EMERGY EVALUATION

Howard T. Odum
Environmental Engineering Sciences
University of Florida, Gainesville, 32611

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An extended explanation of emergy as an environmental accounting and assessment tool can be found in:
Odum, H.T. 1996. Environmental Accounting, Emergy and Decision Making. John Wiley, NY, 370 pp.

Abstract

After reviewing the concepts of energy hierarchy and scale, emergy terms are defined including transformity, emergy storage, empower, mass emergy, empower density, work and emdollars. Emergy is related to spatial centers and to pulsing with time. Evaluations include macroeconomics of states and nations and the economic-environmental interface of microeconomics. Emergy indices are used to evaluate alternatives for primary energy sources, environmental impacts, and international exchange. Maximizing empower is a policy criterion for selecting alternatives that maximize production and use of real wealth. Systems diagrams help clarify emergy evaluation for some of the many different ways and scales the human mind aggregates and simplifies the networks of society and environment. An example is included of emergy evaluation in a lawsuit.

1. Introduction, Energy Systems

In this chapter let's look at the basic energetics of systems to show how the work of nature and society can be evaluated on a common basis so as to select alternatives which succeed. Systems diagrams are used to clarify the simplifications that humans need in their window of attention.

The structures and storages that operate our world of humanity and environment are sustained against the depreciation of the second law by productive inputs for replacement and maintenance. Maximizing the products and services for growth and support appears to be a design principle of self organization as given by Alfred Lotka as the maximum power principle. Pathways in Figure 1 illustrate the flows and conservation of energy. The storage is represented with a tank symbol. The heat sink symbol represents the dispersal of available energy from processes and storages according to the second law. The feedback from right to left interacts as a multiplier increasing energy intake. This autocatalytic loop is one of the designs that prevail because they reinforce power intake and efficient use.

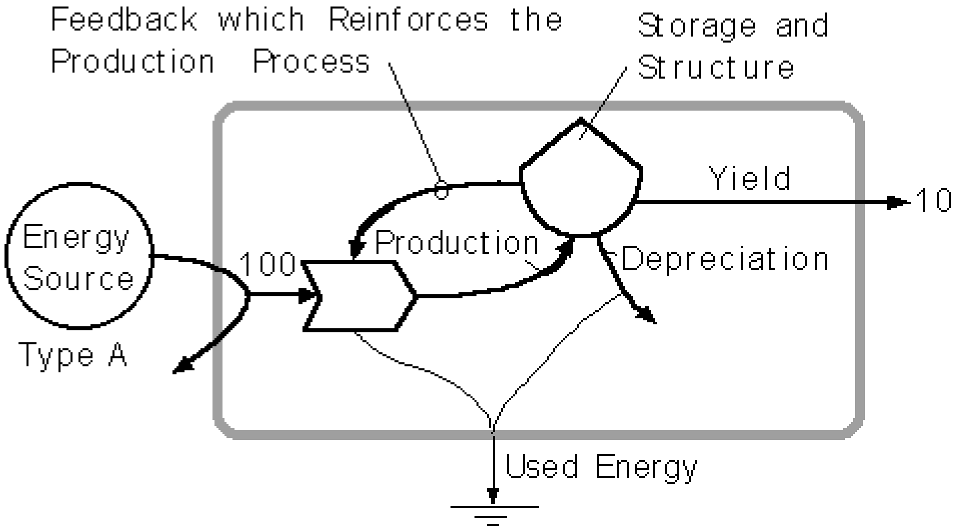

Figure 1. Energy transformation, storage, and feedback reinforcement found in units self organized for maximum performance. Energy systems symbols (3).

2. Energy Hierarchy

Self organization develops a network of energy transformations in a series. With Figure 2 we put our window of attention on a typical network of energy transforming components like the one discussed in Figure 1. From left to right the total quantity of energy decreases, but the quality increases (in the sense of more energy transformations required in the making). Since energy flows are converging at each step to make fewer flows of energy at the next, it is an energy hierarchy. Energy decreases from left to right, but the transformed energy increases its ability to reinforce other units of the system. Since all known processes can be arranged with each other in series network like that in Figure 2, the energy hierarchy appears to be a universal law. Examples are the energy chains in organisms, ecosystems, economies, earth processes, and the stars.

Work is defined here as the available energy degraded in an energy transformation. Since many joules of available energy on the left are required to make the successive transformations to form a few joules of available energy on the right, it is quite invalid to use joules of one kind of energy as equivalent to joules of another for purposes of evaluating contributions (1, 6). However, we can express each kind of available energy in units of one kind of available energy.

