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Energy analysis and EMERGY analysis—a comparison

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1. Introduction

The dialog between energy analysis (EA) and EMERGY analysis (EMA) is imbedded in the larger search for indicators to guide our lives and behaviors in environmentally desirable directions. Both have policy overtones as well as scientific underpinnings. EMA is the more ambitious of the two: it has a broader purview, it is bolder in claiming a direct connection to economics and it has an internal optimizing principle. With such ambitions, EMA is more subject to criticism, and more likely to fail in its putative policy uses, but EA is hardly immune. Criticism of both came from without, especially from economists concentrating on application. Criticism of each also came from the other, often concentrating on details of accounting and bookkeeping: how to calculate and use the quantitative results. This article will concentrate on these latter issues.

Mark Brown (an EMA developer and user) and I (an EA developer and user) published a detailed comparison in 1996. This was after a number of partial dialogues between H.T. Odum (the originator of EMA) and me. In 1996 Odum published the book *Environmental Accounting*, which explicitly laid out the accounting rules for EMA, which Brown had already used in preparing our joint article. Unfortunately, that book does not present a consistent comparison of EA and EMA applied to *the same system*, and Brown and Herendeen (1996) remains as the only such comparison. Thus, the present article is a reaction to the 1996 Odum book, although it is actually a restatement of the 1996 Brown and Herendeen article. Now, as then, Brown and I agree to disagree on the validity and usefulness of several applications of EMA and EA. In further interactions with Brown and with Odum, I have come to respect EMA more as a large view of ecology supporting humankind and a vivid portrayer of our dependence on the sun directly and indirectly. But to do this I have come to expect less of EMA as a prescriptive tool, as a guide for what to do. This brings its ambitions into line with the more modest ones of EA.

In Section 2, I give a broad comparison of EMA and EA. In Section 3, I discuss EA and EMA in more detail, summarizing the issues in Table 1. In Section 4, I present the Brown and Herendeen comparison of EA and EMA applied to a simple model ecosystem. This illustrates the differences quantitatively.

2. EA and EMA-A broad comparison

The overall context is that of a human economic/social subsystem of the biophysical environment, all driven by the dissipation of free energy. (Natural) ecological systems are almost exclusively powered by current sunlight, while economic and social systems have the added use of fossil fuel. Both EA and EMA address the indirectness of a system's dependence on energy in all interactions between system components (here called "compartments"). Thus,

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Table 1
Detailed dialog comparison of EMA and EA (based on Brown and Herendeen, 1996)

Issue	EMERGY analysis (EMA) proponent's view	Energy analysis (EA) proponent's view
1. Why do this analysis?	In order to quantitatively evaluate public policy options, environmental impacts and to lend quantitative insight into questions of resource management. EMERGY analysis expresses all energies and resources in the same type of energy . . . most often in solar EMERGY	Energy is important, more so than monetary price implies. For example, energy is a good first-order indicator of environmental impact. Indirect effects are important, and EA explicitly addresses them. Results are to be used in conjunction with other indicators, likely including economic and ecological ones. The approach is easily extended to indirect effects in materials, pollution, and employment
2. What are applications?	Policy analysis, net energy analysis, import–export balances	Policy analysis, net energy analysis, import-export balances
3. What are connections to economic analysis?	Strong connection through revolutionary and controversial conversion of EMERGY to monetary equivalents. Not covered in this article	Mostly conventional: combine EA results with "right" prices. Not covered in this article
4. Transformity/energy intensity	Central concept. Indirect effects are quantified. The EMERGY required to produce a good or service divided by the energy of the good or service equals its transformity	Central concept. Indirect effects are quantified. Embodied energy = the direct and indirect energy required to produce a good, service, or entity
Discussion	While EA quantifies indirect energy it does not account for energy of different types. EA does not explicitly require that all energy be expressed as energy of one type	EA has used different types of energy (coal, crude oil, natural gas, nuclear and hydro) in the same analysis (Bullard et al., 1975). In ecological applications, EA can account for trophic levels and positions
5. Is there an internal optimizing principle?	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	EA has no optimizing principle. There is often an underlying assumption that minimizing non-renewable energy inputs is desirable, but that follows from an external constraint
Discussion		The Maximum EMERGY Principle is incomplete, basically replacing the term to be defined (maximum EMERGY) with another, undefined term (useful work)
6. Choice of flow variable(s)	The flow variable is usually energy, although mass is sometimes used	The flow variable can be energy (in ecological applications, for example), but usually is not in economic applications: dollars of product, tons of steel, liters of herbicide, etc. Different units can be used for different compartments. Comparing results with different flow variables is often insightful, e.g., biomass energy vs. nutrient in ecosystems (the latter have more feedback) (Herendeen, 1990)
Discussion	EA's allowance for anything as a carrier produces quite different results in the same system if analyzed using different carriers. This is because energy, dollar, and nutrient flows are not analogous	EMA's preoccupation with energy as carrier has reduced attention to feedback and produced accounting rules that are confounded and cumbersome when feedback occurs
	EMA accounting rules are straightforward and easily mastered. All feedbacks within a system are explicitly dealt with	EMA's rules on double counting prematurely truncate feedback loops

