Emergy synthesis: an introduction

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Emergy Synthesis: An Introduction

Mark T. Brown, Sherry Brandt-Williams, David Tilley, and Sergio Ulgiati

Synthesis is the act of combining elements into coherent wholes. Emergy synthesis is a "top-down" approach to quantitative policy decision making and evaluation. Rather than dissect and break apart systems and build understanding from the pieces upward, emergy synthesis strives for understanding by grasping the wholeness of systems. Emergy is a systems concept, and cannot be fully understood or utilized outside of systems. Emergy is context driven and has been described as the memory of energy used in the past to make something (Scienceman, 1987). Put another way, emergy is the amount of energy of a single type consumed, either directly or indirectly, to make another form of energy, a product, or a service. By evaluating complex systems using emergy methods, the major inputs from the human economy and those coming "free" from the environment can be integrated to analyze questions of public policy and environmental management holistically. A full explanation of concepts, principles and applications of emergy can be found in "Environmental Accounting" by H.T. Odum (1996).

In this volume twenty-five papers are presented that resulted from the First Biennial Emergy conference held in Gainesville, Florida in September 1999. The papers span the interests of the twenty-five scientists who presented them representing both theory and applications of the emergy methodology. Together, they form an interesting blend of theory and application, and while few papers are seldom wholly theoretical or applied, these twenty-five papers are split almost equally between subjects that stress theoretical aspects and those that stress applications.

In the following sections of this Introduction, we summarize the general conceptual and theoretical basis of the emergy methodology, describe the general methodology for conducting an emergy evaluation, and finally summarize how evaluations are applied to policy and environmental management decision making.

Emergy Theory

The theoretical and conceptual basis for the emergy methodology is grounded in thermodynamics and general system theory. Evolution of the theory during the past thirty years was documented by H.T Odum in Environmental Accounting (1996) and in the volume edited by C.A.S. Hall titled Maximum Power (Odum, 1995). A critical central concept that has occupied emergy theory during its evolution has been the concept of energy quality. To understand energy quality, we build a case for it by first defining energy.

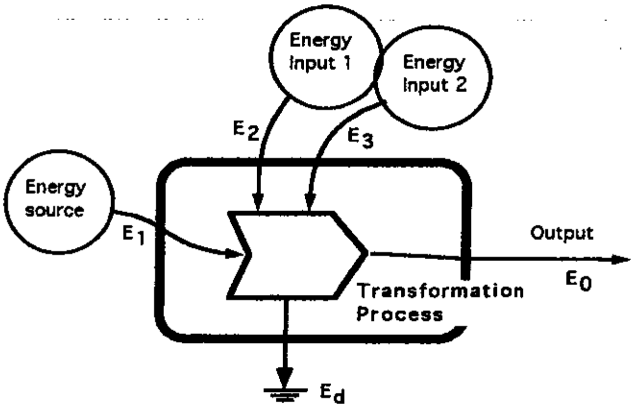
Energy has been defined as the ability to do work, based on the physical principle that work requires energy input. Energy is measured in units of heat, or molecular motion...the degree of motion resulting in expansion and quantified in calories or Joules.

Heat energy is a good measure of the ability to raise water temperature. However, it is not a good measure of more complex work processes. Processes outside of the window defined by heat engine technology, do not use energies that lend themselves to thermodynamic heat transfers. As a result, converting all energies of the biosphere to their heat equivalents reduces all work process of the biosphere to heat engines. Different forms of energy have different abilities to do work, and it is necessary to account for these different abilities if energies are to be evaluated correctly. A Joule of sunlight is not the same as a Joule of fossil fuel, or a Joule of food, unless it is being used to power a steam engine. A system organized to use concentrated energies like fossil fuels cannot process a more dilute energy form like sunlight. Evaluation of energy sources is system dependent. The processes of the biosphere are infinitely varied and are more than just thermodynamic heat engines. As a result, the use of heat measures of energy that can only recognize one aspect of energy, its ability to raise the temperature of things, cannot adequately quantify the work potential of energies used in more complex processes of the biosphere. As in thermodynamic systems where energies are converted to heat to express their relative values, in the larger biosphere, as a whole, energies should be converted to units that span this greater realm. In this way multiple levels of system processes other than heat engine technology, ranging from the smallest scale to the largest scales of the biosphere, can be accounted for.

Emergy And Transformity

Emergy accounts for, and in effect measures quality differences between forms of energy. Emergy is an expression of all the energy used in the work processes that generate a product or service in units of one type of energy. By definition, emergy is the amount of energy of one form (usually solar) that is required, directly or indirectly, to provide a given flow or storage of energy or matter. The ratio of emergy required to make a product to the energy of the product is called transformity. Solar emergy is expressed in solar emergy joules (sej, solar emjoules), while solar transformity is expressed in solar emergy joules per Joule of output flow (sej/J). Figure 1 illustrates how emergy is assigned to an output flow, and how the transformity of an output flow is calculated. The simple process has three energy inputs whose transformities are known from previous calculations. Therefore the emergy of each input is its energy multiplied by its transformity. The total emergy of the output is the sum of the emergy inputs, and the transformity of the output is its emergy divided by its energy.