3. Emergy

Emergy (spelled with an "m") evaluates the work previously done to make a product or service. Emergy is a measure of energy used in the past and thus is different from a measure of energy now. The unit of emergy (past available energy use) is the emjoule to distinguish it from joules used for available energy remaining now. Scienceman describes emergy as energy memory (Odum, 4, 6, 10; Scienceman, 9, 10). A book summary of emergy concepts and accounting is available (6), and elementary introductions and examples are included in our new text on Florida (7). Definitions are summarized in Table 1.

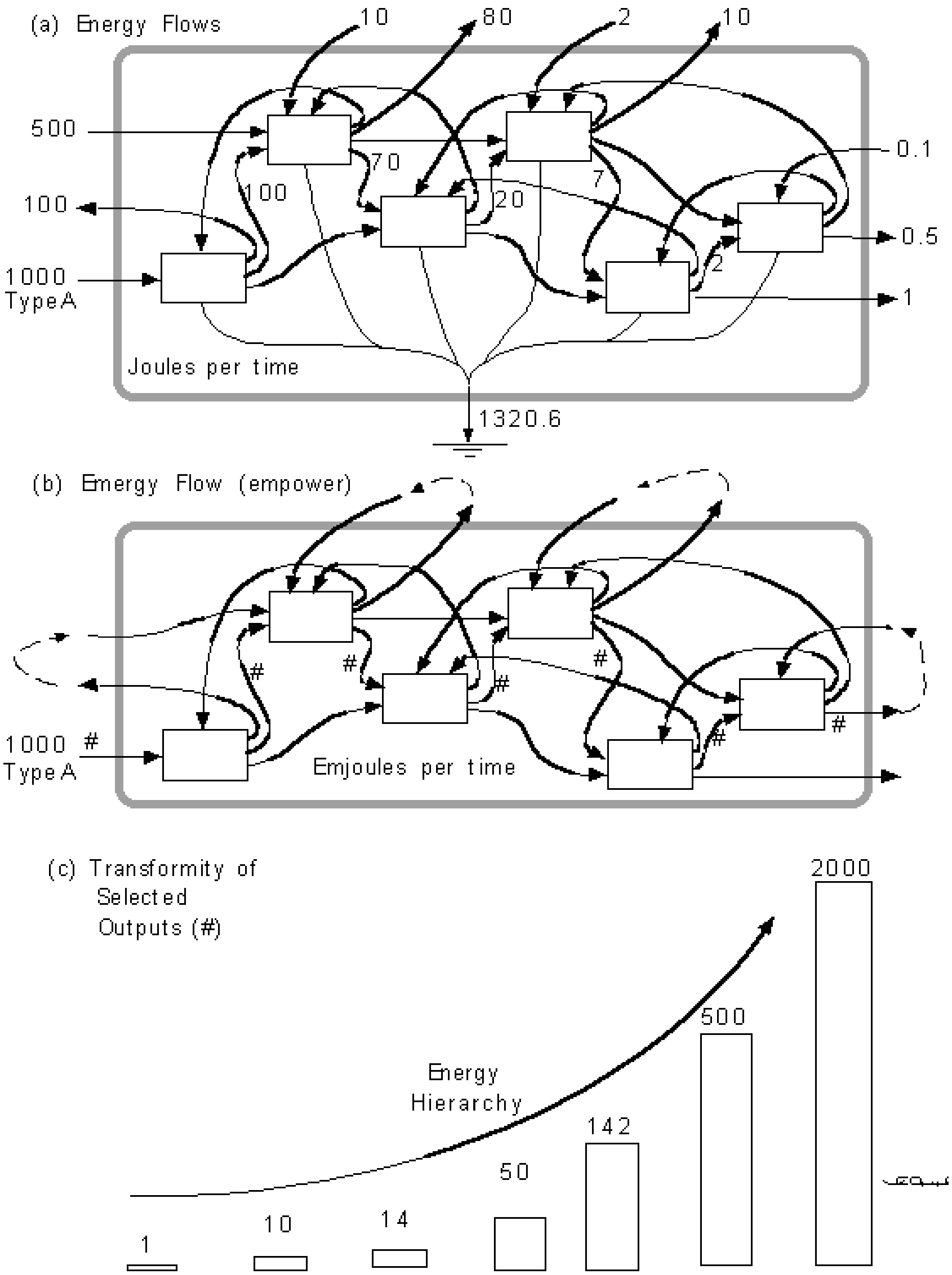

Figure 2. Systems window-view of a network of mutually necessary, energy transformation running on the same source.

There is a different kind of emergy for each kind of available energy. For example: solar emergy is in units of solar emjoules, coal emergy in units of coal emjoules, and electrical emergy in units of electrical emjoules. There is no emergy in degraded energy (energy without availability to do work). Like energy, emergy is measured in relation to a reference level. In most applications we have expressed everything in units of solar emergy.