Table 1 (*Continued*)

Issue	EMERGY analysis (EMA) proponent's view	Energy analysis (EA) proponent's view
7. Accounting procedures	All energy required to make a product is accounted for in energy of one type. This includes renewable, non-renewable and energy in services. There are Four Rules for accounting: see section 3. The ratio of EMERGY flows so reckoned, to original energy flows, is transformity	Every compartment is in embodied energy balance, as expressed in Fig. 1. This balance is an assumption, and not a direct consequence of the First Law of Thermodynamics. The same "conserving" accounting is used for applications of the method to materials, pollution, and employment. Resulting equations yield energy intensities, measured in units of energy/(flow variable). Embodied energy flows = (energy intensity)*(flow)
8. How are by-products dealt with?	Byproducts are necessary outflows from most processes and as such must be accounted for. In some case they are useful, for instance, sawdust may be burned to generate steam. In other cases they are not immediately useful, such as lignin wastes from a pulp mill. Nevertheless, they are outputs and their EMERGY content is equal to the sum of the EMERGY inputs to the process. EA has no explicit method for dealing with byproducts, but must assume them away to satisfy a conservation principle	EA performs a necessary but transparent manipulation to remove byproducts to prevent what EA considers double counting
Discussion	Byproducts cannot be dealt with using the EA method. Therefore they are either assumed not important and neglected, or a process that generates more than one output is split into a number of process that equal the number of outputs	It is true that EA's manipulation is equivalent to assuming that byproducts can be produced separately. This is unfortunate, but is the price paid for conservation of embodied energy. It is impossible to conserve embodied energy while tracking byproducts as EMA does. One must choose between the two approaches
9. Relationship of interior flows to system inputs	The Four Rules above forbid any interior EMERGY flow to exceed summed EMERGY inputs to system. Fig. 6 shows this	Interior embodied energy flows can exceed summed embodied energy inputs to system. Fig. 5 shows this. All compartments are still in balance, as is entire system. It quantitatively reflects the effect of feedback on flows
Discussion	The fact that interior flows of embodied energy can exceed input flows makes it difficult to balance units	The bookkeeping that produces this apparent contradiction for embodied energy also predicts that nutrient flows should show the same effect. But nutrient flows are measurable. Therefore, the effect is real and the bookkeeping is valid
10. Relationship of system output to system input	A consequence of the Four Rules is that inputs can be larger than, equal to, or smaller than outputs	The assumption of embodied energy balance in every compartment requires total system balance as well
11. Relative weight given to higher vs. lower ("trophic") levels, as indicated by transformities and energy intensities	EMA attaches more relative importance to higher order pathways than does EA. This importance is indicated by the ratio of the largest to smallest transformity (for EMA) or of the largest to smallest energy intensity (for EA)	It can go either way depending on the details of the original energy flows. What is "high" and "low" depends on the degree of feedback. For a linear chain without byproducts, EMA's transformities = EA's energy intensities. In EA, a feedback-rich system will tend to have less disparity in energy intensities of different compartments