The transformity of solar radiation is assumed equal to one (1). Transformities of the main natural flows in the biosphere (wind, rain, ocean currents, geological cycles, etc) are calculated as the ratio of total emergy driving the biosphere as a whole to the actual energy of the flow under consideration (Odum, 1996, 2000).



Energy in = Energy out...($E_1+E_2+E_3 = E_d+E_0$)

Solar emergy output = $E_1{*}Tr_1 + E_2{*}Tr_2 + E_3{*}Tr_3$

Solar transformity of output = $\dfrac{\text{Solar emergy of output}}{\text{Energy of output}}$

Figure 1. *Aggregated diagram of a transformation process where low quality energy (E1) is upgraded to a higher quality energy (E0), requiring the input of two other energy sources (E2 and E3).*

The total emergy driving a process becomes a measure of the self-organization activity of the surrounding environment, that is converged to make that process possible. It is a measure of the environmental work (in both the present and past) necessary to provide a given resource, be it the present oxygen stock in the atmosphere or the present stock of gold or oil deep in the planet.

Maximum Empower

Lotka (1922a and 1922b), following Boltzman (1886) enunciated a fundamental organizing principle of all systems in the maximum power principle. He stated "...that in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favorable to the preservation of the species." Further he stated "...natural selection tends to make the energy flux through the system a maximum, so far as compatible with constraints to which the system is subjected." Lotka suggested power maximization as a 4th Law of Thermodynamics as has Odum (1996). While, power maximization might be a measure of fitness. it may suggest maximizing energy flows through self-organizing process at low transformity scales where the energy flow is greatest. Restated using emergy, Lotka's maximum power principle becomes the maximum empower principle and suggests maximizing useful work at all scales:

> Maximum Empower Principle: At all scales, systems prevail through system organization that first, develop the most useful work with inflowing emergy sources by reinforcing productive processes and overcoming limitations and second by increasing the efficiency of useful work.

Maximizing useful work at all scales, at the same time, is required to maximize the combined economy of humans and environment. Useful work means utilizing inflowing emergy in reinforcement actions that ensure and, if possible, increase inflowing emergy. Processes that dissipate energy without

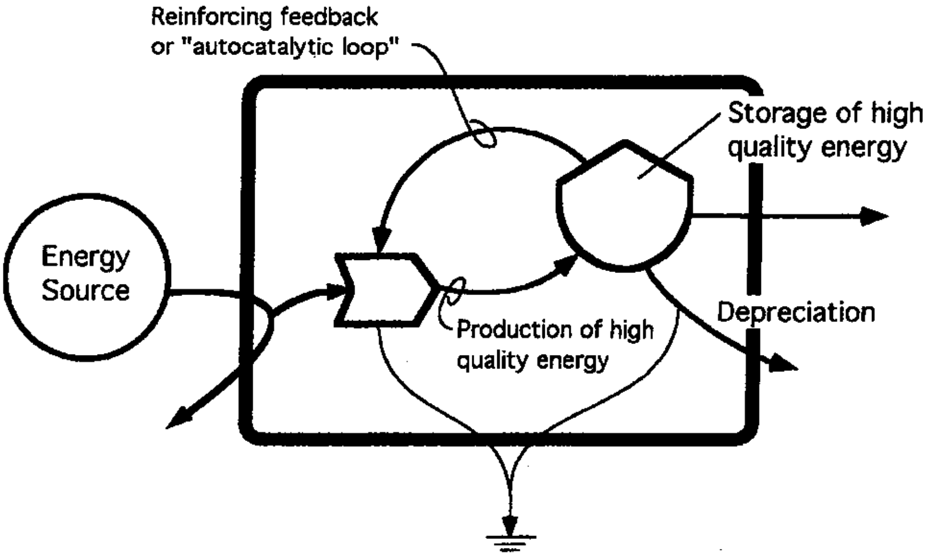


Figure 2. *Diagram illustrating maximum empower. Inflowing energy is upgraded and used in reinforcement actions to ensure, and when possible, increase inflowing energy.*

useful contribution to increasing inflowing emergy are not reinforcing, and thus cannot compete with systems that use inflowing emergy in self-reinforcing ways. Figure 2 illustrates an extremely aggregated system and the self-reinforcing feedback (autocatalytic loop) that increases inflowing energy.

Energy Flows Generate Hierarchies

Geologic processes, atmospheric systems, ecosystems, and societies are interconnected through a series of energy transformations...each receiving energy and materials from the other, returning same, and acting through feedback mechanisms to self-organize the whole in a grand interplay of space, time, energy and information. Processes of energy transformation throughout the biosphere build order, degrade energy in the process, and cycle materials and information in networks of hierarchically organized systems of ever increasing spatial and temporal scales.

When the actions of a large number of units of one type contribute to forming a few of another, a hierarchical relationship results. Convergence of energy in steps of transformations results in energy hierarchies. With each transformation many joules of energy of one kind loses its availability (potential, or ability to drive further processes) to produce fewer joules of another kind. This is a consequence of the 2nd Law of Thermodynamics. Since there is energy in everything including information and since there are energy transformations in all processes on earth and possibly in the universe as well, all energy processes can be regarded as part of an energy hierarchy. Using a broad definition of work as an energy transformation, then a series of successive work processes (a series of energy transformations) generates an energy hierarchy.