4. Empower

The rate of emergy flow is named empower with units: emjoules per time. Flows of entirely different kind may be compared by expressing them all in empower units of the same kind such as solar empower or electrical empower. For the example in Figure 2b, which has only one independent source, the empower of all the pathways is 1000 Type A emjoules per time.

5. Transformity

The transformity is defined as the emergy (in emjoules) of one kind of available energy required directly and indirectly (through all the pathways required) to make one joule of energy of another type. Transformity is the ratio of emergy to available energy. In Figure 1 the transformity of the output is 10 type A emjoules per joule. With the units sej/J, transformity is not a dimensionless ratio. Ten ways of calculating transformities were suggested (6, p. 277). The most common way is to evaluate a system in which the item of interest is a product.

In going from left to right through the energy hierarchy in Figure 2, transformity increases greatly. Transformity measures the position of any energy flow or storage in the universal energy hierarchy.

A familiar plot in many fields of science is the graph of turnover time versus territory. Items of larger territory have longer turnover times. Transformity also increases with scale. In our systems diagrams, items are placed in their position according to their transformity. Scale of time, space, and transformity increases from left to right.

Table 1. Emergy and Related Definitions (6)

Available Energy = Potential energy capable of doing work and being degraded in the process (Units: kilocalories, joules, BTUs, etc.)
Useful Energy = Available energy used to increase system production and efficiency (units: available joules, kilocalories, etc.)
Power = Useful energy flow per unit time (units: joules per time)
Emergy = Available energy of one kind previously required directly and indirectly to make a product or service (units: emjoules, emkilocalories, etc.)
Empower = Emergy flow per unit time (units: emjoules per unit time)
Work = An energy transformation process which results in a change in concentration or form of energy.
Transformity = Emergy per unit available energy of one kind (units: emjoule per joule)
Solar Emergy = Solar energy required directly and indirectly to make a product or service (units: solar emjoules)
Solar Empower = Solar emergy flow per unit time (units: solar emjoules per unit time)
Solar Transformity = Solar emergy per unit available energy (units: solar emjoules per joule

Figure 3 summarizes the energy hierarchy of the biosphere starting with the abundant but dilute solar energy. The annual global emergy budget was calculated as the sum of solar energy, tidal energy, and geological deep energy contributing to surface transformations each expressed as solar emergy. Transformities increase to the right as energy flows decrease. Information has the highest transformities. The rate of use of fossil fuels emergy is now of the same order of magnitude as the other planetary inputs. As the global climate and other earth processes becomes coupled to this additional but temporary emergy source, rains, winds, and waves may be developing higher transformities.

The distribution of transformities is suggested with Figure 4, inverse to energy flow. Energy of one kind is effectively used only when it interacts with (amplifies) matching energy of lower or higher transformity. Thus there is an appropriate position in the energy spectrum for efficient use of each kind of energy.

In theory every item has a minimum transformity from the most efficient formation possible consistent with operations at the optimal loading for maximum empower. However, where a system is newly developed, is operating faster than the rate for maximum empower, or is otherwise inefficient, the transformity may be much higher than the thermodynamic minimum. Both transformities (a minimum value and the observed larger values) are useful, one to compare potentials, the other to evaluate current practices.