Table 1 (*Continued*)

Issue	EMERGY analysis (EMA) proponent's view	Energy analysis (EA) proponent's view
Discussion	Proponents of EA assume that because feedback flows often have more embodied energy assigned to them than the sum total of inputs, they somehow account for feedback better than EMA. Yet the fact that they do not reflect the hierarchical structure of systems (i.e. "they tend to have less disparity. . . ") shows that EA does not account adequately for the value of higher order flows and compartments	EMA's Rule 4 against "double counting feedback energy" diminishes feedback's role, which tends to support EMA's claim. However, the EMA rules on byproducts can reverse this, as can be shown explicitly. But the real question is "What is the meaning of hierarchy in a feedback-rich system?" EA lets the feedback answer that question. If herbivores also eat detritus, that will affect how much sunlight is required to produce a carnivore that eats the herbivore. EA deliberately includes the effects of this feedback, as it should. EMA truncates these effects
12. Is human labor included?	It routinely is, because not to count labor leaves out a significant portion of the energy required to make economic products	It can be, though EA usually does not include it. A common application of energy intensities has been to investigate the energy requirements of different consumer spending patterns ("market baskets"). Including labor as an aggregated sector with an immutable market basket negates this idea
13. Is renewable energy included?	Because renewable energy accounts for roughly half the total energy driving the combined system of humanity and nature, EMA routinely includes it	EA was originally developed for fossil and hydro energy, but renewable energy can easily be included
Discussion	Proponents of EA suggest renewable energy can easily be included in the analysis; however routinely it is not included and in those rare occasions where it is included, it is quantified as heat energy of sunlight, with no accounting of rain, tides, waves, etc. and their differing qualities	EA does not attempt to quantify, comprehensively, in energy or other terms, the environmental services that support human activity. This laudable objective is pursued by EMA

in both approaches an eagle is made of sunlight and a potato is made of sunlight and oil. Odum said the latter in *Environment, Power, and Society* in 1971 (Odum, 1971).

2.1. Energy analysis (EA) and embodied energy

Energy analysis is the process of determining the energy (actually, free energy in thermodynamic terms) 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 calculating embodied anything, for example, copper, SO_2 (Leontief, 1970, 1973), nitrogen (Herendeen, 1990), or labor (Bezdek and Hannon, 1974).

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. There are two things EA does not do:

1. EA does not have an internal optimizing principle. (EA's results can be used to implement external

principles such as minimum fossil fuel use, minimum CO_2, release, or maximum net energy return.)
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 analysis (EMA), transformity, and maximum EMERGY (based on Brown and Herendeen, 1996)

EMA determines the values of non-monied and monied resources, services and commodities in common units of the solar energy it took to make them (called solar EMERGY) (Odum, 1975, 1983, 1988, 1991). One of its fundamental principles is the maximum EMERGY principle (Brown and Herendeen, 1996):

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.

The crux is the term "useful". Energy dissipation without useful 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. (Brown in Brown and Herendeen, 1996).

The Maximum EMERGY Principle suggests a system of value that is donor based rather than receiver based, that the value of something derives from how much goes into it rather than how much one is willing to pay for it. Any expenditure of energy has to return useful work equivalent to at least what was expended. Proponents of EMA believe that this holds for all systems over all time and spatial scales (Brown and Herendeen, 1996).

The EMERGY of renewable energies, nonrenewable resources, goods, services and even information, is the energy required to make them. When expressed as the amount of solar energy that was used, the units of EMERGY are solar EMERGY, the units of which are solar emjoules (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, one often uses transformities that have been previously calculated. (Likewise, EA often uses pre-calculated energy intensities, assuming that they apply to the current problem.)

3. Detailed comparison of accounting schemes

3.1. Energy analysis accounting procedures

The accounting framework for EA has been in the literature for 30 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 byproducts. 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 be resolved *only* by judgmental decision.

