ELSEVIER

Ecological Economics 19 (1996) 219–235

ECOLOGICAL ECONOMICS

Methods and Ideological Options

Embodied energy analysis and EMERGY analysis: a comparative view

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Received 28 May 1995; accepted 22 March 1996

Abstract

Similarities and differences between energy analysis and EMERGY analysis are discussed and highlighted using the two approaches to analyze the same systems. With particular emphasis on accounting schemes, parallel quantitative analyses of several simple model systems are performed. For the first time in the open literature EMERGY accounting procedures are given in detail. The discussion is presented in alternating sections since the authors still disagree on several fundamental issues.

1. Introduction

1.1. Statement of the problem

This is a dialogue between a practitioner of EMERGY analysis (EMA) and one of energy analysis (EA) to assess questions of usefulness, comprehensiveness, self-consistency and consistency with accepted science. The dialogue began in earnest after the May 1990 meeting of the International Society for Ecological Economics in Washington, DC, where H.T. Odum called for parallel analysis using the two approaches. It has continued through the American Association for the Advancement of Science meeting in Chicago in January 1992 and the Denver meeting of the International Society for the Systems Sciences in July 1992.

Our hope is that this paper will exhibit our approaches and viewpoints for scrutiny by others. We do not agree on many points, but by analyzing the same system we have been able to crystallize our areas of agreement and disagreement and to present them consistently. The energy analyst (Herendeen) enters into this discussion because he sees the need for, and admires, the broad purview of EMA, in which there is a comprehensive scheme to quantify all environmental services that sustain humans. He acknowledges that the scope of EA is much narrower, but is concerned that the conceptual details of EMA, which ultimately determine if EMA will be applied in real decisions, are currently inadequate. The EMERGY analyst (Brown) has agreed to this discussion as a means of presenting differences and

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PII S0921-8009(96)00046-8

similarities between the two methods with the hopes that a better understanding of the conceptual basis and quantitative details of the approach can be realized.

In Section 2 we present definitions and principles of the two methods. Our discussion is concerned to a major degree with accounting procedures, which we present in Section 3. In Section 4 we compare the results of the two approaches for specific, simple flow diagrams. In Section 5 we review agreements and disagreements and in Section 6 we summarize. Sections representing only one author's viewpoint are identified as such.

2. Definition of terms and principles

2.1. Energy analysis (EA) and embodied energy (Herendeen)

Energy analysis is the process of determining the energy required directly and indirectly to allow a system (usually an economic system) to produce a specified good or service (IFIAS, 1974). The bookkeeping used in this determination can be used for embodied anything—for example, copper, SO_2 (Leontief, 1970, 1973), nitrogen (Herendeen, 1990) or labor (Bezdek and Hannon, 1974). The basic motivation for energy analysis is to quantify the connection between human activities and the demand for this important resource. The implication is that energy is more important than conventional economic reckoning indicates. Of course the question of how much more is arguable. In the 1970s the oil embargo brought energy to economic center stage, and many environmental analysts were satisfied to treat energy use as a first-order indicator of overall environmental impact. In the 1980s the world oil price dropped and environmental analysts wanted a more detailed accounting of environmental impacts. In the 1990s the greenhouse implications of fossil fuel burning have again promoted energy's use as an environmental indicator.

Energy analysis explicitly and rigorously calculates indirect effects. For example, about 86% of the energy required to produce an automobile is burned in industries outside the auto assembly plant (Bullard et al., 1975). The bookkeeping to account for indirect flows has strong similarities to that in Input–Output (I–O) economics (Bullard and Herendeen, 1975), and some of the machinery of that economic technique has often been used in energy analysis for ecological systems as well as economic ones. (Hannon, 1973; Finn, 1976, 1980; Patten et al., 1990). Indirect effects are especially important in the question of net energy: how the energy produced by an energy technology compares with the energy required to produce its inputs (Chapman, 1975; Chambers et al., 1979; Herendeen et al., 1979; Herendeen, 1988).

Energy analysis can include renewable energy sources; attentive bookkeeping is required to keep them separate from non-renewable sources. While energy analysis is based on the notion that energy is more important than most people think, it typically is not used to support an 'energy theory of value.' The more moderate view is that energy analysis is one information input, like economics, to the process of making a decision (Herendeen, 1988).

There are two things EA does not do:

(1) EA does not have an optimizing principle.

(2) While direct and indirect pollution releases can be calculated using the EA framework, EA does not quantify the environment's role in absorbing and processing pollution.

2.2. EMERGY, transformity and maximum EMERGY (Brown)

EMERGY has been referred to as energy memory (Scienceman, 1989). This is often a convenient way of visualizing EMERGY. When a system is evaluated in solar EMERGY the quantities represented are the 'memory' of the solar energy used to make it. As a result, the quantities are not energy and do not behave like energy.

EMERGY analysis (EMA) is a technique of quantitative analysis which determines the values of nonmonied and monied resources, services and commodities in common units of the solar energy it took to make them (called Solar EMERGY). The technique is based on the principles of energetics (Lotka, 1922, 1925, 1945), system theory (von Bertalanffy, 1968) and systems ecology (Odum, 1975, 1983, 1988, 1991). One of its fundamental organizing principles is the maximum EMERGY principle. Stated as simply as possible the maximum EMERGY principle is as follows:

Maximum EMERGY principle: Systems that will prevail in competition with others, develop the most useful work with inflowing EMERGY sources by reinforcing productive processes and overcoming limitations through system organization.

It is important that the term 'useful' is used here. Useful work is self-reinforcing and defined as the use of inflowing EMERGY in feedback actions that ensure and, if possible, increase inflowing EMERGY. Energy dissipation without contribution to increasing inflowing EMERGY is not reinforcing, and thus cannot compete with systems that use inflowing EMERGY in self-reinforcing ways. For example, drilling oil wells and then burning off the oil may use oil faster (in the short run) than refining and using it to run machines, but it will not compete, in the long run, with a system that uses oil to develop and run machines that increase drilling capacity and ultimately the rate at which oil can be supplied.

The maximum EMERGY principle suggests a system of value that is donor based rather than receiver based. By this we mean that the value of something is derived from how much goes into it rather than how much one is willing to pay for it. The line of reasoning is that, since systems are organized to maximize power (using their inflowing energies in ways that reinforce productive processes), any expenditure of energy has to return useful work equivalent to at least what was expended. We believe that this holds for all systems over all time and spatial scales. Yet, we recognize that at any one moment in time, one might observe an expenditure of energy that does not, in any way, appear to maximize power. And while such circumstances may seem a violation, they are things that are tried, but do not maximize power. Some examples are inventions, random chance events or choices generated by the universe that fail eventually. If they do not maximize power they will be selected against. The speed with which that will happen depends on many things, not the least of which is the degree of subsidy involved in the trial.

The EMERGY of renewable energies, nonrenewable resources, goods, services and even information are determined by the energy required to make them. When values are expressed in these terms, we call the new measure EMERGY and define it as the amount of one type of energy that it takes to make another. When expressed as the amount of solar energy that was used, the units of EMERGY are solar EMERGY, the units of which are solar *em*joules (abbreviated sej).