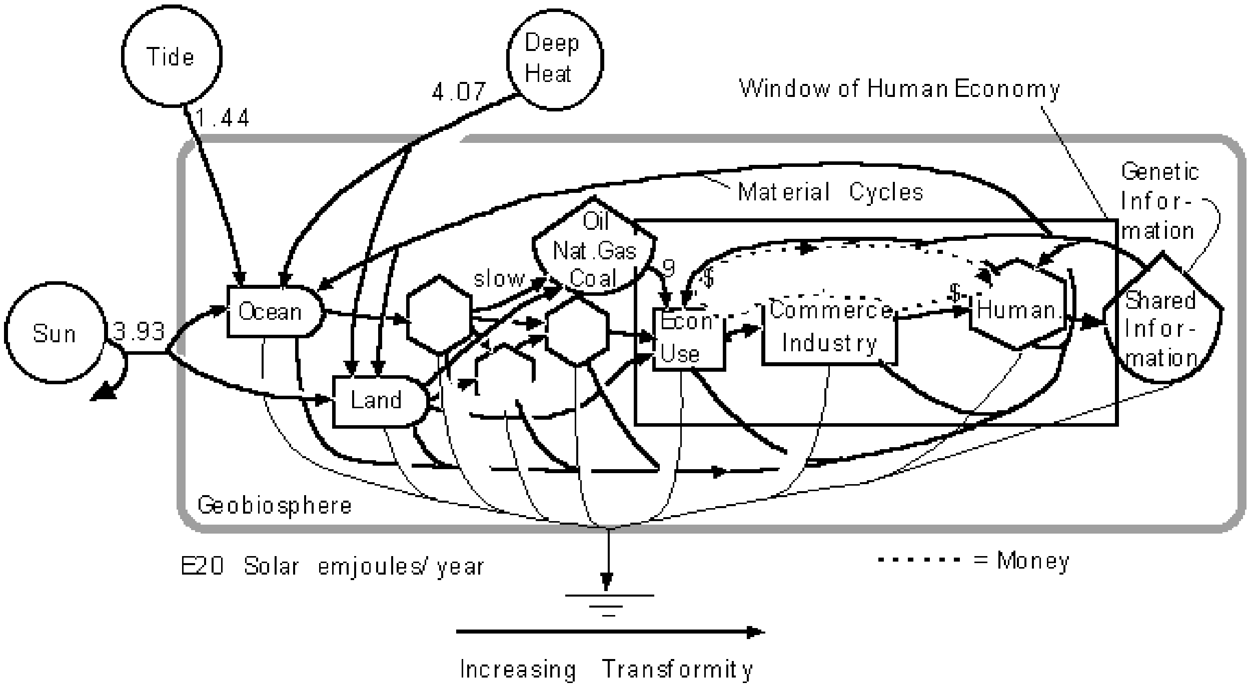

Figure 3. Aggregated view of the main energy hierarchy of the earth biosphere which starts with 3 main energy sources.

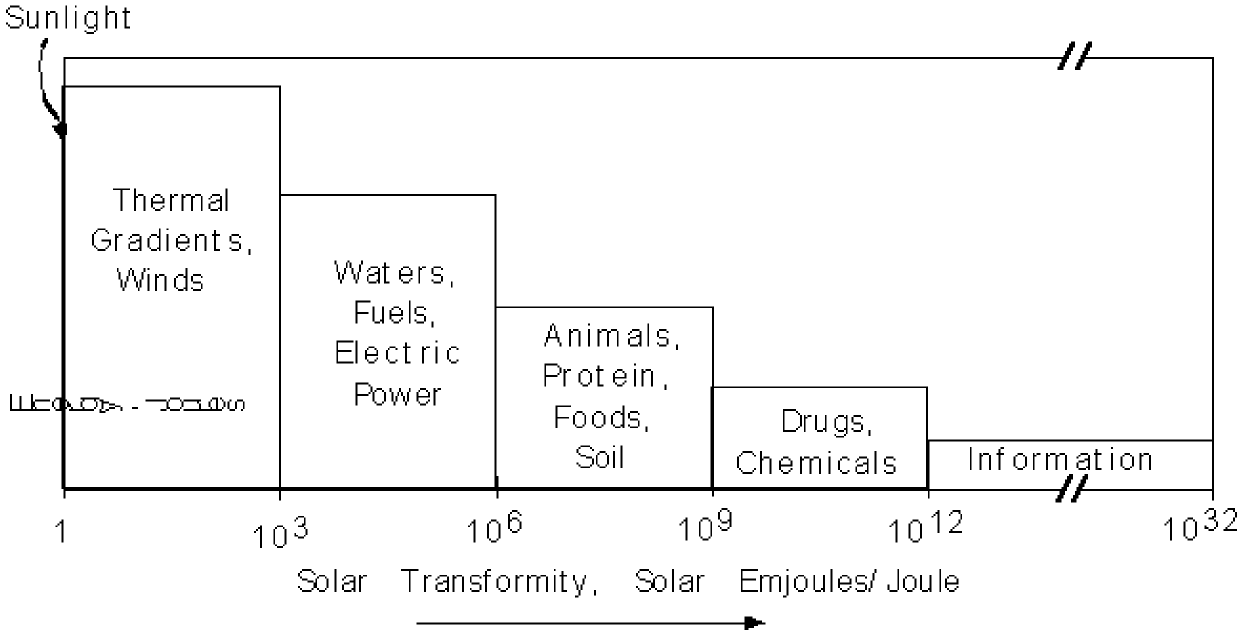

Figure 4. Distribution of transformities.

6. Centers of Spatial Organization

Self organization generates spatial centers as part of energy hierarchy. One reason is that spatial concentration is a way of making transformed high quality flows of less energy have a commensurate feedback effect outward to reinforce the system. Examples are the information centers of cities, the water convergence at the mouths of rivers, and the concentration of organic matter in tree trunks. Concentrations are readily measured as areal empower density with values ranging from less than 1 E11 sej/m2/yr in wilderness to 50,000 E11 sej/m2/yr in city centers.