To determine the energy to produce a product, the most direct approach would be to perform a detailed "vertical analysis" (also called "process 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 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 of vertical analysis is Berry and Fels' (1973) study of automobile production.

Vertical analyses are expensive. To save money, analysts were drawn to the input–output (I–O) 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., Lawson et al., 2002) 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 (such as aggregation, and uncertainties in inflation and technical change over the inevitable several-year time lag) are listed in Brown and Herendeen (1996).

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

How EA calculates energy intensities is illustrated by Fig. 1. We start with compartment "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 ε_i, which defines the energy intensity of compartment i as ε_i. ε_i is measured in units of E (say kcal per day) divided by units of X_{ij} (say \$ per day) = (therefore) kcal \$$^{-1}$. The fundamental assumption of EA is that compartment j is in embodied energy balance. Fig. 1 thus represents a balance equation for the conservation of embodied energy:

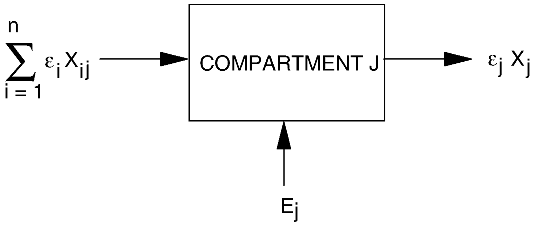

Fig. 1. The basic assumption of EA is that embodied energy inputs = embodied energy outputs for each compartment.

$$\sum_{i=1}^{n} \varepsilon_i X_{ij} + E_j = \varepsilon_i X_j \quad (1)$$

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

$$\underline{\varepsilon}\,\underline{\underline{X}} + \underline{E} = \underline{\varepsilon}\,\hat{\underline{\underline{X}}}$$
$$\underline{\varepsilon} = \underline{E}(\hat{\underline{\underline{X}}} - \underline{\underline{X}})^{-1} \quad (2)$$

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

To reemphasize, the balance diagram in Fig. 1 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 compartment-by-compartment balance of embodied energy is an *assumption* of EA. EA argues that this assumption captures the intent of calculating indirect effects: to allocate something normally not accounted for, to the products ultimately produced. The "something" may be dissipated (e.g., energy or labor; Bezdek and Hannon, 1974) or it may not (e.g., nutrient, if it is never "leaked"). In the case of "non-leaked" nutrient the assumption is equivalent to conservation of mass (Herendeen, 1990), but in general this bookkeeping scheme has nothing fundamental to do with any thermodynamic law.

Compartment-by-compartment 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

$$\sum_{i=1}^{n} E_i = \sum_{i=1}^{n} \varepsilon_i Y_i \qquad (3)$$

where

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

where Y_i is 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 energy is not available 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. Because this is a bone of contention between EA and EMA, I discuss it in detail next.

Consider Fig. 2a. In this system, biomass energy is the numeraire, there is feedback (the biomass flow from B to A), 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 of compartment B, as shown in Fig. 2b. The resulting nutrient intensities are $\eta_A = 2\,\mathrm{g\,kcal}^{-1}$ and $\eta_B = 20\,\mathrm{g\,kcal}^{-1}$. The internal embodied nutrient flows $A \rightarrow B$ and $B \rightarrow A$ do exceed the system input of 20 g per day. 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 $B \rightarrow A$. The key point here is that we are discussing flow as distinct from stock. If one measures the nutrient flux (g per day) one will find that this much nutrient actually does flow. Because this flux