To derive solar EMERGY of a resource or commodity, it is necessary to trace back through all the resources and energy that are used to produce it and express them in the amount of solar energy that went into their production. This has been done for a wide variety of resources and commodities and the renewable energies driving the biogeochemical process of the earth. When expressed as a ratio of the total EMERGY used to the energy produced, a transformity results (dimensions are sej/J). As its name implies, the transformity can be used to 'transform' a given energy into EMERGY, by multiplying the energy by the transformity. For convenience, in order not to have to calculate the EMERGY in resources and commodities every time a process is evaluated, we use transformities that have been previously calculated.

This use of transformities calculated at other times and for processes that may be in another part of the globe is bothersome to some. In fact, we know full well that there is no single transformity for most commodities, but a range of transformities. There is probably a lower limit, below which a commodity cannot be made, and there is some upper limit, although in theory, one could make corn, for instance, with an infinite amount of wasted fuel and thus have an infinitely high transformity. For some commodities we have calculated several transformities in different parts of the globe and for different ways of making them. Shrimp is an example. In the Gulf of California, shrimp caught by the mechanized Mexican shrimping fleet have a transformity of 13.0 E6 sej/J, while those caught with artisanal fishing techniques have a transformity of 4.0 E6 sej/J (Brown et al., 1988). Shrimp grown in shrimp ponds in Ecuador have still another transformity equal to 18.9 E6 sej/J (Odum and Arding, 1991). Average transformities are used whenever the exact origin of a resource or commodity is not known.

Uncertainties surrounding transformities are related to the resource in question. For instance, transformities for renewable energies like wind, rain, tides and so forth were calculated using global inputs from sunlight, deep heat, and tidal momentum. The best estimates (from the literature) of the total energy in global winds, total amount of global rainfall, and global tidal energy, were divided by the total EMERGY in sunlight, deep heat and tidal momentum to obtain their transformities. These renewable energy transformities are the basis for most other transformities, since all 'higher order' processes and commodities include some proportion of renewable energy. The uncertainty then becomes relative, since if the transformities for renewable energies are too high or too low, then the EMERGY in higher order products is off as well, but by equal amounts.

3. Accounting rules and procedures

3.1. *Energy analysis accounting procedures (Herendeen)*

The accounting framework for EA has been in the literature for 20 + years (IFIAS, 1974; Bullard and Herendeen, 1975; Bullard et al., 1978). This framework is subject to inherent, inevitable difficulties which must be dealt with explicitly (Herendeen, 1988). Examples are questions of system boundary, how to merge several kinds of energy, and energy credit for by-products. It should be stressed that these problems do not result from confusion or lack of study. On the contrary, they are fundamental issues which research has shown can only be resolved by judgmental decision.

To determine the energy to produce a product, the most direct approach would be to perform a detailed 'vertical analysis' covering the manufacturer, its suppliers, their suppliers, and so on. At each stage one tallies the energy inputs per unit of output, and then the inputs of everything else. One crucial assumption is that the measured quantities (say tons, liters, or even dollars) are adequate carriers, or numeraires, for embodied energy. This process spreads out dendritically (see Fig. 1) and can even turn back to the beginning (steel is an input to cars, and cars are an input to steel), thus leading to an infinite series, but the calculation converges mathematically. Often the process is truncated after just a few steps with negligible loss in accuracy. A classic example

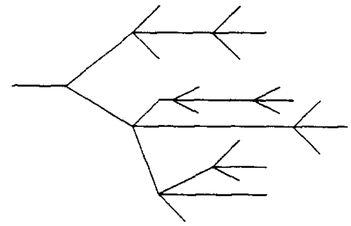

Fig. 1. Schematic diagram of dendritic structure symbolizing vertical analysis.

of a vertical analysis is the study of Berry and Fels (1973) of automobile production.

Vertical analyses are expensive. To save money, analysts were drawn to the input–output economic technique, which organizes large amounts of economic flow data between economic sectors to allow calculation of monetary indirect effects. Such data bases (e.g., U.S. Department of Commerce, 1984) cover all economic sectors and are checked and adjusted for self-consistency. The attraction of a complete flow table for ca. 350 sectors covering the US economy is strong, and much energy analysis has been based on using these dollar flows to calculate energy intensities (Bullard and Herendeen, 1975). The approach has also been used for foreign economies (Denton, 1975; Herendeen, 1978; Peet, 1986). Use of the consumer expenditures portion of the data base in conjunction with the energy intensities has yielded the energy impacts of specific consumer market baskets (Herendeen, 1978; Herendeen et al., 1981). Drawbacks of this data base are:

(1) it is typically 5–7 years old at the least,

(2) dollars may not be appropriate for conveying the linkages that embodied energy implies (instead of tons or liters),

(3) even with 350 sectors, a sector may not be disaggregated enough for the purpose at hand. For example, the (aggregated) sector 'automobiles and parts' is potentially not detailed enough to compare Fords and Cadillacs.

The machinery of EA and I–O analysis solves n simultaneous linear equations. One way to do this is to invert a matrix of coefficients, and that matrix inverse can be written as a converging infinite series of matrix products, each progressively representing a more indirect process. This infinite series corresponds exactly to the implied infinite step process in

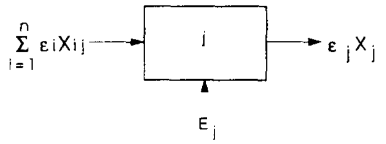

Fig. 2. The fundamental sector embodied energy balance equation of energy analysis.

a vertical analysis; the two methods are equivalent for identical technologies.

The easiest way to see how EA calculates energy intensities is by use of a diagram (Fig. 2). We start with compartment (or sector) 'j', with inputs of goods and services X_{ij}, output X_j, and actual energy input E_j. All are flows, measured per unit time. We now assume that all flows carry an embodied energy given by $\epsilon \sim {}_iX_{ij}$, which defines the energy intensity of sector i as ϵ_i. ϵ_i is measured in units of E (say kcal day^{-1}) divided by units of X_{ij} (say \$ day^{-1}) = (therefore) kcal \$$^{-1}$. The fundamental assumption of EA is that sector j is in embodied energy balance. Fig. 2 thus represents a balance equation for the conservation of embodied energy:

$$\sum_{i=1}^{n} \epsilon_i X_{ij} + E_j = \epsilon_j X_j. \tag{1}$$

If there are n sectors, there are n simultaneous balance equations for the n energy intensities, which can be expressed concisely in matrix form:

$$\underline{\epsilon} \underline{\underline{X}} + \underline{E} = \underline{\epsilon} \hat{\underline{\underline{X}}}$$

$$\underline{\epsilon} = \underline{E}\left(\hat{\underline{\underline{X}}} - \underline{\underline{X}}\right)^{-1}, \tag{2}$$

where $\underline{E}$ is a vector of energy inputs, $\underline{\epsilon}$ a vector of energy intensities, $\underline{\underline{X}}$ a matrix of the flows X_{ij}, and $\hat{\underline{\underline{X}}}$ a diagonal matrix of the outputs X_j.