7. Emergy and Matter

Flows and storages of matter carry available energy and emergy. Transformations that concentrate matter require emergy inputs. For example, emergy per mass of lead increases with lead concentration (8). For the practical purpose of making emergy calculations, it is convenient to develop tables of mass emergy (emergy per unit mass). McGrane (2) evaluated materials of the earth cycles. Traditional biogeochemical cycles should be redrawn to reflect their position in energy hierarchy according to their emergy/mass. Cycles of materials converge to hierarchical centers and diverge again as they return to more dilute environment. Emergy contribution of land can be evaluated from the erosion rate times the transformity of the geologic substrate, which was formed at an earlier time.

8. Emergy and Information

Information including learned information and genetic information has energy carriers (examples: paper, neurons, computer disk, sound waves), which can disperse, depreciate, and develop error. Information has emergy according to the emergy required to make and sustain it. Information is something which requires less emergy to copy than to generate anew. Although copying is cheap, maintaining information without error requires a population of duplicates and a circular process of duplication, dispersal, reapplication, selection and duplication again. Someone needs to rearrange the thousands of life cycle diagrams of plants and animal life histories taught in biology courses in order of the transformity of the stages and evaluate their emergy bases. Transformity of extracted information (examples: a seed, code, or house plan) is higher than the same information within the system it is operating (corresponding examples: a plant, a computer, or a house). Values are large where information is widely shared (examples: genetic plan of life, bible). Emergy of generating new information from precursors can be huge, as in evolution.

9. Emergy and Systems Aggregation

Emergy evaluation has to adapt to the way systems are aggregated in the window view of the mind's eye. Figure 5a, called a split, drawn with a branch, has a product outflow divided into two flows of the same kind (same transformity) dividing energy and the emergy by the same percentages. Splits add if recombined. For example, a stream may split as it flows around an island, recombining on the other side. Figure 5b shows co-products, drawn with separate lines from the transformation unit. Both have the same empower, but their energy flows are different so the output transformities are different. Examples are the meat and wool from sheep production and limbs and leaves from forest production. Dashed lines within the block in Figure 5b suggests the way the two outputs may develop different transformities by arising from a different level in the energy hierarchy. Care has to be exerted not to double count the same emergy if these flows recombine. Figure 5c is a mixture with co-products and a split. To evaluate a mix, the emergy of each input flow is traced separately to the place where its last available energy is used up and the results added (11). The numerical results are given in the figure legend.