Hierarchies result from organizational structure of systems where energy transformation processes organized as webs converge and concentrate energies into fewer and fewer components at higher levels in the web. Web can be aggregated to chains of transformations where many small scale processes contribute to fewer and fewer larger scale processes (Figure 3). Familiar examples of energy transformation series are: streams and rivers converging in a watershed, the convergence of energy in food chains, road networks, or cities distributed in landscapes according to Central Place Theory (Christaller,1966; Losch, 1954) . Convergence of energy through a series of energy transformations yields a final product which carries less energy than invested to start the chain, due to the entropic degradation. However, the higher position of the item in the energy hierarchy makes it more valuable, as a large convergence of resources was required to support the process. We may say that the final product has a higher quality than initial products. Odum has suggested the energy hierarchy as a 5th Law of Thermodynamics (Odum 1996)

METHODS OF EMERGY ACCOUNTING

Emergy Basis of Value

Emergy accounting (Odum, 1996) uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy, usually sunlight. Emergy is the amount of energy that is required to make something. The units of emergy are emjoules, to distinguish them from joules. Most often emergy of fuels, materials, services etc. is expressed in solar emjoules (abbreviated sej). Emergy then, is a measure of the global processes required to produce something expressed in units of the same energy form. The more work done to produce something, that is the more energy transformed, the higher the emergy content of that which is produced.

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 each 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 (Odum, 1996, 2000). When expressed as a ratio of the total emergy used to the energy of the product, a transformation coefficient results (called transformity whose dimensions are sej/J). As its name implies, the transformity can be used to "transform" a given energy

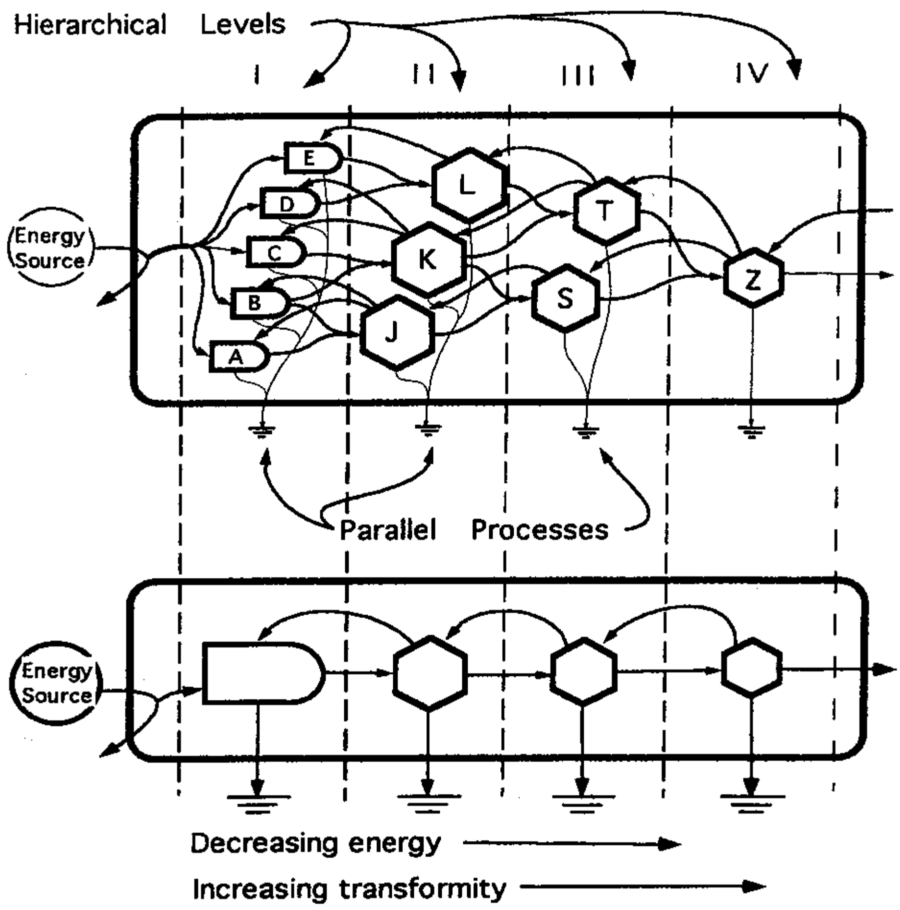


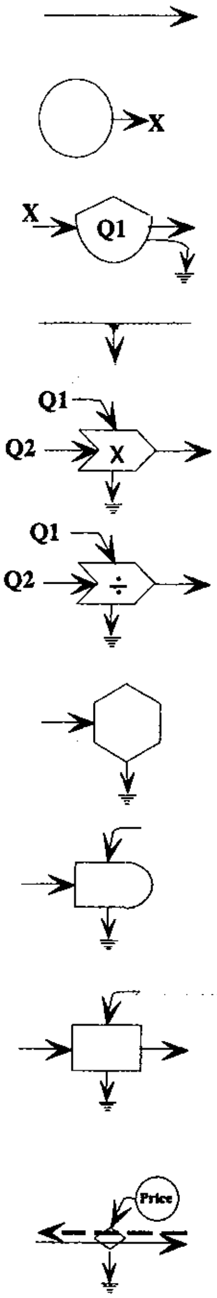
Figure 3. Systems are organized in webs of energy transformations that are hierarchical in organization. Transformation webs can be aggregated into transformation chains where energy flows decrease with each transformation step (a consequence of the 2nd Law) and transformity increases.

into emergy, by multiplying the energy by the transformity. Ratios of emergy per mass (sej/g) are also calculated for materials. For convenience, in order not to have to calculate the emergy in resources and commodities every time a process is evaluated, previously calculated transformities are often used. [Definitions of terms used in emergy accounting can be found at the end of this chapter as an Appendix]

Emergy measures value of both energy and material resources within a common framework. Transformities provide a quality factor as they account for convergence of biosphere processes required to produce something. Embodied in the emergy value are the services provided by the environment which are free and outside the monied economy. By accounting for quality and free environmental services, resources are not valued by their money cost or society's willingness to pay, which are often very misleading.