To reemphasize, the balance diagram in Fig. 2 and the resulting equations are applicable not only to energy, but any input-materials, labor, etc. In that case E_j is replaced with the flow of the desired input, the X_{ij} are chosen to be acceptable carriers for the embodied input, and the ϵ_i are replaced with the intensities for that input.

The balance of embodied energy is an *assumption*. I argue that this assumption captures the intent of calculating indirect effects: to allocate something normally not accounted for, which may (e.g., energy) or may not (e.g., copper) be dissipated, to the products ultimately produced. This balance has nothing fundamental to do with any thermodynamic law, as it is assumed when calculating non-energy intensities such as labor (Bezdek and Hannon, 1974) and nutrient (Herendeen, 1990). I use embodied energy/labor/nutrient analysis as the core of an accounting scheme designed to keep track of and account for something otherwise lost from scrutiny.

The sector-by-sector conservation of embodied energy leads to overall conservation for the entire system, which is desirable from an aggregation criterion (see Fig. 3). Mathematically, this overall balance is expressed as

$$\sum_{i=1}^{n} E_i = \sum_{i=1}^{n} \epsilon_i Y_i, \tag{3}$$

where

$$X_i = \sum_{j=1}^{n} X_{ij} + Y_i \tag{4}$$

Y_i being the compartment's flow to exports/final consumption. Eq. (3) results from substituting Eq. (4) into Eq. (1) (Bullard and Herendeen, 1975).

An unavoidable consequence of this embodied energy balance is that internal embodied energy flows can exceed the actual real energy inputs to the system when there is feedback. At first this seems impossible. A potential disclaimer is that embodied

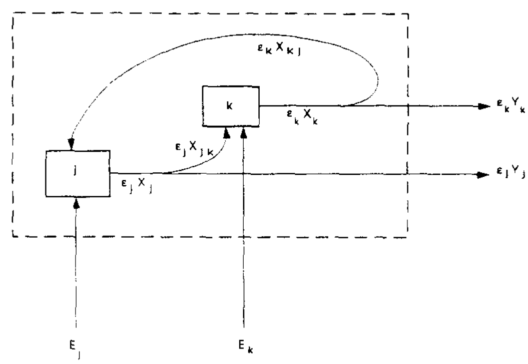

Fig. 3. Embodied energy flows (from EA) in a 2-compartment system. E's represent actual energy per unit time; ϵ's represent energy intensities (energy per unit of X). $\epsilon_j X_j$ is the embodied energy flowing out of compartment j. $E_j + E_k$ is the energy entering the system per unit time; $\epsilon_j Y_j + \epsilon_k Y_k$ is the embodied energy leaving the system. In EA, these two flows are equal.

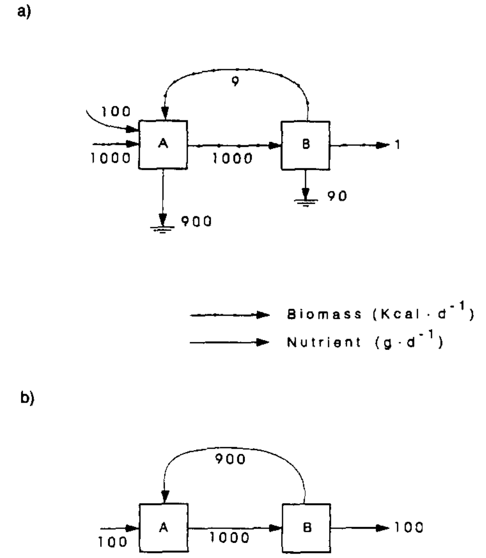

Fig. 4. Effect of feedback on embodied energy and nutrient flows. (a) Biomass flows and nutrient input. (b) Embodied nutrient flows (g day^{-1}). Because no nutrient is dissipated, embodied nutrient is nutrient. These flows are actual, measurable flows.

energy is not actual free energy, so that this flow which seems too large should not be of concern. However, this is not the fundamental reason. In fact this internal flow 'problem' is a logical consequence of feedback flows, and applies whether or not one uses energy as numeraire. For example, one could verify it *by measurement* for the case of nutrient intensity in a system that 'leaks' no nutrient, as discussed following.

Consider Fig. 4a. In this system, biomass energy is the numeraire, there is feedback, and nutrient enters compartment A. Nutrient does not leak or dissipate. Therefore embodied nutrient flows = actual nutrient flows, and all entering nutrient is embodied in the output. The resulting nutrient intensities are $\eta_A = 10$ g kcal^{-1} and $\eta_B = 100$ g kcal^{-1}. As shown in Fig. 4b, the internal embodied nutrient flows A → B and B → A do exceed the system input of 100 g day^{-1}. The apparently too-large flow is physically possible because feedback occasions and *requires* that molecules of nutrient passing through A come from both downstream and upstream. The nutrient intensity is increased by the feedback flow of high nutrient-intensity from B → A. If one measures the nutrient flux (g day^{-1}) one will find that much nutrient actually does flow. Because this flux is measurable for a non-dissipated input, I argue that it is permissible, in fact desirable, to use the same accounting scheme for the embodied flows of a dissipated input.

Following from I–O analysis, there are a number of conventions and manipulations that can be applied in EA to more complicated flows than those in Fig. 3 and Fig. 4. If a sector has multiple outputs but there are still n total products for n sectors, then there are at least two manipulations which reduce the problem

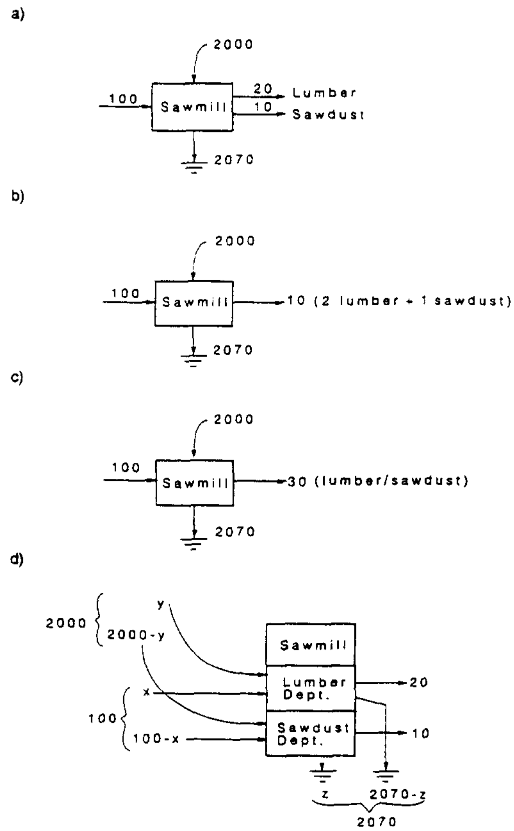

Fig. 5. Example flow diagram to illustrate possible ways to account for byproducts in EA. All units = J/time. (a) Example: sawmill produces lumber and sawdust. Embodied energy in each output is undefined without more information. (b) Output defined in units of (2 lumber + 1 sawdust), of which output = 10 units. (c) Output defined as lumber or sawdust, of which output = 30 units. (d) Inputs and dissipation assigned arbitrarily to two parallel processes, one producing lumber and one producing sawdust. x, y and z can have any values consistent with energy conservation. Embodied energy out of sawmill = energy input.