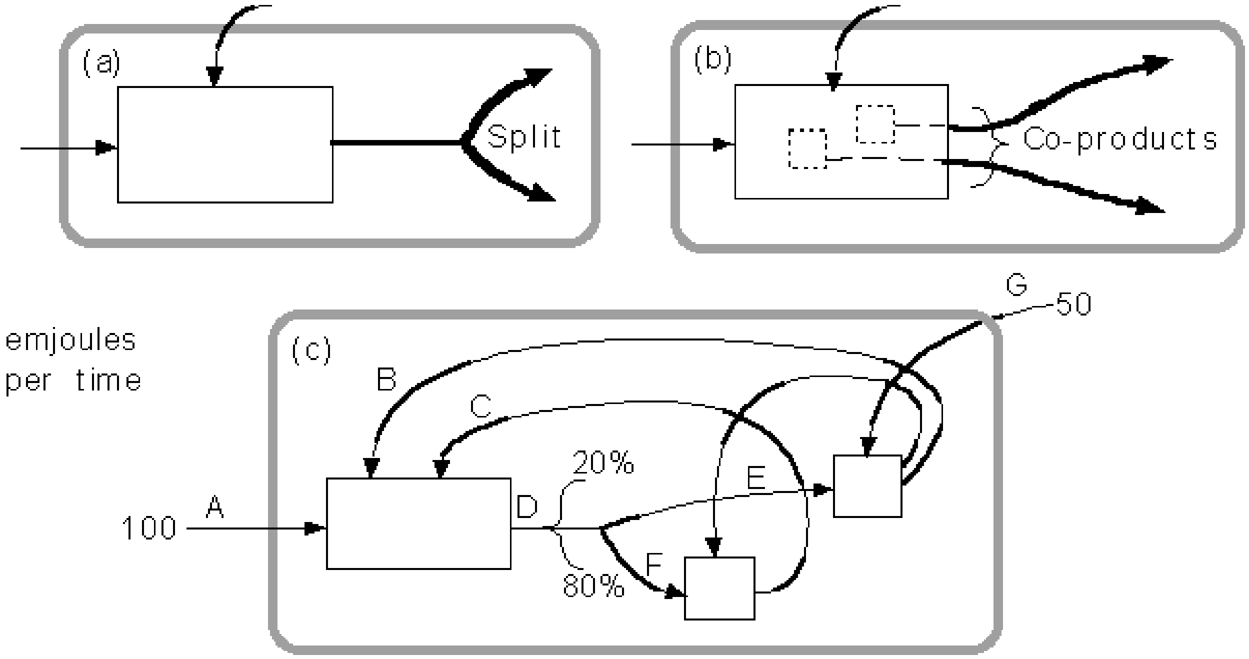

Figure 5. Types of system aggregation. (a) Splits; (b) co-products; (c) mix of splits and co-products with flows from each source evaluated separately and added: A = 100; B = 20 + 50; C = 80 + 50; D = 100 + 50; E = 20 + 10; F = 80 +40; G = 50.

10. Emergy Evaluation and Pulsing

Apparently, all systems on all scales pulse (Figure 6). Gradual accumulation of one storage is followed by a short period of frenzied consumer use and development which disperses materials, setting up the next growth period. Pulses cause oscillations in emergy, empower, and transformity. Inputs from pulses on smaller scale than the window of interest look like noise and can be averaged as if there was a steady state. The infrequent pulses from the larger scale than the window of interest are catastrophic with high transformity and effect (hurricanes, earthquakes, economic pulses, information storms, etc.).

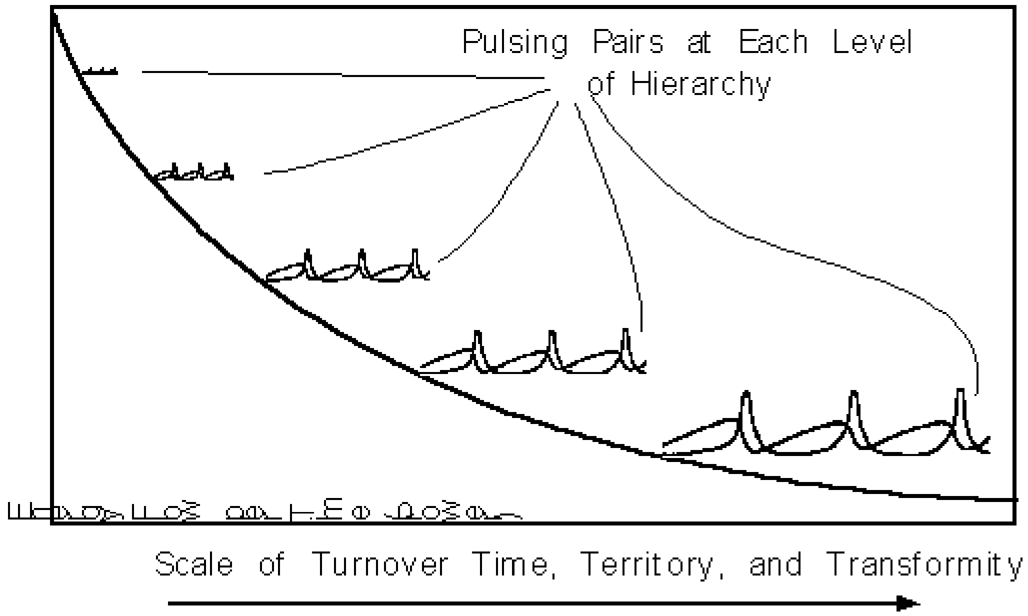

Figure 6. Pulsing on many scales.

To include emergy in a simulation model, three emergy evaluation equations are added for each state variable: one for periods of storage growth, one for periods of unchanging storage, and one for periods of declining storage. (1) If there is growth, emergy increases as the sum of the contributing inflows used times their transformities minus any outflow to other use (but not minus depreciation). Depreciation during growth is a necessary energy dispersal to the transforming and storing process. (2) If the storage is unchanging the emergy is constant. 3) If the storage is declining for whatever reason, emergy loss is the loss of storage times its transformity. The expression for storage transformity is the emergy accumulated divided by the energy accumulated. For the program EXTEND, Odum and Petersen (5) programmed icon-objects that automatically evaluate emergy when connected on computer screen and simulated.

11. Emergy and Money, Emdollars

Real wealth (food, clothes, houses, materials, water, jewelry, knowledge, literature, art, etc.) is measured by its emergy. Money buys real wealth according to market prices. By dividing the total emergy use of a country by its gross economic product, an emergy/money ratio is obtained

(Figure 7). The part of the gross economic product due to an emergy contribution can be estimated as the emergy value divided by the emergy/money ratio. The result is in emdollars (abbreviated em$). The emergy/money ratios of two countries are required to evaluate the real wealth benefits of their international trade and financial exchanges.