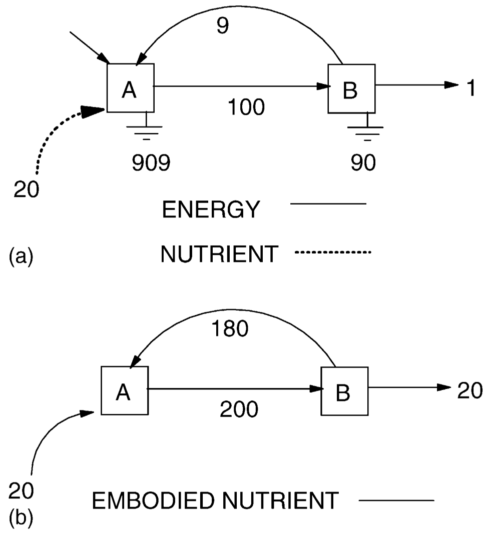

Fig. 2. (a) Flows in feedback system with nutrient input. "Energy" is metabolizable biomass or heat. Each compartment is in balance by The First Law of Thermodynamics. Units: energy, kcal/time; nutrient, g/time). (b) Embodied nutrient flows for system in (a). This follows from Eq. (2), which is solved to give nutrient intensities of $\eta_A = 2\,\mathrm{g\,kcal}^{-1}$ and $\eta_B = 20\,\mathrm{g\,kcal}^{-1}$.

is measurable for a non-dissipated input, EA argues that it is permissible, in fact desirable, to use the same accounting scheme for the embodied flows of a dissipated input such as energy.

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. 2. If a compartment has multiple outputs (e.g., a factory producing both crude iron and finished steel automobile parts), but there are still n total products for n compartments, then there are at least two manipulations which reduce the problem to the form in Fig. 2. If there are more outputs than compartments, there is a manipulation ("market shares" assumption) which again reduces the problem to the form in Fig. 2. If there are byproducts (e.g., leather from a slaughterhouse whose primary product is meat), EA, following I–O, manipulates to assume them away. Examples are in Brown and Herendeen (1996). There is no way to maintain conservation of embodied energy, materials, etc., if the product and byproducts are independently assigned the total input to produce product and byproduct 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 byproduct option.

3.2. EMERGY accounting procedures

There are four rules that are followed to assign EMERGY to flows of energy (Brown and Herendeen, 1996).

Rule 1	All source EMERGY to a process is assigned to the process's output(s)
Rule 2	Each byproduct from a process has the total EMERGY assigned to each pathway
Rule 3	When a pathway splits, EMERGY is assigned to each "leg" of the split based on its percent of the total energy flow on the pathway

The difference between byproducts and splits of the same output is important. Many processes produce more than one output (for instance, a saw mill that produces lumber and sawdust or a manufacturing process that produces a good and one or more "waste" byproducts). Byproducts by definition must be produced together; therefore, EMA assumes the total EMERGY input is assigned to each output.

The fourth rule describes how EMERGY is assigned within systems of interconnected components.

Rule 4 EMERGY cannot be counted twice within a system
- (a) EMERGY in feedbacks cannot be double counted
- (b) Byproducts, when reunited, cannot be added to equal a sum greater than the source EMERGY from which they were derived

Rules 2 and 3 are illustrated in Fig. 3a and b. In Fig. 3b the treatment of byproducts (Rule 2) results in an EMERGY input of 500 units but an output of 1000 units. Rule 4 will be illustrated in the comparison of EA and EMA in Section 4. EA accepts Rules 1 and 3, but disagrees with Rules 2 and 4. Table 1 summarizes this comparison of EA and EMA.

4. Numerical comparison of EA and EMA of the same system

Fig. 4 shows energy flows (sunlight and metabolizable biomass) in an idealized five-compartment

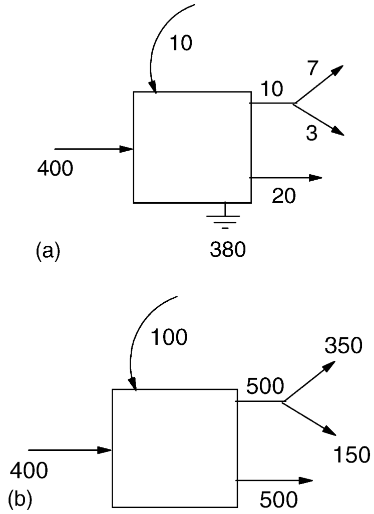

Fig. 3. (a). Energy flows in system for illustrating EMA's treatment of byproducts and splits. "Energy" is metabolizable biomass or heat. Balance is a consequence of the The First Law of Thermodynamics. The flows of 10 and 20 are byproducts; the flows of 7 and 3 are splits. (b) EMERGY flows for system in (a). It is assumed that the flow in from the top in (a) has a transformity of 10 sej/J. Because of EMA's treatment of byproducts, the system in (b) has an output that is twice the input.