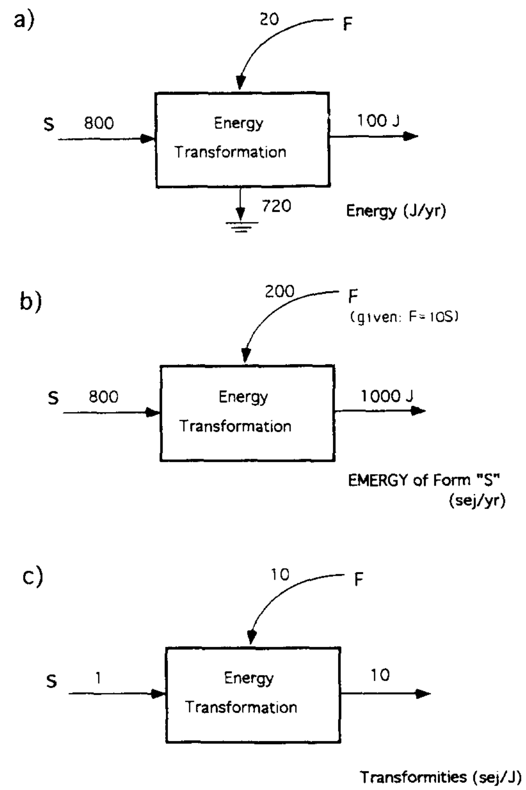

Fig. 6. Diagram to illustrate EMERGY flows and transformity in a single-output system. (a) energy flows, (b) EMERGY flows and (c) transformities.

to the form in Fig. 3 and Fig. 4. If there are more commodities than sectors, there is a manipulation ('market shares' assumption) which again reduces the problem to the form in Fig. 3 and Fig. 4. If there are by-products, EA, following I–O, manipulates to assume them away. There is no way to maintain conservation if the product and by-products are independently assigned the total input to produce product and by-product together. One must choose one convention or the other. EA chooses to maintain conservation of embodied energy, believing that to be more useful than preserving the by-product option.

Thus in Fig. 5 EA can manipulate outputs in at least three ways:

1. EA could sum the output into an aggregated commodity '2 lumber + 1 sawdust' (of which there are 10 units) with an energy intensity = 2100/10 = 210 J/aggregated unit (Fig. 5b), or

2. EA could sum that the output as if sawdust and lumber are identical (of which there are 30 units) with an energy intensity of 2100/30 = 70 J/disaggregated unit (Fig. 5c), or

3. EA could assume the products are made in two parallel processes and assign input energy based on any scheme that assures that the total embodied energy flow out is 2100 J/unit time.

3.2. *EMERGY accounting procedures (EMERGY algebra) (Brown)*

EMERGY is the amount of a source energy it takes to make another form of energy. There are definite rules that are followed to assign EMERGY to flows of energy (see Odum, 1996). We have termed the sum total of these rules EMERGY Algebra (Scienceman, 1987).

The first rule is: • *"All source EMERGY to a process is assigned to the processes' output (S)"*.

Fig. 6 shows a process that has several sources of EMERGY. In Fig. 6a, the pathways are evaluated in

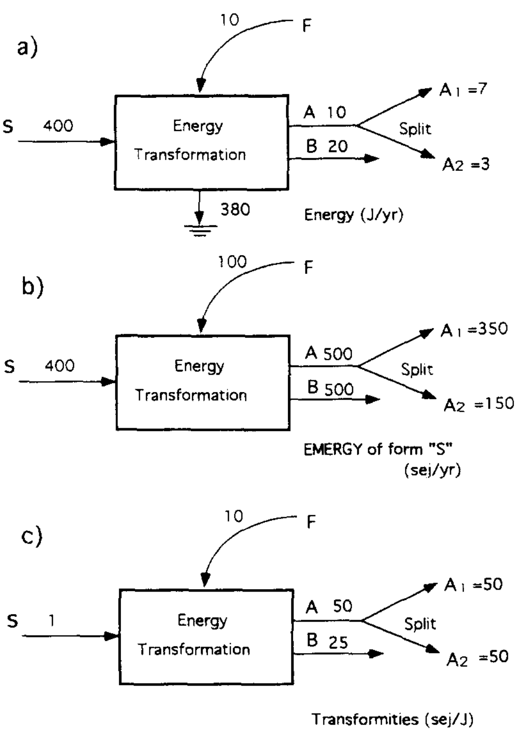

Fig. 7. EMERGY flows and transformities in a dual output system, illustrating both byproducts and splits. (a) Energy flows, (b) EMERGY flows and (c) transformities.

heat energy, and all energy is accounted for as either output, or dissipated energy. In Fig. 6b, EMERGY is assigned based on rule 1. The outflow pathway has a total EMERGY of 1000 sej. Fig. 6c shows that the transformity of the output is 100 sej/J.

The second rule concerns processes with more than one output (by-products) • *"By-products from a process have the total EMERGY assigned to each pathway"*.

The third rule relates to an output from a process that is divided into two separate flows (a split of EMERGY): • *"When a pathway splits, the EMERGY is assigned to each 'leg' of the split based on its percent of the total energy flow on the pathway"*.

Fig. 7 shows the assignment of EMERGY to by-products (A and B) from the same process and assignment of EMERGY to a split (A1 and A2). The pathways are evaluated in heat energy in Fig. 7a, then total EMERGY is assigned to the outputs equally in Fig. 7b. Notice that the same EMERGY is assigned to both outputs, A and B, and then A is split based on the percentage of total energy that is on

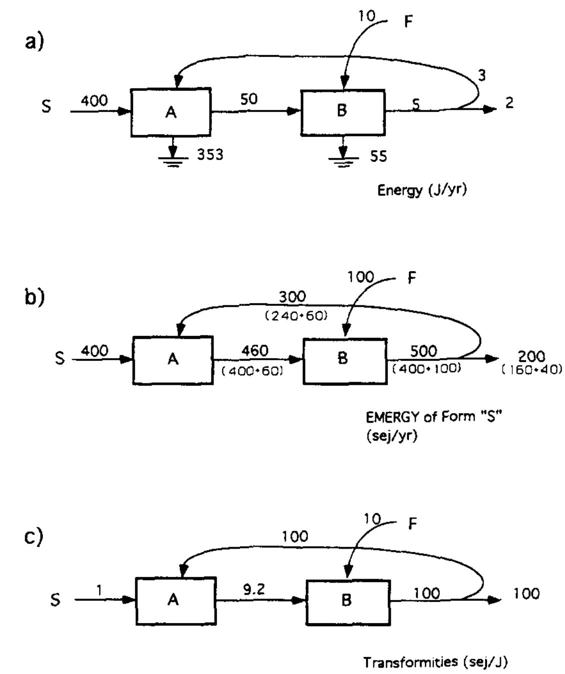

Fig. 8. EMERGY flows and transformities in a 2-compartment system with feedback. (a) Energy flows, (b) EMERGY flows, (c) transformities.