Emergy Accounting and Emergy Based Indicators

The general methodology for emergy analysis has been explained in detail by Odum in Environmental Accounting (Odum, 1996). Emergy accounting is organized as a top down approach where first a system diagram of a process or system under consideration is drawn to organize evaluations and account for all inputs and outflows. Papers in this volume use the systems symbols given in Figure 4



Energy circuit: A pathway whose flow is proportional to the quantity in the storage or source upstream (see equation given with tank).

Source: Outside source of energy delivering forces according to a program controlled from outside; a forcing function, eg. the sun or electricity.

Storage: A storage of energy or material within the system tracking a quantity as the balance of inflows and outflows; a state variable; $dQ1/dt = X - k1*Q1 - k2*Q1$.

Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages;

Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion (k) to a function of both (Q1 and Q2); the first intersection represents the term $k*Q1*Q2$, eg. the limiting interaction of light and phosphorus on the growth of a plant;

the second intersection represents $k*(Q2/Q1)$, eg. the drain on a population created by toxic substances

Consumer: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow, eg. a lion or a city.

Producer: Unit that collects and transforms low-quality energy under control interactions of high-quality flows, eg. a vascular plant or a forest.

Box: Miscellaneous symbol to use for whatever unit or function is labeled without showing all the internal processes, eg. an industrial process.

Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 4. *An abridged list of symbols and definitions of the energy systems language (Odum, 1994).*

for diagramming, but other diagramming languages can be used. The purpose of the system diagram is to conduct a critical inventory of processes, storages and flows that are important to the system under consideration and are therefore necessary to evaluate.

Tables of the actual flows of materials, labor and energy are constructed from the diagram. Raw data on flows and storage reserves are converted into emergy units, and then added up into a total emergy flow to the system. Inputs that come from the same source are not added, to avoid double counting. Only the larger input is accounted for. If the table is for the evaluation of a process, it represents flows per unit time (usually per year). If the table is for the evaluation of reserve storages, it includes those storages with a turnover time longer than a year.

Evaluation tables are usually constructed in the same format, as given by the column headings and format below:

1	2	3	4	5	6	7
Note	Item	Data	Units	Emergy/Unit (sej/unit)	Solar Emergy (E+15 sej/yr)	em$ Value* (1998 em$/yr)
1.	First item	xx.x	J/yr	xxx.x	xxx.x	xxx.x
2.	Second item	xx.x	g/yr	xxx.x	xxx.x	xxx.x
	. . .					
n.	nth item	xx.x	$/yr	xxx.x	xxx.x	xxx.x

Column #1 is the line item number, which is also the number of the footnote found below the table where raw data sources are cited and calculations are shown.

Column # 2 is the name of the item, which is also shown on the aggregated diagram.

Column # 3 is the raw data in joules, grams, dollars or other units. The units for each raw data item are shown in column #4.

Column # 5 is the transformity used for calculations, expressed in solar emergy joules per Joule. Sometimes, inputs are expressed in grams, hours, dollars, therefore an appropriate conversion ratio is used (sej/hr; sej/g; sej/$). Transformities may be obtained from previous studies or calculated for the system under investigation. If transformities from other authors are used, source reference should be shown in footnotes.

Column # 6 is the solar emergy of a given flow, calculated as raw input times the transformity (Column 3 times Column 5).

Column # 7 is the "emdollar value" of a given item for a given year. This is obtained by dividing the emergy in Column # 6 by the "emergy-to-GDP ratio" for the country and selected year of the evaluation (units are sej/$). The emergy/GDP ratio is calculated independently. The value in this column expresses the amount of economic activity that can be supported by a given emergy flow or storage.

The final step of an emergy evaluation involves interpreting the quantitative results. In some cases, the evaluation is done to determine fitness of a development proposal, in others it may be a question of comparing different alternatives. The evaluation may be seeking the best use of resources to maximize economic vitality. So the final step in the evaluation is to calculate several emergy indices that relate emergy flows of the economy with those of the environment, and allow the prediction of economic viability, carrying capacity or fitness. Additionally, using the results of the emergy analysis tables, comparisons between the emergy costs and benefits of proposed developments as well as insights related to the sustainable use of resources can be made. Definitions of concepts used in this book are given in the Appendix to this chapter.

