Available online at www.sciencedirect.com

SCIENCE DIRECT®

Ecological Modelling 178 (2004) 201–213

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems

Mark T. Brown [a,*], Sergio Ulgiati [b]

[a] *Department of Environmental Engineering Sciences, University of Florida, Orlando, FL, USA*
[b] *Department of Chemistry, University of Siena, Italy*

Abstract

We present in this article, a brief historical overview of the development of the concepts and theories of energy quality, and net energy that were the precursors to emergy. The concepts evolved over decades, beginning in the 1950s with Odum's work on tracing energy flows in ecosystems. During the 1970s, Odum's attention was drawn to larger scale systems that included the economies of humans and the concept of net energy. In the 1980s, Odum quantified energy quality and defined it as a "donor-based" evaluation technique. In the 1990s, energy quality was further refined and rigorous definitions for "emergy" and "transformity" were given. The units of emergy were defined as solar emjoules (abbreviated seJ) and the units of transformity were seJ/J. In addition, we provide some insights into the types of processes and systems that have been evaluated using emergy methods.

Keywords: Emergy; Energy quality; Transformity

1. Introduction

Probably, the least understood and most criticized of H.T. Odum's body of work is his concepts and theories of energy quality that are embodied in the 35 year development of the emergy concept. The development of emergy and its theoretical base cannot be separated from development of the concept of energy quality. We do not really know when Odum first considered that different forms of energy had different "qualities". We do know that in the 1950s and early 1960s, he was tracing energy flows in ecosystems and was probably reflecting on the differences in the work potential of energy among sunlight, the currents of water erupting from Silver Springs (Florida) and the currents bathing the coral reefs of Eniwetok (Marshall Islands). It was in his book *Environment Power and Society* (1971) that Odum first touched on the concept of energy quality formally when he stated...

> Beginning in the last century man began to develop an entirely new basis for power with the use of coal, oil, and other stored-energy sources to supplement solar energy. Concentrated inputs of power whose accumulation had been the work of billions of acres of solar energy, became available for manipulation by man. (Odum, 1971a)

Concepts of energy quality evolved over the decades from the early 1970s, where it was primarily a qualitative description of different energy forms to a quantitative method of expressing different forms relative to a common basis for comparative purposes. Through the decades, it became clearer and clearer to Odum that all forms of energy do not have the same ability to do work and that "quality corrections" were necessary if one were to compare the different forms with respect to their differential ability to do work. Reflecting on

* Corresponding author.
E-mail address: mtb@ufl.edu (M.T. Brown).

0304-3800/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2004.03.002

these differences, he was one of the first to point out the fallacies of energy technologies that promised unlimited energy for society from the sun or from vast quantities of oil trapped in the western shales, In the first case, the source was too dilute and the energy costs of concentration were too high for the source ever to have a net yield once the cost of the collectors was subtracted. In the second case, the energy costs of "liberating" the oil shale, including many energy costs associated with getting water to the mountain-top site was so great that again there would be no net yield.

Odum's major efforts during the 1970s were aimed at quantitatively defining energy quality and toward understanding the net yields of many energy sources, but it must be understood that it was not just defining energy sources and their net yields that drove Odum to explore energy quality. It was his desire to understand how the biosphere worked from the smallest scales to the largest, and the fact that his brand of science required that more than one level or scale of the biogeosphere be considered in order to understand any single level. In order to combine scales in the same analysis or to jump from one scale to another as the systems of interest shifted, it was crystal clear to Odum that a very different approach to defining energy and ability to do useful work was necessary. It was apparent that the ability to do work was dependent on not only the form of energy but also the system being considered.

2. Energy quality: a historical perspective

Odum recognized principles of energy quality as an outgrowth of his investigations into the works of the combined systems of humanity and nature. As a systems ecologist, he observed energies of many different forms at many different scales. He reasoned that a system organized to use concentrated energies like fossil fuels cannot process a more dilute energy form like sunlight, joule for joule. Since the processes of the biosphere are infinitely varied and are more than just thermodynamic heat engines, the use of heat measures for energy that can recognize only 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. The recognition that resource flows drive processes other than engine-like ones lead to the concept of energy quality, and eventually to the measure of quality now called EMERGY.

Beginning in about 1966, Odum referred to "energy of one kind" as a common denominator with the name "energy cost" (Odum, 1967b; Odum, 1971a). In a presentation to the President's Science Advisory Committee, Panel on World Food Supply titled *Energetics of food production*, Odum referred to the giant energy subsidies that were inherent in the green revolution that made possible "delusions regarding the capacity of science to develop means for feeding growing populations" (Odum, 1967b). In this same publication, Odum made that statement more explicit by beginning the process of quantifying the energy cost of energy by quantifying the fossil fuel energy required to produce food. He suggested that there was roughly one calorie of fossil energy required per calorie of food delivered through modern agriculture. In a review of a special issue of Scientific American in 1971 devoted to "Energy and Power", Odum suggested that "Sunlight is dilute energy, and the costs of concentrating it have already been optimized and yield maximized by the millions of years of natural selection for this maximization" (Odum, 1972a).

The first definition of energy quality appears in an article in AMBIO in 1973:

> Energy is measured by calories, btu's, kilowatt hours, and other intraconvertable units, but energy has a scale of quality which is not indicated by these measures. The ability to do work for man depends on the energy quality and quantity and this is measurable by the amount of energy of a lower quality grade required to develop the higher grade. The scale of energy goes from dilute sunlight up to plant matter, to coal, from coal to oil, to electricity and up to the high quality efforts of computer and human information processing. (Odum, 1973)

Certainly, Odum was thinking about "quality" during the early 1970s, and it appears that the first quantitative evaluation of the concept was in 1975. While the concepts of energy quality were, no doubt, still developing in 1975 when Odum received the Prize Institute la Vie in Paris, his acceptance speech titled "Energy Quality and Carrying Capacity of the Earth" contained a table of "Energy Quality Factors", or the kilocalories of sunlight energy required to make a kilocalorie of a higher quality energy (Odum, 1976a). It was in this same speech that Odum unveiled his energy hierarchy principle and that "energy quality is measured by the energy used in the transformations" from one type of energy to the next.