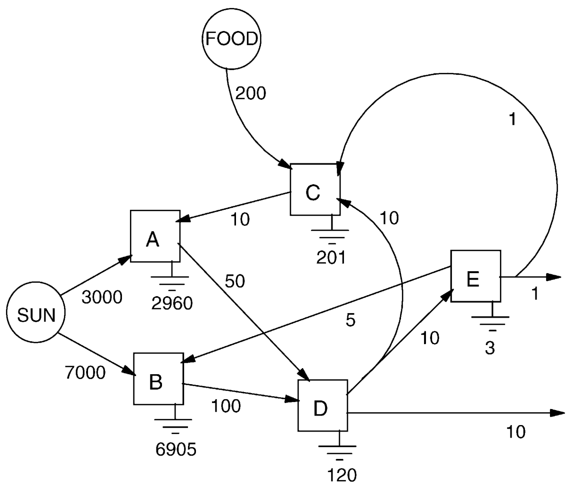

Fig. 4. Energy flows in an idealized, steady-state ecosystem. All units are J/time. System inputs are sunlight to compartments A and B, and imported food to compartment C. System outputs are exports from compartments D and E (plus waste heat from all compartments).

Table 2
Steady-state energy flows in Fig. 4

From/to	A	B	C	D	E	Dissipation	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/time. The sum of actual energy inputs, 10,200, exactly balances the sum of dissipation and exports by the First Law of Thermodynamics.

ecosystem. Two compartments are producers, fixing sunlight. The other three are consumers and feed on the first two compartments or, for compartment 3, on imported food. Table 2 is a flow table equivalent to Fig. 4. Table 2 also states that the food imported to compartment C already has an energy intensity or transformity of 100 J/J, so that the flow of 100 J/time requires a flow of 20,000 J/time somewhere in the sub-system that provides that food. The system has both split and byproduct flows in places. This diagram first appeared in Brown and Herendeen (1996) and Odum (1996).

Figs. 5 and 6 show embodied energy and EMERGY flows, respectively, calculated according to Eqs. (1) and (2) and the four EMERGY rules in section 3, respectively. It should be noted that the dissipation flows in Fig. 4 are absent in the flows shown in Figs. 5 and 6. That is the essence of indirectness; by removing them we assure that their impact is embodied in the flows we retain. This has caused some confusion, even in Odum (1996), Fig. 14.6(b), where a proper removal would give energy intensities that are approximately an order of magnitude larger that those listed there. Figs. 7 and 8 show the energy intensities and transformities. The several concerns so far mentioned apply to these figures because the system has much feedback. Thus:

1. While all compartments are in balance in embodied energy, for EMERGY, compartments A and B have more “in” than “out”, compartments D and E have more “out” than “in”, and compartment C is in balance.
2. The entire system is in balance for embodied energy, but not for EMERGY: more EMERGY leaves than enters.

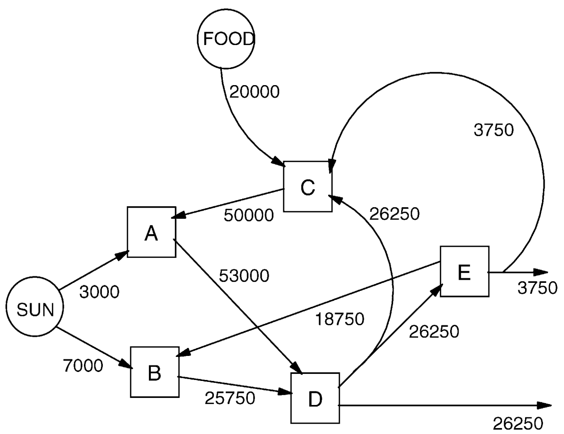

Fig. 5. Embodied energy flows for Fig. 4 determined using EA. Units = J/time.