When comparisons are made following an emergy analysis, it is sometimes easier to express the emergy in more familiar terms. So emergy is converted to dollars of buying power, based on a average ratio of emergy per dollar of Gross Domestic Product (GDP) in the local economy. The emergy dollar ratio (sej/$) is calculated for a given economy in a given year by dividing the total emergy use in the economy by the GDP for that year. It is a measure of buying power, in essence it quantifies the average amount of emergy that circulates in the economy for every dollar that circulates. Emergy is converted to "emdollars' (the term used to describe emergy buying power) by dividing emergy of a product or process by the emergy dollar ratio. The abbreviation for emdollars is em$ to distinguish them from currency dollars.

Emergy and Environmental Decision Making

All decisions are environmental decisions. Every policy decision made has environmental consequences, some larger than others, but environmental consequences none the less. Since all actions of humans are within an environmental bubble, so to speak, and all actions require some form of resource input, which leads to a waste output, the action has environmental consequences. Consequences that result from the input of resources from the environment include how the environment will be affected as a result of extracting and using resources. Consequences on the output side include how the environment will be affected by the wastes that are generated as a result of some activity.

Increasingly those interested in conservation and management of the biosphere's ecosystems are recognizing that the human use of resources and the human development of landscapes are driving forces behind the need for conservation and management. Issues of wise use revolve around balancing human needs with ecological realities. Sustainability, the new buzz word for carrying capacity, is another way of approaching the same old problem...how to balance human needs on the one hand, ecological needs on the other and ultimately the interaction of both now and in the future. Human systems are not sustainable if the result of extracting resources for one use, is the loss of ecological systems that provide resources for another use...or if the result of development in one area causes greater losses of ecological productivity and ultimately economic vitality in another area.

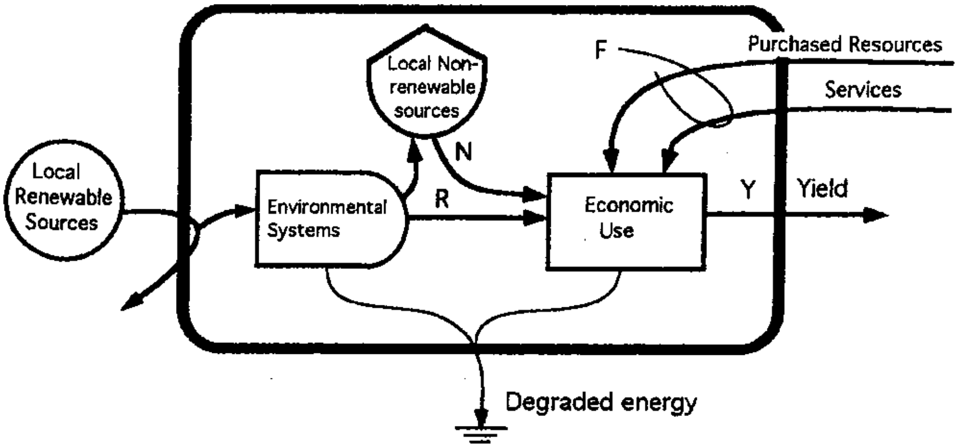
Decisions regarding resource conservation and environmental management often become a question of trade-offs, for instance, trade-offs between human needs for resources and the loss of ecological functions that may result. In the best of all worlds, the decision is made based on criteria concerning perceived benefits and impacts. However, even in the best of circumstances, benefits and impacts often do not have equally definable or measurable criteria. On the one hand there are the human needs measured in jobs, food that can be produced, or economic activity that may result. On the other hand there are ecosystem losses, measurable in grams carbon of primary production, diversity of animals present, or ecological functions that are supported.

Clearly, if this wider perspective in resource conservation and management is going to work there is a need for methods of evaluation that can bridge across the divide between human needs and values and ecosystem requirements. The emergy evaluation technique bridges this divide.

By evaluating policy and management questions using emergy methods, the major inputs from the human economy and those coming "free" from the environment can be integrated to analyze problems holistically. We call this evaluation technique "emergy synthesis" rather than emergy analysis since it is an integration or amalgamation. Emergy synthesis is a tool that can complement traditional cost-benefit analysis to make more integrated resource management decisions. The values obtained using emergy accounting are independent of human preferences and do not rely on artificial markets or shadow pricing.

Evaluating Environmental Contributions

The systems diagram of an economic use interface in Figure 5 shows non-renewable environmental contributions (N) as an emergy storage of materials, renewable environmental inputs (R), and inputs from the economy as purchased (F) goods and services. Purchased inputs are needed for the



Yield (Y) = R+N+F
%Renew = R/(R+N+F)
Nonrenewable to Renewable Ratio = (N+F)/R
Emergy Yield Ratio = Y/F
Emergy Investment Ratio = F/(R+N)
Environmental Loading Ratio = (F+N)/R

Figure 5. *Simplified diagram of an economic sector showing non-renewable environmental contributions (N) as an emergy storage of materials, renewable environmental inputs (R), and inputs from the economy as purchased goods and services (F). Ratios and emergy indices are defined using the flows of renewable, non-renewable, and purchased emergy.*

process to take place and include human service and purchased non-renewable energy and material brought in from elsewhere (fuels, minerals, electricity, machinery, fertilizer, etc). Environmental inputs (R and N) are things like water or topsoil and are evaluated as the amount of emergy required to make them. Environmental inputs often have high emergy values because of the time required to make them (it can take hundreds of years to make 1 cm of topsoil, for instance), or the very large area required for convergence of environmental services to provide them (water in a reservoir, for instance).