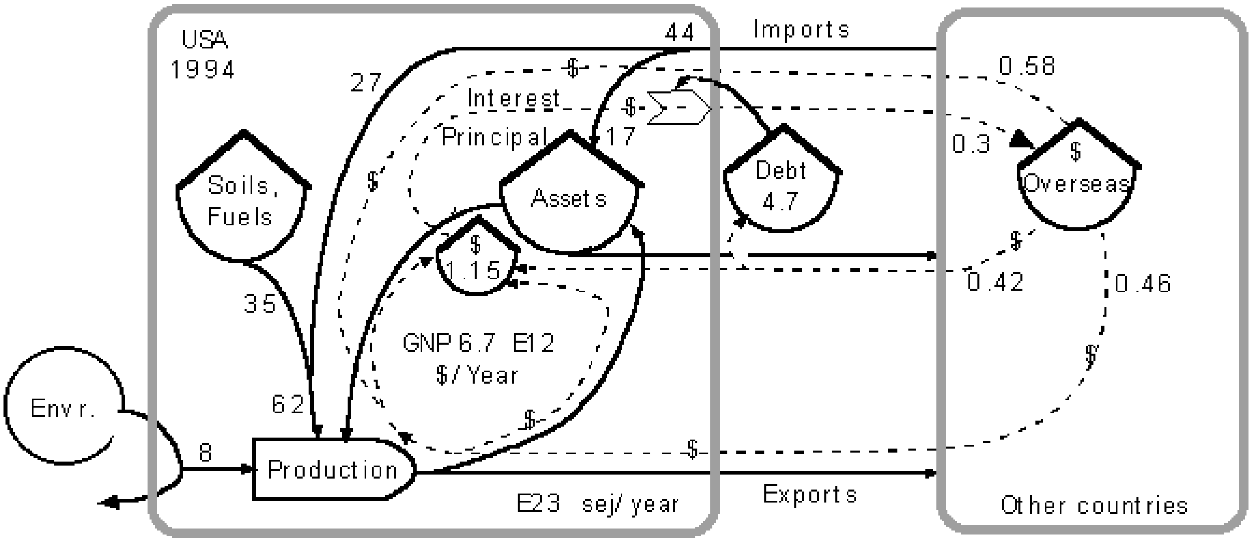

Figure 7. Emergy overview of the macroeconomy of the United States.

Emergy/money ratio = [(45+35+8) E23 solar emjoules/yr] / [6.7 E12 $/yr] = 1.33 E12 sej/$.

12. Microeconomic Evaluation of an Environmental-Economic Interface

Economic use of environmental resources involves free inputs from environment and purchased inputs from the economy (Figure 8). Resource use is evaluated with energy and transformities.

Where data on labor and services are in money units, the average empower can be estimated using the emergy/money ratio of the economy contributing the services. However, allocating emergy according to an average does not evaluate many services correctly. Some are not paid for. With a wide range of transformities services do not correspond to money paid. However, evaluation can be made using transformities of occupations, education, and experience. Purchased inputs such as fuels, electricity, and critical materials have high emergy values in addition to that in the services involved.

13. Emergy Indices

Useful emergy indices for comparing states and nations include: emergy use per person, fraction of emergy that is electrical power, emergy self sufficiency, net benefit from foreign exchange, ratio of economic emergy/free emergy, and emergy signature (graph of emergy inputs versus transformity).

For economic use of resources (Figure 8), the net emergy ratio measures the net benefit to the economy (emergy of the yield Y divided by the emergy of the feedback F from the economy). Because of the high emergy of human services required, net emergy contributions of some alternate energy sources such as biomass ethanol and solar technology are small or negative.

