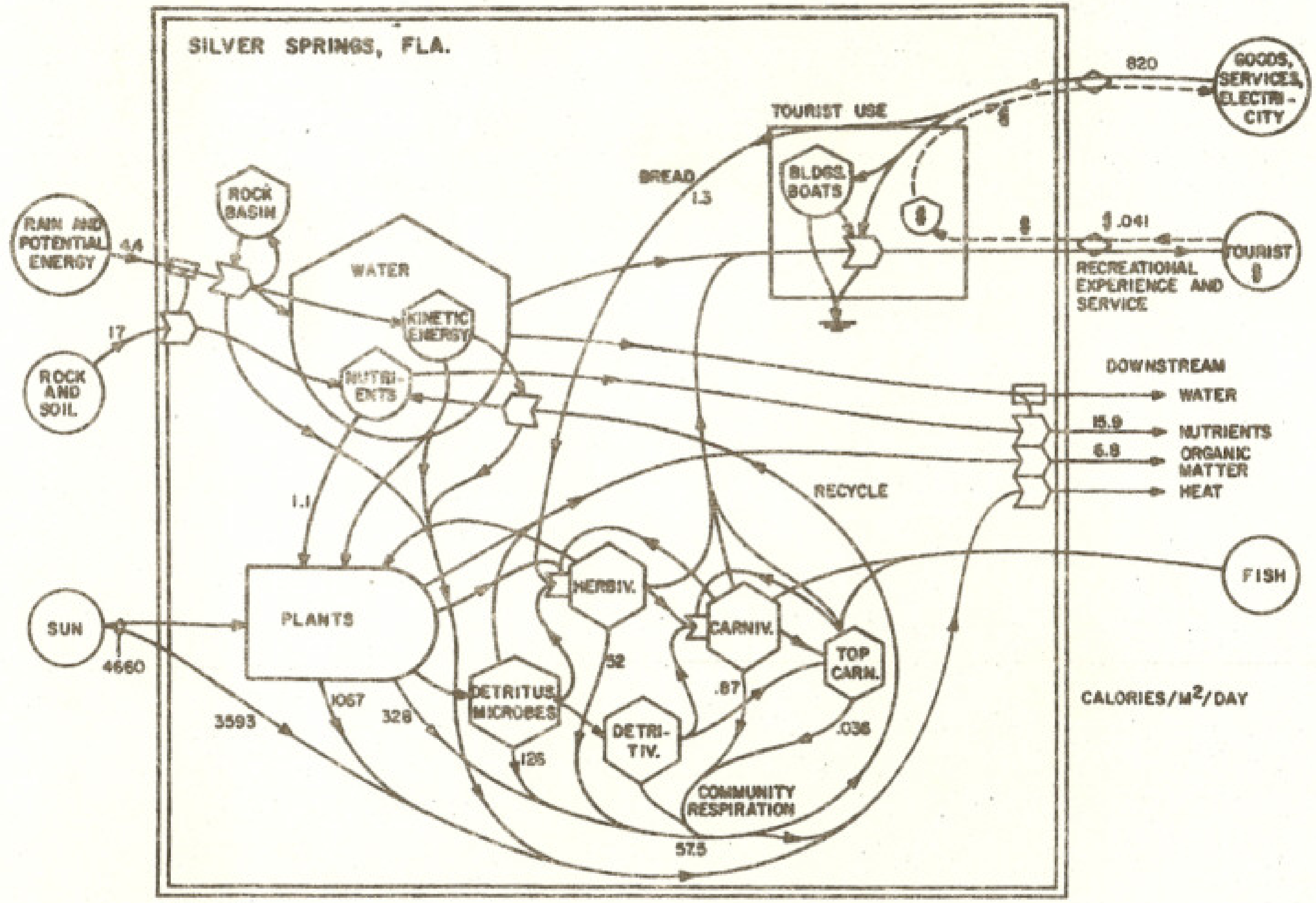
SILVER SPRINGS, FLA.
TOURIST USE
BLDGS. BOATS
$
820
GOODS, SERVICES, ELECTRI-CITY
$ .041
TOURIST $
RECREATIONAL EXPERIENCE AND SERVICE
BREAD
1.3
ROCK BASIN
RAIN AND POTENTIAL ENERGY
4.4
WATER
KINETIC ENERGY
17
ROCK AND SOIL
NUTRI-ENTS
DOWNSTREAM
WATER
15.9
NUTRIENTS
6.8
ORGANIC MATTER
HEAT
RECYCLE
1.1
PLANTS
HERBIV.
CARNIV.
TOP CARN.
FISH
SUN
4660
3593
1067
326
DETRITUS MICROBES
125
32
DETRI-TIV.
.87
.036
COMMUNITY RESPIRATION
57.5
CALORIES/M^2/DAY

Fig. 2

Fig 2