There are other environmental services provided by the environment in absorbing and recycling by-products and are of fundamental importance to a sustainable production pattern. When the free work of the environment in absorbing wastes is overloaded, it must be replaced with technology. Recycle of by-products requires that they "fit" the patterns and organization of the environment, making production processes time and location dependent. When the support area of a process is taken into account, wastes and by-products can be absorbed and recycled by the environment within the material cycles that are driven by solar energy.

Evaluating Net Emergy Benefits

Investments in activities should lead to net benefit. The concept of net emergy benefit is that any investment or development action, when considered holistically, should lead to more emergy flow in the economy and environment than the "costs". Emergy evaluations done for proposed development actions whether the development of an extractive use of the environment, new urban structure, or waste disposal account for the emergy used in the process, the emergy values of environment "lost" as a result of the project, and finally the emergy gained by the economy as a result of the project. Figure 5 is a much aggregated systems diagram of an economic use interface between the environment and economy. The flows of money, environmental contributions, and emergy investment from the economy are shown, as well as the environmental losses resulting from the economic use. A main evaluation tool to determine net benefit, is the Emergy Yield Ratio (EYR) described in Figure 5 as the total emergy contributed divided by the feedback from the economy.

Evaluating Carrying Capacity

The concept of carrying capacity relates resource use to environmental support. To sustain a carrying capacity for a population or an economic development requires that there is a balance between the supply of resources and the impacts sustained as a result of that supply. The population size or development intensity that can be sustained results from a balance between the use of environment as a source of resources and its use as a sink for wastes. It is true of all economic development that there is a carrying capacity, beyond which further development causes declines in resource availability and environmental integrity. The scale or intensity of development in relation to its environment may be critical in predicting its effect and ultimately its sustainability. Large-scale developments can be integrated into the environment if there is sufficient regional support area to balance its effect. As the intensity of development increases (and therefore its consumption of resources and environmental impacts increase), the area of natural undeveloped environment required for its support must increase.

Ultimately, carrying capacity is related to the ability of a local environment to provide necessary resources for a population or economic endeavor on a renewable basis since non-renewable energy by its very definition cannot be depended on in the long term. In emergy terms, the long term carrying capacity of an area is limited by the flux of renewable emergy that is characteristic of that area. One might term this " renewable carrying capacity", since it relies on an environment's ability to support economic development based solely on its renewable emergy sources. In many respects renewable carrying capacity is an unrealistic number, since all economic developments by their very nature require non-renewable emergy and match that emergy with renewable resource base to extract a net yield. However, the renewable carrying capacity provides a benchmark that might be used to establish a lower limit to the carrying capacity of a region.

Renewable carrying capacity is calculated using the average renewable emergy inputs to a region and determining how much area is required to supply the total emergy requirements of a population. Since renewable emergy sources are aerial based, carrying capacity becomes an aerial measurement. The same techniques are applied to any economic development once emergy requirements for the development are known. They are expressed in equivalent renewable emergy and then the required support area is calculated. The renewable carrying capacity calculated in this way may be a predictor of long run sustainability.

A second approach to carrying capacity is related to the "fitness" of development within a local "eco-economic system" (the local system is composed of both a human dominated economy and an environment that supports that economy). This second approach is based on the intensity of development, which we call "environmental loading." The scale or intensity of development is used and related to existing conditions under the theory that if a development's intensity is much greater than that which is characteristic of the surrounding region, on average, the development has greater capacity to alter existing social, economic, and ecologic patterns. If it is similar in intensity it is more easily integrated into existing patterns. This second method of evaluating carrying capacity uses a ratio of non-renewable emergy to renewable emergy, called an Environmental Loading Ratio (ELR) and provides an upper limit to carrying capacity.

The two approaches combined, provide upper and lower bounds to carrying capacity. In the first case, the renewable emergy carrying capacity assumes that all resources sustaining an economic endeavor must come from the local renewable resource base. The second case suggests that to remain competitive, development should maintain a similar intensity as the average environmental loading ratio of the local environment under current conditions.

Evaluating Development Alternatives

Often policy decisions require a choice between more than one development alternative. Under such circumstances, emergy evaluation provides quantitative measures for decision making. Three principles are used in judging fitness, sustainability and economic vitality between alternatives:

(1) When alternative investments are compared, which contributes the most emergy value to the public economy? (2) Which alternative's emergy intensity nearly matches that of the local economy. (3) Which alternative maximizes use of renewable sources and minimizes "load" on the environment. Several indices are calculated from the emergy evaluations that are used to judge sustainability and fitness, they are: Empower Density (ED), Percent Renewable (%Ren), and the Environmental Loading Ratio (ELR). Several other indices help in gaining perspective about alternatives and are necessary complements to the above ratios. They are: Solar Transformity, Emergy / GDP Ratio, Emergy Investment Ratio, Emergy Per capita, Emergy Exchange Ratio, Emergy Yield Ratio, and Emergy Sustainability Index. All of these indices are listed and defined in the Appendix to this chapter.