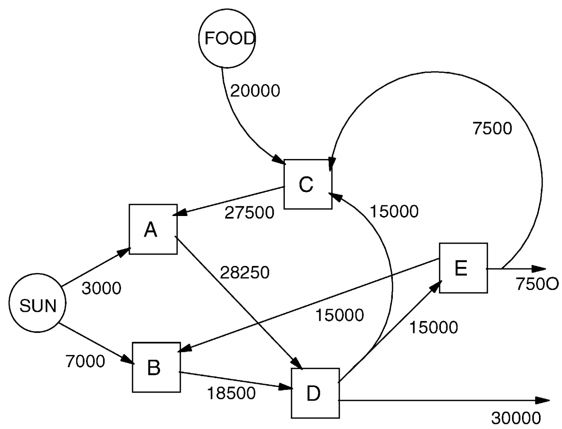

Fig. 6. EMERGY flows for Fig. 4 determined using EMA’s Four Rules. Details are given in the notes to Fig. 6.8 of Odum (1996). Units = J/time.

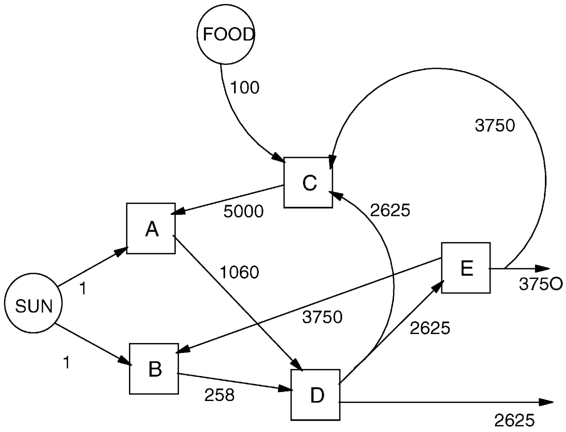

Fig. 7. Energy intensities for Fig. 4. These are the embodied energy flows in Fig. 5 divided by the corresponding energy flows in Fig. 4. Units = J/J.

3. Energy intensities for all flows from a given compartment are equal, but this is not always true for transformities.
4. For embodied energy, flows internal to the system do sometimes exceed the sum of embodied energy inputs to the system (30,000 J/time). For EMERGY this does not occur.

As discussed above, all of these differences are expected.

The differences disappear for a strictly hierarchical system, which would be represented as a linear chain with no feedback. EMA deliberately truncates feedback effects when they have looped back to the source, maintaining an essence of hierarchy. EA allows feedback to circulate freely as would be expected in a physical model of feedback. EA argues that a system with strong feedback is by definition no longer hierarchical and that energy intensities and embodied energy flows should reflect this.

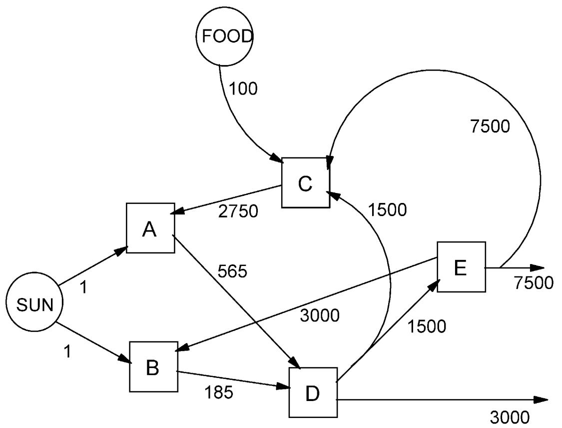

Fig. 8. Transformities for Fig. 4. These are the EMERGY flows in Fig. 6 divided by the corresponding energy flows in Fig. 4. Note different transformities for different outputs of compartment D. Units = 5ej/J.

References

Berry, R.S., Fels, M., 1973. Energy cost of automobiles, Bull. Atom. Scientists 29, 11–17, 58–60.