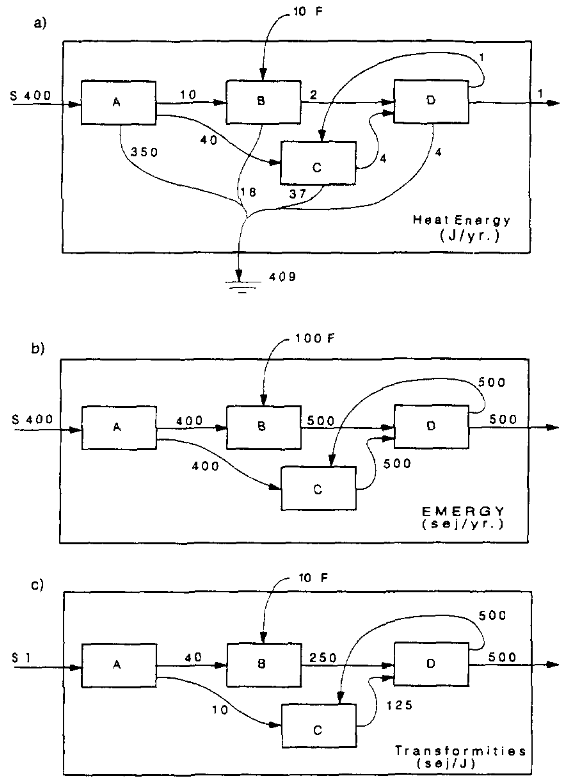

Fig. 9. EMERGY flows and transformities in a 4-compartment system, demonstrating the fourth rule of EMERGY algebra.

each of the two split pathways. Transformities are calculated in Fig. 7c by dividing the EMERGY on each pathway by the energy.

The difference between by-products and splits of the same output is important. Many processes produce more than one output (for instance, agriculture that produces ears of corn and corn stalks, a saw mill that produces lumber and sawdust, or a manufacturing process that produces a good and one or more 'waste' by-products). Since a process that produces two or more outputs cannot produce one without producing the other, the total EMERGY input is assigned to each output. Each is required, and each requires the total input of EMERGY for its production.

The fourth rule describes how EMERGY is assigned within systems of interconnected components. • *"EMERGY cannot be counted twice within a system: (a) EMERGY in feedbacks cannot* *be double counted; (b) by-products, when reunited, cannot be added to equal a sum greater than the source EMERGY from which they were derived*".

Fig. 8 is a simple system of two components having two energy sources and a 'feedback' from component B to component A. In practice it is often easiest to assign EMERGY by writing the EMERGY assigned to each pathway as the sum of inputs from different sources. Beginning on the left the output from A is the sum of 400 sej from source S and 3/5ths of source F, or 60 sej, for a total EMERGY of 460 sej. Notice that only that portion of the feedback from B that did not come from source S, through A, is counted in the output of A. The 400 sej coming originally from A cannot be counted a second time.

Fig. 9 illustrates a second consequence of the fourth rule. The system illustrated has two parallel pathways that are 'reunited' at component D. To simplify the illustration, it is drawn with only by-products (no splits), and only one feedback from D to C. Beginning on the left, the EMERGY assigned to both outputs of A is the total of source S (400 sej). The output from B is 500 sej, or the sum of the EMERGY coming from A and source F. The output from C is the sum of EMERGY coming from A and the EMERGY of source F coming through components B and then D. Since EMERGY cannot be counted twice within the same system, the input to component D can only be a total of 500 sej. The EMERGY from source S that comes through components B and C cannot be counted twice when these two pathways are reunited at D.

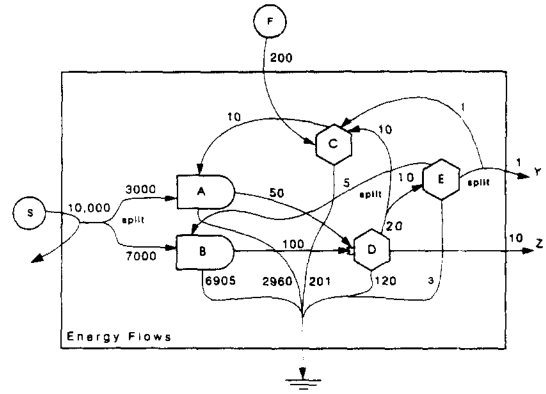

Fig. 10. Energy flows in a 5-compartment system in units of J/time.

4. Comparison of emergy and embodied energy accounting

4.1. Brown comments

Fig. 10 is a systems diagram having 5 components (A–E) and two energy sources (S and F). The flows are also given in Table 1. Components of the system are organized and interconnected with pathways of energy flow, where the numbers on each pathway represent hypothetical yearly energy fluxes.

Table 1
Energy flows in Fig. 10

From \ to	A	B	C	D	E	Dissip	Export	Total output
A	0	0	0	50	0	2960	0	3010
B	0	0	0	100	0	6905	0	7005
C	10	0	0	0	0	201	0	211
D	0	0	10	0	10	120	10	150
E	0	5	1	0	0	3	1	10
Column sum						10189	11	
Energy input	3000	7000	200					
Embodied energy input	3000	7000	20000					

Units = J per time unit. The sum of actual energy inputs, 10200, exactly balances the sum of dissipation and exports by the first law of thermodynamics. The sum of total outputs exceeds this figure because, for example, part of compartment A's output is counted in compartment D's.

The energy sources are of different 'forms', the one to the left (S) is a renewable flow-limited energy source such as the sun. Its inflow to the system is 'split' between components A and B, 3/10ths to A and 7/10ths to B. Components of the system are arranged hierarchically and according to energy flow from left to right. Using a food chain analogy, lower, more abundant members of the chain (green plants) are to the left, while higher and higher trophic levels are to the right. The energy source from the top (F) is a nonrenewable source of higher 'quality' than S.

Fig. 10 illustrates the fundamental reason that recognition of the differences in form energy is necessary. From a thermodynamic perspective the system is correct, having all energy accounted for because the inflows equal the outflows. However, when evaluated in heat energy (as the diagram is) energy flows to the right are so small as to be insignificant when compared with the flows farther to the left. Yet it is apparent from a systems perspective that the processes and flows to the right cannot exist without the inputs, nor since there are feedbacks, can the processes to the left exist without those to the right. In other words since the system is interconnected all components and flows are necessary, yet when evaluated in their heat value, many flows (especially those at the top of energy hierarchies) seem insignificant and of little importance. EMERGY evaluations make the assumption that they are essential for the entire system, their value is the total EMERGY that contributes to them.

The flows from each component can be expressed in the amount of form energy of type S it takes to support it, deriving an equivalent basis for relative comparison. The only thing that is needed is the expression of energy source F in the equivalent form energy of S.

Fig. 11a shows the amount of solar EMERGY assigned to each pathway using the four conventions (rules) described in the previous section. Fig. 11b shows the embodied energy assigned to each pathway using the conventions of embodied energy accounting and matrix inversion in Eq. (2).