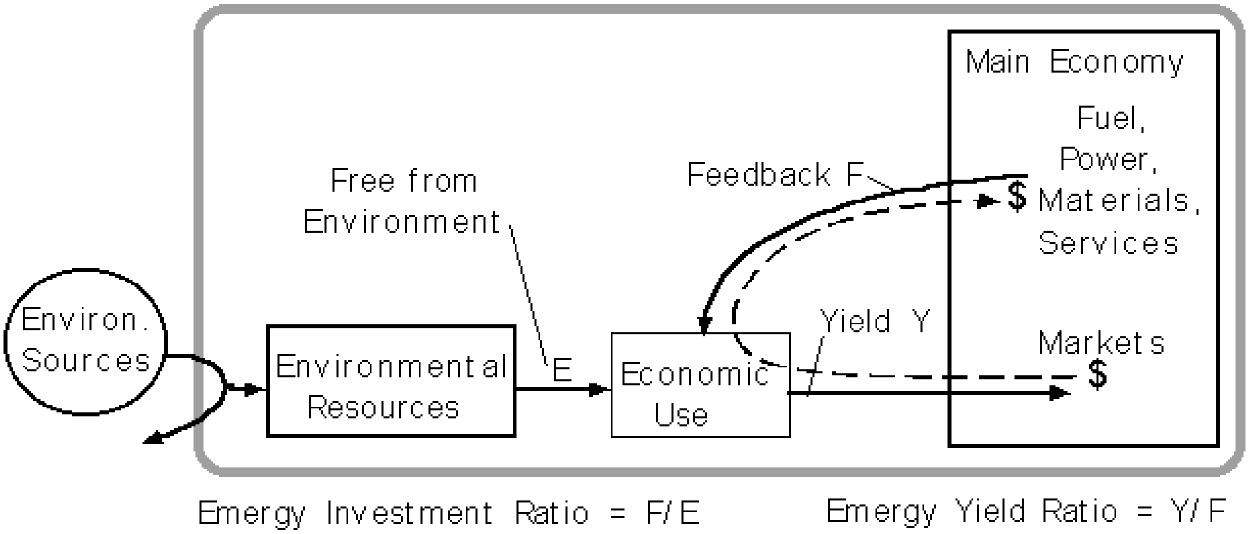

Figure 8. Interface between environment and economic use.

Environmental impact (Figure 8) is measured by the emergy investment ratio defined as the ratio of the emergy purchased from the economy divided by the emergy from the local environment. Developed states have ratios of 7 or higher. National parks and wilderness have ratios of 1 or less. Ratios higher than those of the surrounding area do not compete economically because costs are higher than alternative investments.

14. Beneficial Public Policy

To form public policy for maximum benefit, select alternatives that maximize useful empower. By restating Lotka's principle in empower units we recognize that beneficial organization increases intake emergy (first priority) and its efficient use (second priority) on all scales (not just maximizing levels with more energy; not maximizing some levels at the expense of others).

The net emergy ratio of its best fuel sources determines a state's support for other activity. Developed countries in recent years have had ratios between 3 and 12 times more emergy input than was used to get it.

15. Example of Emdollar Evaluation, an Environmental Lawsuit

In practical applications evaluation starts by defining a window and drawing a systems diagram usually with energy language symbols. Important pathways are identified and data are assembled for each line item. Energy flows and storages are multiplied by transformities to get emergy values and divided by emergy/money ratios to get emdollars. Table 2 is an emergy evaluation table used in a lawsuit.

A landowner destroyed 84 hectares of mangrove ecosystems and their water exchange pattern in Lee County Florida. Environmental protection agencies engaged him in a regulatory lawsuit in which the value of the mangroves was in debate. The market value of the fish and mangrove wood was in the thousand dollar range. Market evaluations are usually smaller than emdollar evaluations, because economic values only cover the services involved,

The Florida State Environmental Protection lawyers asked for an emdollar evaluation. The annual emergy previously harnessed by mangrove production was in the million emdollar dollar range, just from a partial analysis in Table 2. In mangroves that required 30 years to develop, the natural capital stored was 30 times greater. After two formal depositions, the landowner settled out of court.

Table 2. Annual Emergy Uses by 84 ha of Mangroves in Lee County, Florida

Note	Item	Solar Energy Environment (b) J/yr	Transformity (d) sej/J	Real Wealth (a) 1000 U.S. Emdollars	ValueAttracted (c)
1	Tidal exchange	3.0 E12	2.4 E4	55	440
2	Freshwater inflow	5.5 E12	4.9 E4	207	1,652
3	Rain used	4.2 E12	1.8 E4	58	464
4	Total			320	2,556

Footnotes

a (energy in J/yr)(solar transformity in sej/J)/(1.3 E12 sej/1997 U.S. $)

b Direct environmental contributions

c Direct environmental contribution plus its attracted economic inputs assuming regional emergy investment ratio for Florida of 7/1.

d Transformities from page 309 in Environmental Accounting

1. (0.5 m tide)(706 tides/yr)(1.02 E3 kg/m3)(9.8 m/sec2)(8.4 E5 m2 area) = 3.0 E12 J/yr

2 .Freshwater flow from inland:

(1.3 m3/m2/yr)(1 E6 g/m3)(5 J Gibbs En./g)(8.4 E5 m2) = 5.5 E12 J/yr

3. Rain used: (1.0 m3/m2/yr)(1 E6 g/m3)(5 J Gibbs En/g)(8.4 E5 m2) = 4.2 E12 J/yr

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