Bezdek, R., Hannon, B., 1974. Energy, manpower, and the highway trust fund. Science 85, 669–675.

Brown, M.T., Herendeen, R., 1996. Embodied energy analysis and EMERGY analysis: a comparative view. Ecol. Econ. 19, 219–236.

Bullard, C., Herendeen, R., 1975. The energy costs of goods and services. Energy Policy 3, 268–278.

Bullard, C.W., Hannon, B., Herendeen, R., 1975. Energy flow through the United States economy. Wall Chart, University of Illinois Press, Urbana.

Bullard, C., Penner, P., Pilati, D., 1978. Net energy analysis: handbook for combining process and input–output analysis. Resour. Energy 1, 267–313.

Chambers, R.S., Herendeen, R.A., Joyce, J.J., Penner, P.S., 1979. Gasohol: does it or doesn't it . . . produce positive net energy? Science 206, 789–795.

Chapman, P., 1975. Energy analysis of nuclear power stations. Energy Policy 3, 285–298.

Denton, R.V., 1975. The energy costs of goods and services in the Federal Republic of Germany. Energy Policy 3, 279–284.

Finn, J.T., 1980. Flow analysis of models of the Hubbard Brook ecosystem. Ecology 6, 562–571.

Finn, J.T., 1976. Measures of ecosystem structure and function derived from analysis of flows. J. Theor. Biol. 56, 115–124.

Hannon, B., 1973. The structure of ecosystems. J. Theor. Biol. 41, 535–546.

Herendeen, R., 1978. Total energy cost of household consumption in Norway, 1973. Energy 4, 615–630.

Herendeen, R., Ford, C., Hannon, B., 1981. Energy cost of living, 1972–1973. Energy 6, 1433–1450.

Herendeen, R., 1988. Net energy considerations. In: West, R., Kreith, F. (Eds.), Economic Analysis of Solar Thermal Energy Systems. MIT Press, Cambridge, MA, pp. 255–273.

Herendeen, R., 1990. System-level indicators in dynamic ecosystems: comparison based on energy and nutrient flows. J. Theor. Biol. 143, 523–553.

Herendeen, R., Kary, T., Rebitzer, J., 1979. Energy analysis of the solar power satellite. Science 205, 451–454.

IFIAS, 1974. Energy Analysis Workshop on Methodology and Conventions. International Federation of Institutes for Advanced Study, Nobel House, Stockholm, Sweden, 89 pp.

Lawson, A., Bersani, K., Fahim-Nader, M., Guo, J., 2002. U.S. Department of Commerce, Benchmark Input–Output Accounts of the United States, 1997. Survey of Current Business 82 (12), 19–109.

Leontief, W., 1970. The dynamic inverse. In: Carter, A., Brody, A. (Eds.), Contributions to Input–Output Analysis. Elsevier, New York.

Leontief, W., 1973. Input–Output Economics. Oxford University Press, New York.

Odum, H.T., 1971. Environment, Power, and Society. Wiley, New York.

Odum, H.T., 1975. Energy Quality and Carrying Capacity of the Earth (Response at Prize Ceremony, Institute La Vie, Paris). Trop. Ecol. 16 (1), 14. (CFW−75−33).

Odum, H.T., 1983. Systems Ecology: An Introduction. Wiley, New York, NY, 644 pp.

Odum, H.T., 1988. Self−organization, transformity, and information. Science 242, 1132–1139 (CFW−88−12).

Odum, H.T., 1991. Emergy and biogeochemical cycles. In: Rossi, C., Tiezzi, E. (Eds.), Ecological Physical Chemistry, Proceedings of an International Workshop, 8–12 November 1990, Elsevier, Amsterdam, 16 pp.

Odum, H.T. 1996. Environmental Accounting. Wiley, New York.

Patten, B., Higashi, M., Burns, T., 1990. Trophic dynamics in ecosystem networks: significance of cycles and storage. Ecol. Model. 51, 1–28.

Peet, N.J., 1986. Energy requirements of the output of the New Zealand economy 1976–1977. Energy 11, 659–670.