Differences in the magnitudes of EMERGY and embodied energy assigned to each pathway result from the different techniques and rules. Quantitatively, there are some significant differences between the diagrams evaluated in EMERGY and embodied

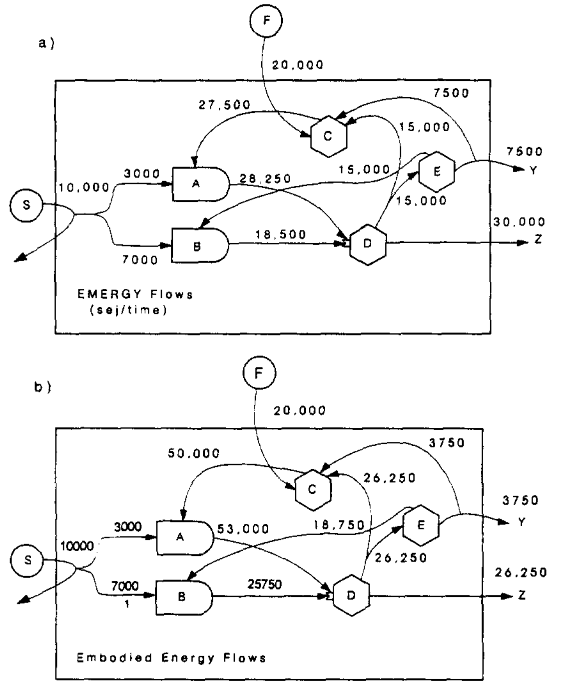

Fig. 11. EMERGY (a) and embodied energy (b) flows of the 5-compartment system in Fig. 10.

energy. One of the first differences is that the outputs (Y and Z) total 37 500 sej for the EMERGY diagram (Fig. 10) and 30 000 J, for the embodied energy diagram (Fig. 11b) where the sum of the outputs equals the sum of the inputs. When the evaluated pathways (Y and Z) are added together, their sum in the EMERGY diagram (37 500 sej) is greater than the sum of the inputs, an apparent problem and the basis for much confusion and misguided criticism since it appears EMERGY is not conserved. When a process results in the output of two different products (i.e., by-products) the entire input EMERGY is assigned to both outputs, since each cannot be made without the other and all EMERGY is required to make each. This fact creates much confusion since at first glance it appears that more EMERGY is output from the process than is input, and thus a violation of the Conservation Law of Thermodynamics. However, under no circumstances should the EMERGY outputs from a process be added together. It is a violation of rule four and results in double counting the EMERGY. Additionally, at times, all EMERGY inflows to a process may not all be assigned to its outflows (see, for instance, Fig. 9b where the inflows to component C total 900 sej, if they were added together, while the output is 500 sej). EMERGY cannot be counted twice in the same system; and if through feedback actions EMERGY returns to a component, it cannot be added into its output again.

Using the rules of EMERGY algebra, it is impossible for any single pathway to have more EMERGY assigned to it than is inflowing to the system. Using the matrix inversion techniques of embodied energy, however, pathways often have more embodied energy assigned than is inflowing (pathways from C to A, and from A to D), again providing fodder for much confusion and misguided criticism. We will discuss these apparent problems in a later section.

The most important difference that results when the two accounting procedures are used is that on pathways from lower order components the embodied energy is about 1.8-times as much as the EMERGY, but on the highest order pathways, the EMERGY is 1.1–2.0-times as great as the embodied energy. The significance is that the differences between lower and higher order pathways are amplified between the two accounting systems. Embodied energy accounting gives more weight (more relative importance) to lower order pathways over higher order ones, while EMERGY accounting gives more relative importance to higher order pathways.

Fig. 12 shows the solar transformities and embodied energy intensities that result when the energy on pathways (Fig. 10) is divided into EMERGY (Fig. 11a), and embodied energy (Fig. 11b). The units of solar transformities are sej/J. The units of intensities are joules of embodied energy per joule. The relative importance of lower and higher order pathways, discussed above, is more easily seen when transformities and intensities are compared. This can be seen in Fig. 12a and b, where the relative values of transformities and intensities for lower order outputs (component A and B) and higher order outputs (components D and E) are significantly larger in the EMERGY evaluated diagram (Fig. 11a) than in the embodied energy accounting (Fig. 11b). Transformities for higher order pathways are 13–16-times as great as lower order pathways, while intensities for higher order pathways are 3–10-times as great as lower order pathways.

The significance of these differences is in interpretation of what transformities and intensities mean. If, as theory suggests, transformities are a relative measure of flexibility, substitution, or value (the energy required), and if embodied energy intensities are analogous to transformities, then relative importance can be significant. In EMERGY terms, the output of component E has a transformity that is 13 × as great as the output from component A (Fig. 12a), while the embodied energy intensity is only 3.5-times as great for the same outputs (Fig. 12b). In like manner the transformity for the output from component D is 16-times that of component B, while the intensity factor is only 10-times as great.

Differences in relative importance of outputs is also revealed from the fact that each system assigns highest intensity and transformity to different outputs. The largest intensity is associated with the output from C (5000 embodied energy joules per joule), while the largest transformity is the output from E (7500 sej/J). In other words, embodied energy accounting assigns highest relative importance (highest intensity) to an intermediate compo-

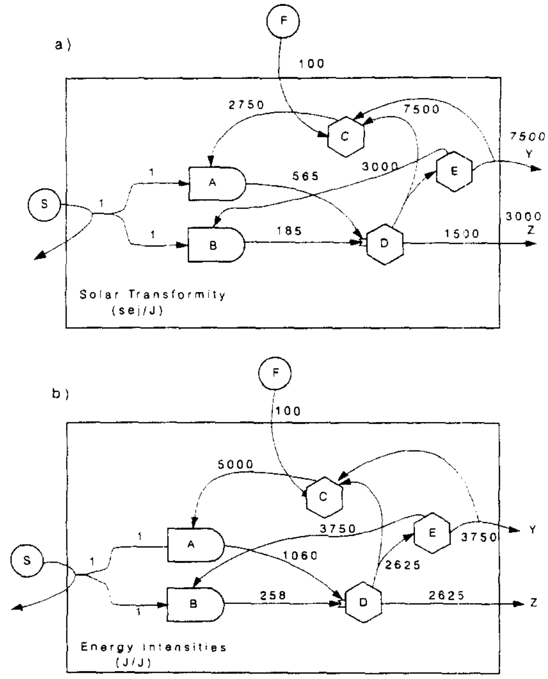

Fig. 12. Transformities (a) and energy intensities (b) of the 5-compartment system in Fig. 10.

nent and its output, while EMERGY analysis assigns greatest importance to the highest order component (top of the energy hierarchy).

4.2. Herendeen comments

Eq. (2) is applied to the flows in Fig. 10 (also given in Table 1) to give the energy intensities in Fig. 12b and the embodied energy flows in Fig. 11b. The energy intensities in Fig. 12 range from 258 to 5000 sej/j, a range of 19.4. Feedback is the reason that the spread in values is not greater; feedback has the effect of mixing what otherwise would be 'high' and 'low' compartments and destroying the otherwise more hierarchical structure. This is not a defect of EA; it is a strong point. If, for example, herbivores also eat detritus (which is partially composed of dead carnivores), that will affect how much sunlight is required to produce a carnivore that eats the herbivore. EA deliberately includes the effects of this feedback, but EMA truncates these effects. EA explicitly accounts for feedback loops. (Other indications of the strength of feedback can be had by calculating trophic position and path length (Ulanowicz, 1986; Wulff and Ulanowicz, 1989; Herendeen, 1990). (Similar mixing of 'high' and 'low' levels occurs, but I do not illustrate here.) Fig. 11b shows that each compartment is in embodied energy balance, as is the overall system.