CONCLUDING REMARKS: EMERGY SYNTHESIS

The papers in this volume provide information valuable for the next step in evolution of emergy synthesis. Some of the papers provide examples of comparative assessments with resource policy recommendations. Others develop and discuss new theoretical concepts. All of them apply their emergy perspectives toward a better understanding of the integration of humans in their environment. This collection of papers covers a wide range of subjects: evaluations of agriculture, the life cycle of building materials; evaluations of natural resource distribution and the work of natural systems at several different scales; mathematical emergy constructs and comparisons between emergy and exergy; incorporating emergy into traditional economic evaluations and Freudian psychological profiles; and a proposed 6th Law of Thermodynamics. The following list provides a very aggregated subject index of the papers in this volume presented in the order they appear in the text.

- Energy, Emergy and Embodied Exergy: diverging or converging approaches?, emphasizes clearer statement of its thermodynamic basis for the emergy methodology, and suggests integration with other forms of biophysical analysis
- The Transformity of Riverine Sediments in the Mississippi Delta, presents an emergy per mass calculation as a first step in evaluating river diversion scenarios
- Emternalities - Theory and Assessment, proposes the use of emergy to place a value on the environmental inputs not included in commercial agricultural markets
- Emergy Analysis of the New Bolivia-Brazil Gas Pipeline, uses emergy yield ratios to evaluate project feasibility of a gas pipeline
- Transformities and Exergetic Cost - A Discussion, examines similarities and dissimilarities between energy, exergy and emergy methodologies
- Emergy Evaluation of Ecosystems: a basis for environmental decision making, uses emergy evaluation to value ecosystems and their structure and environmental services
- Emergy Analysis of Tomato Production Systems, compares different heating and fertilizer strategies in Sweden's conventional and organic production of tomatoes
- Sustainable Use of Potable Water in Florida: an Emergy Analysis of Water Supply and Treatment Alternatives evaluates, using emergy, alternatives for supplying freshwater to areas with a limited supply and calculates several transformities for water
- Simulating Emergy and Materials in Hierarchical Steps, uses computer simulations of key parameters in determining organizational hierarchy to allow synthesis of multiple concepts in the evaluation of a system
- The Hierarchical Pattern of Energy Flow in Ecological-Economic Systems Representing Three Geographic Scales, proposes the use of power and empower spectra (energy and emergy as a function of transformity) to assess ecological-economic systems
- Emergy Evaluations of Material Cycles and Recycle Options, used emergy to evaluate the comparative advantages of recycling and adaptive reuse of major construction materials

- Toward a Mathematical Formulation of the Maximum Em-Power Principle, presents a mathe-matical definition for emergy and formulates a mathematical foundation for the Maximum Empower Principle
- Emergy Analysis of Channel Catfish Farming in Alabama, U.S., uses emergy to compare Alabama aquiculture to conventional animal meat production systems
- Emergy Evaluations of Organic and Conventional Horticultural Production in Botucatu, Sao Paulo State, Brazil, illustrates the value of emergy in evaluating different agricultural production techniques
- Embodied Energy and Emergy Analysis of Wastewater Treatment Using Wetlands, compares the use of wetlands to conventional treatment for wastewater using three different methods of accounting - emergy, cost-benefit and embodied energy
- Sweden Food Systems Analysis, evaluates the resource basis of the Swedish food system including farm production, processing, distribution and consumption to quantify investments, environmental support and environmental loading.
- Spatial Transformities for Alachua County, Florida, uses a GIS and spatial analysis techniques to assign emergy and transformities to landscape
- An Energy Hierarchy Law for Biogeochemical Cycles, proposes a sixth energy law – a principle of material hierarchy
- Transformity and Potential Effect of Feedback in Human Dominated Systems – using Wastewater as an Example, discusses the dilemma of calculating transformities in systems that may not be operating at maximum efficiency
- A Revised Solar Transformity for Tidal Energy Received by the Earth and Dissipated Globally: Implications for Emergy Analysis presents a revised tidal energy transformity with values for use in two different time scales of evaluation
- Calculating Transformities with an Eigenvector Method illustrates the usefulness of matrix algebra in quickly calculating transformities from sets of emergy equations generated in a systems diagram method
- Emergy Analysis and Trends for Ethanol Production in Brazil presents several indices for ethanol production as a basis for assessing fuel market trends
- Emergy Evaluation of the Environment and Economy of Nicaragua, examines the economy and environment of Nicaragua and compares it with other nations
- Energy and Emergy Assessment of Municipal Waste Collection. A Case Study uses a joint mass/energy/emergy approach to evaluate municipal waste collection in Siena,Italy
- Sublimation diagrams Sigmund Freud's theories of sublimation, culture and personality using energy systems language

Emergy synthesis is the step beyond analysis. By evaluating the emergy basis for systems and their processes, products, and services, components essential to more complete evaluations are included. The services and natural capital of the environment are included along with purchased materials, energy and human services. The values of environmental components can be compared to values generated from economic exchanges. Policy decisions now take on a more holistic perspective with the more complete information that is afforded when both the products and services of the human sector are given equal weight with the services and capital of nature. More informed decisions are possible when both environmental and social system tradeoffs are understood and quantified.

In all, emergy synthesis generates a deeper understanding of how one might apply principles of self-organization and maximum power at every scale in the hierarchy of the universe.

The publication of this first proceedings represents the conclusion of the first conference and a lead-in to an even stronger, more ambitious second conference.