For a chain (without feedback) with no by-products, EMAs transformities and EAs energy intensities are identical, and both EMERGY and embodied energy flows are conserved. With feedback (i.e., a web instead of a chain) and/or by-products, EMA allows that EMERGY flows are not necessarily conserved, either in individual compartments or the system as a whole. EA assures that embodied energy is conserved. There is no way to treat feedback and by-products as EMA does and still conserve EMERGY flows. Regarding the first cause of non-conservation, EMA's treatment of feedback: EA objects strongly, as argued above using a physical example of nutrient flows. Regarding the second cause of non-conservation, EMA's treatment of by-products: EA is sympathetic to by-product accounting problems. Further work may resolve this latter issue.

5. Agreements and differences

5.1. Assigning embodied energy based on dollars, materials, or energy (Brown)

In practice, embodied energy can be assigned to products based on money flows, material flows, or energy flows. Odum (1996) has shown that very different results are obtained in a system when each of these is used to assign embodied energy to the same pathways. The practice of using commodities and money to assign embodied energy is a questionable one since there is no logical reason that embodied energy is related to money, carbon, labor, or anything else.

5.2. Accounting for labor and renewable energy in EMERGY analysis (Brown)

Most embodied energy evaluations researched in the literature do not include labor, or if it is included, only a portion of the energy of a human is considered as an input to the process (Costanza and Herendeen, 1984; Hall et al., 1986). In general, there is much debate over whether or not labor should be included, and if included, how to account for it.

In EMERGY analysis, all labor (service) is accounted for using the dollar costs of products, since dollars spent in the economy always purchase services. A ratio of EMERGY to dollars is calculated from year to year for an economy and used to determine how much EMERGY is 'behind' any expenditure for services. All dollars spent for a commodity, service, or fuel, when transformed to EMERGY, are necessary inputs to the process. They are accounted for as being used to produce it, even if the EMERGY may be partially used by labor for activities not directly related to production of the commodity purchased. Accounting for labor is a question of whether the outputs of human production are considered by-products or splits. In EMERGY accounting the outputs of human production are considered by-products and thus the EMERGY value of labor is the sum of all EMERGIES used in support of humans.

Renewable energy inputs to processes are evaluated in EMERGY units (solar emjoules) by using previously calculated transformities based on the distribution of solar energy in the biosphere, the output energy of the various processes (rainfall, total wind energy, total wave energy, etc.) and the assumption that these processes are by-products of the biosphere.

In practice, both renewable and nonrenewable energies are included in EMERGY evaluations. This is extremely important since an economy does not run on fossil fuels alone, but requires an environmental support base. Energy analysis on the other hand, routinely leaves out the renewable energy contributions to economies including only, what Herendeen terms, 'cultural energy' sometimes accounting for differences in quality (Cleveland, 1992). Such omissions can leave out significant portions of economies (in developing nations over half their resource base often comes from renewable sources) leading to inflated incremental energy ratios and underestimates of environmental impacts and net effects of development proposals.

5.3. Accounting for labor and renewable energy in energy analysis (Herendeen)

EA is a conserving accounting scheme and the framework can apply to any input, including renew-

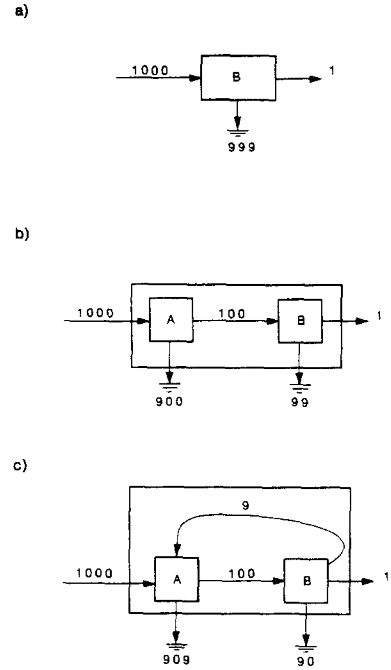

Fig. 14. Two-compartment system to illustrate EA treatment of aggregation. All flows in kcal day^{-1}. (a) Initial stage: one compartment with one output. $\epsilon_B = 1000$ kcal/kcal. (b) Internal details are revealed; system can also produce a second product. $\epsilon_A = 10$ kcal/kcal; $\epsilon_B = 1000$ kcal/kcal. (c) Internal details include feedback. $\epsilon_A = 100$ kcal/kcal; $\epsilon_B = 1000$ kcal/kcal.

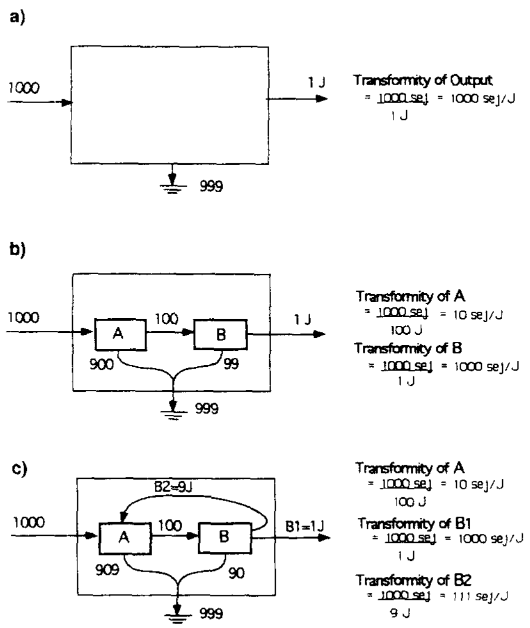

Fig. 13. A 2-compartment system (the same as Fig. 14) to illustrate aggregation questions in EMA.

able resources. Indeed it is routinely applied to solar energy intensities of different compartments in ecological food chains and webs (Hannon, 1973; Hannon and Joiris, 1989; Herendeen, 1990). The input can be labor as well (Bezdek and Hannon, 1974; Hannon et al., 1975; Herendeen and Sebald, 1975). There is a side issue about labor: whether consumers are free to alter their purchasing patterns, i.e., whether the economic system is closed or open with respect to personal consumption expenditures (see Costanza and Herendeen, 1984), but that is peripheral to this discussion.

5.4. Disaggregation, by-products and splits (Brown)

In EMERGY analysis, as in all investigations into the nature of things, it is essential that the system be diagrammed and understood as completely as possible prior to evaluation. For comparative purposes Fig. 13 and Fig. 14 show the same simple aggregated system and two disaggregations. In the top diagram of Fig. 13, all that is 'known' is that the process has a single output. The total inflowing EMERGY is assigned to the output and its transformity is 1000 sej/J. However, when the system is studied in more detail, it is revealed that the system is composed of two processes, A and B (Fig. 13b). The revealed internal structure does not change the transformity of the output, however, we now have a new 'intermediate' product (A) whose transformity is 10 sej/J. Further study reveals there is a feedback from B to A (Fig. 13c). The new information does not change the previously calculated transformities, but does allow us to calculate a third, whose value is 111 sej/J.

Two aspects of EMERGY analysis are important in this example: first, because of the feedback from B, EMERGY analysis assumes that the process cannot be 'decomposed' into two separate processes, one that makes product A and one that makes product B. And second, neither of the outputs from B can be produced without the other. In this way all input EMERGY is assigned to both outputs, since it takes the entire input to produce both outputs. In all, the new information does not change previously calculated transformities but does allow for calculation of additional transformities for the newly revealed internal structure.

Energy analysis, on the other hand, has no set rule for manipulating by-products. Since the matrix process by which embodied energy is calculated cannot handle two different outputs from the same process, it must divide the process into two different processes or assume the products are the same. Operationally, for processes like that in Fig. 13c, energy analysis must either split them into two different processes, or assume that the outputs are the same product. Obviously, the first is to be preferred. For instance, if the process B is a sawmill producing sawdust (B_2) and lumber (B_1), to assume that sawdust and lumber are the same is a fatal error, especially if one were purchasing a material with which to build a house. However, there is a flaw in splitting any process into different processes for the sake of the convenience of the tool by which accounting is preformed. The flaw is simply one of logic. They are not two different processes and the by-product cannot be produced separately. Assuming the sawmill process can be separated into a process of making lumber and one of making sawdust and that the two processes can exist independently is inconsistent with reality. The first is not possible in a thermodynamic world and the second may be possible, but not competitive in a world that prizes order over disorder.

The EA 'by-products flaw' leads to another problem that has to do with reproducibility. When a process that has by-products is split into two different processes, some decision has to be made concerning the energy inputs and how much of the inputs will be assigned to each of the new, separate processes. If all the energy inputs are assigned to both processes, the assignment violates the basic EA rule that all systems conserve, since assigning the entire amount to both processes will double count the input. The only other alternative is to split the inputs between the two new processes, with an infinite number of possibilities for their allocation. Depending on how input energy is assigned, embodied energy and intensities of outputs will be quite different. There is no rule that suggests how the input energies should be allocated and thus, depending on who does the analysis, the results might vary.

5.5. Disaggregation, by-products and splits (Herendeen)

There *is* an aggregation problem which EA handles as follows. Suppose we have an aggregated system with one energy input and one observed commodity output. The energy intensity of the output is (energy flow in)/(output flow). If we later learn that this system actually has the potential to produce two outputs, then revealing the internal flows should tell us the energy intensity of the second product, but not change the intensity of the first. This is different from the situation in Fig. 5 where we know already that the system can produce more than one output, and for which we now require internal details to decide how to allocate inputs to those outputs.

EA's position is illustrated by Fig. 14. In Fig. 14, 1000 kcal day^{-1} enter, and 1 kcal day^{-1} of product B exit. Therefore $\epsilon_B = 1000$ kcal/kcal. In Fig. 14b and c, additional structure is revealed and we see that the system can produce another product A. In Fig. 14b there is no feedback, and EA, using Eq. (2), gives $\epsilon_A = 10$ kcal/kcal and $\epsilon_B = 1000$ kcal/kcal. In Fig. 14c there is feedback and EA gives $\epsilon_A = 100$ kcal/kcal and $\epsilon_B = 1000$ kcal/kcal. This shows that the intensity of the revealed new product (A) depends on the details of the revealed internal structure, but that the intensity of the sole product known in the aggregated case (B) is unaffected by the revealed internal details. Disaggregation gives us new results for things we learn about only by disaggregating, but does not require us to change what is known about the aggregated system (end Herendeen).

6. Summary

This joint paper was undertaken as a means of illustrating the similarities and differences between energy analysis and EMERGY analysis. One important similarity is apparent: intensities and transformities are analogous concepts, although, in practice they differ markedly because of the energies included and methods employed in their calculation. Differences between the two methods stem from different conceptual underpinnings and accounting procedures.

Probably the most significant difference is related to the 'form' of EMERGY and embodied energy. EMERGY is defined as the energy of one type (usually solar energy) that is required to produce something. Energies of different types (i.e., solar, tidal, chemical potential energy in rain, fuels, or electricity) are expressed in the equivalent solar energy required to make them. Embodied energy analysis, as practiced, uses strictly the heat energy of fuels and does not include environmental energies. The embodied energy in goods and services, for instance, does not include the environmental support that is derived from solar, geophysical and tidal energies that drive all economies. It is suggested that these energies could be included, but there is no formal way of including them, no intensities have been calculated for them, and the fact that the biosphere is a single process with multiple outputs precludes the use of the matrix inversion process for their calculation.

EMERGY analysis includes the service input of humans in all evaluations, and does so by considering that the work output of humans is one of several multiple outputs and therefore the total EMERGY support to humans is assigned to their work. Embodied energy analysis routinely does not include human service inputs to processes, but it can. When it does, EA considers their work output to be only some fraction of the total fuel energy used in their support.

Another significant difference is related to the system properties of EMERGY and embodied energy. EMERGY is a system property and is defined as the energy required to produce something. Processes (or systems) having more than one output which cannot be decomposed into separate processes require all the inflowing EMERGY for the production of each output. Energy analysis, on the other hand. chooses to assign embodied energy in a manner that cannot account for multiple products from one process without additional assumptions. Thus processes with multiple outputs are either decomposed into separate processes, each having a single output, or outputs are treated as if they were the same product, or multiple products are ignored in favor of a single output. We can imagine the possibility that EA might attempt to incorporate additional assumptions to cover by-products, but that does not seem imminent.

EA and EMA differ markedly on accounting for feedback flows in a web, rather than a chain, system structure. EMA truncates feedbacks to assure that EMERGY flows within the system cannot exceed EMERGY inputs to the system. EA appeals to a physical model to argue that such apparently-too-large internal flows actually can exist, and that they should be accepted rather than proscribed.

EA has no optimizing principle. An implicit EA goal, often explicit in practice, is to minimize conventional (fossil and hydro) energy inputs per unit of desired system output, everything else being equal. EMA is more definite: the best policy is consistent with the Maximum EMERGY Principle. EA admires the intuitive attractiveness of this principle, but questions its usefulness now. First, the statement is still ambiguous, replacing the term to be defined (maximum EMERGY) with another, undefined term (useful work). Second, there appears to be ambiguity about applicable time scale.

It is quite apparent that EMERGY and embodied energy are two very distinct concepts. EMERGY analysis recognizes and, in fact, has pioneered the concept of energy 'form,' developing the conceptual and empirical basis that all energies are not of the same quality. Embodied energy analysis, and the units of embodied energy, do not recognize the qualities of energy across the energy spectrum of the biosphere, but instead account for only what has been termed 'cultural' energies. In so doing about half of the total energy driving the economies of the biosphere is ignored.

We both acknowledge that EMA attempts a bolder and more comprehensive synthesis of interdependencies driving ecological systems and the economic systems that depend on them than does EA. The question raised by EA is whether the assumptions of EMA, especially regarding bookkeeping of flows and calculations of interdependency, are useful and defensible. We hope this paper will help interested readers to participate in the continuing discussion.

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