BIBLIOGRAPHY

Boltzman, L. 1886. The second law of thermodynamics. Address in English to Imperial Academy of Science in 1886. Populare Schriften. Essay 3: Selected Writings of L. Boltzman. D. Reidel, Dordrecht, Holland

Brown, M.T. and S. Ulgiati. 1997. Emergy Based Indices and Ratios to Evaluate Sustainability: Monitoring technology and economies toward environmentally sound innovation. *Ecological Engineering* 9:51-69

Brown, M.T. and S. Ulgiati.1999. Emergy evaluation of natural capital and biosphere services. *AMBIO*. Vol.28 No.6, Sept. 1999

Christallar, W. 1996. Central Places in southern Germany. (trans. By G.C.W. Baskin) Prentice Hall. Englewood Cliffs, NJ

Losch, A. 1954. The economies of Location (Trans by U. Waglom and W.F. Stalpor) Yale Univ. Press, New Haven CT.

Lotka A.J., 1922a. Contribution to the energetics of evolution. Proceedings of the National Academy of Sciences, U.S., 8, 147-150.

Lotka A.J., 1922b. Natural selection as a Physical Principle. Proceedings of the National Academy of Sciences, 8, 151-155.

Odum, H.T. 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York.

Odum, H.T. 1995 . Energy Systems and the Unification of Science. In CAS Hall (ed) *Maximum Power*. University of Colorado Press.. Niwot, CO. pp365-372

Scienceman, D. 1987. Energy and emergy. in Pillet, G. and T. Murota (eds.) *Environmental Economics—The Analysis of a Major Interface*. Geneva, Switzerland: Roland, Leimgruber. pp. 257-276.

Ulgiati, S. and M.T. Brown. 1998. Monitoring patterns of sustainability in natural and man-made ecosystems. *Ecological Modeling* Vol. 108, Nos.1-3, 1 May 1998

Ulgiati, S., M.T. Brown, S. Bastianoni, and N. Marchettini, 1996. Emergy Based Indices and Ratios to Evaluate Sustainable Use of Resources. *Ecological Engineering* 5 pp497-517.

Ulgiati, S., H.T. Odum, and S. Bastianoni, 1994. Emergy Use, Environmental Loading and Sustainability. An Emergy Analysis of Italy. *Ecological Modeling*, 73: 215-268.

APPENDIX: Definitions of terms used in emergy evaluations

Further discussion and definitions can be found in Odum, 1996; Brown and Ulgiati, 1997; Ulgiati et al. 1995

Definitions

Energy. Sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat and is measured in heat units (BTUs, calories, or joules)

Emergy. An expression of all the energy used in the work processes that generate a product or service in units of one type of energy. Solar emergy of a product is the emergy of the product expressed in equivalent solar energy required to generate it. Sometimes its convenient to think of emergy as energy memory.

Emjoule. The unit of measure of emergy, "emergy joule." It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood.

Empower. An expression of emergy per unit time. Analogous to power, where the units are the flow of energy per time. Empower is a measure of the emergy used in a process per unit time.

Non-renewable Emergy. The emergy of energy and material storages like fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced by geologic processes.

Renewable Emergy. The emergy of energy flows of the biosphere that are more or less constant and reoccurring, and that ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.

Resident Emergy (or local emergy). The renewable emergy flows that are characteristic of a region such as sunlight, winds, rain, and tidal flux.

Indices

Emergy / money ratio (Emergy / GDP ratio). The ratio of total emergy use in the economy of a region or nation to the GDP of the region or nation. The emergy / GDP ratio is a relative measure of purchasing power when the ratios of two or more nations or regions are compared.

Empower density. The ratio of total emergy use in the economy of a region or nation to the total area of the region or nation. Renewable and nonrenewable empower density are also calculated separately by dividing the total renewable empower by area and the total nonrenewable empower by area, respectively.

Emergy exchange ratio. The ratio of emergy exchanged in a trade or purchase (what is received to what is given). The ratio is always expressed relative to one or the other trading partners and is a measure of the relative trade advantage of one partner over the other.

Emergy Investment ratio. The ratio of emergy fed back from outside a system to the indigenous emergy inputs (both renewable and non-renewable). It evaluates if a process is a good user of the emergy that is invested, in comparison with alternatives.

Environmental loading ratio. The ratio of nonrenewable and imported emergy use to renewable emergy use

Emergy per capita. The ratio of total emergy use in the economy of a region or nation to the total population. Emergy per capita can be used as a measure of potential, average standard of living of the population.

Emergy Sustainability Index. The ratio of the Emergy Yield Ratio to the Environmental Loading Ratio. It measures the contribution of a resource or process to the economy per unit of environmental loading.

Emergy yield ratio. The ratio of the emergy yield from a process to the emergy costs. The ratio is a measure of how much a process will contribute to the economy.

Percent renewable emergy (%Ren). The ratio of renewable emergy to total emergy use. In the long run, only processes with high %Ren are sustainable.

Solar transformity. The ratio of the solar emergy that is required to generate a product or service to the actual energy in that product of service. Transformities have the dimensions of emergy/energy (sej/J). A transformity for a product is calculated by summing all the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert resources of different types to emergy of the same type. The transformity is a measure of the "value" with the assumption that systems operating under the constraints of the maximum emergy principle generate products that stimulate productive process at least as much as they cost (Odum, 1996).