The concept of net energy played an important role in the development of energy quality and emergy. Odum was used to the concept of "net production" in the ecosystems he had studied over the years, and when applied to the human economy suggested that an energy source must be able to provide a net contribution to the economy of the larger system in which it is embedded, i.e. it must provide more energy than it costs to extract and process it. Odum suggested that this principle applied to every system at all levels, from ATP-providing energy to the biochemical reactions in living systems, to photosynthesis, to the energy expended by animals as they grazed or chased prey. And so it was logical that it applied also to the fossil fuels driving economic sectors and human societies.

In the 1970s, Odum's work had turned toward larger scale investigations of the interactions of energy, ecology, and economics. This in turn led to the application of net energy to energy sources for economies and his suggestion that ... "*The true value of energy to society is the net energy, which is that after the costs of getting and concentrating that energy are subtracted*" (Odum, 1973). The concept of net energy as Odum presented was almost revolutionary, and after a presentation to the US House of Representatives Subcommittee on Energy and Power, and a meeting with Senator Mark Hatfield of Oregon, a bill was introduced in the Senate in 1975 for a federal law that made net energy analysis a requirement of proposed alternative energy systems. (Odum, 1976b). This legal requirement was enforced for a while but is now largely ignored.

Odum's concept of net energy was inextricably connected to energy quality, since the "true costs of getting and concentrating energy" included not only high quality fossil fuel inputs but also human services and environmental inputs and these inputs required "quality correction". Odum presented his concepts of energy quality linked to net energy at a meeting at Stanford organized by the National Science Foundation in response to the new law (Odum et al., 1976). Those present rejected the concept and settled on net energy strictly defined as the fossil fuel energy required per unit of fossil energy delivered. Hall (1986) nearly a decade later defined Energy Return on Investment (EROI) emphasizing the fossil energy invested although with an acknowledgement of the need to include environmental and labor energy inputs as well for a comprehensive analysis.

3. The emergence of emergy

From 1975 on, Odum's attention was increasingly focused on the development of his theory of energy quality and its quantitative definition. In the latter half of the 1970s, Odum had several research projects in south Florida that were investigations of overall carrying capacity of humans and the environmental changes resulting from human uses. The ultimate purpose of the projects was to make suggestions for maximizing economic and environmental vitality of the region through better environmental management. It was during these projects and the very creative atmosphere that evolved around them that the concept of energy quality matured into the precursors of emergy. Called fossil fuel work equivalents (FFWE), the quality of energy was measured based on a fossil fuel standard with rough equivalents of 1 kcal of fossil fuel equal to 2000 kcal of sunlight. The ratios used to convert all energy forms to FFWE were called "Energy quality ratios". Later termed coal equivalent (CE) calories, eventually the system of evaluating quality was placed on a solar basis and termed solar equivalents (SE) in (Odum, 1977a).

Odum began using the term *embodied energy* to refer to energy quality differences in terms of their costs of generation, and a ratio called a "quality factor" for the calories (or joules) of one kind of energy required to make those of another in 1980 (Odum and Odum, 1980). The term embodied energy was used by others for different ways of thinking and calculating; in essence not including all energies and not using the concept to imply quality, so in 1982, Odum switched to "embodied solar calories" and the quality factors became transformation ratios. Odum abandoned "embodied energy" altogether in favor of "emergy" a term suggested in 1983 by David Scienceman, which was a constriction of embodied energy. Scienceman was a visiting scholar from Australia, who suggested the term, and emjoules or emcalories as the unit of measure to distinguish emergy units from units of available energy. The term transformation ratio gave way

Table 1
Chronology of development of emergy and transformity and conversions

Years	Measures of quality	Unit emergy values	Units	Reference
1967–1971	All energies of higher quality including wood, peat, coal, oil, living biomass, etc. expressed in units of organic matter	Direct sunlight equivalent to organic matter was taken as 1000 solar kcal/kcal of organic matter	Gram dry wt. O.M.; kcal, conversion from OM to kcal = 5 kcal/g dry wt.	Odum (1971a 1967b)
	Recognized energy basis for monetary payments	10,000 kcal of fossil fuels/$		
1973–1980	Energy quality of plants, wood, and fossil fuels were differentiated	Direct sunlight equivalents of fossil fuels = 2000 solar kcal/fossil fuel kcal (first called energy quality factors, later called solar cost equivalents and then energy quality ratio)	fossil fuel equivalents (FFE) and later coal equivalents (CE)	Odum et al. (1976)
	An energy money ratio was further refined as ratio of total fossil fuel use (or coal use) to GNP	25 000 fuel kcal/1973$, 19 000 CE/1975$, revised in 1980 to 11 000 CE per 1980$	Called energy dollar ratio (CE/$)	
1980–1982	Energy quality of earths processes driven by solar energy recognized, thus solar energy embodied in winds, rains waves accounted for.	6800 global solar cal/cal of available energy in coal	Called "embodied energy" units were global solar calories.	Odum et al. (1983), Odum (1983)
	Energy money ratio	19 600 fuel kcal/$		
1983–1886	Recognized that solar energy, deep heat, and tidal momentum were basis for global processes total global sources equal to 9.44 E24 solar joules	Embodied solar joules/joule of fossil fuels = 40 000 seJ/J, called energy transformation ratio (ETR)	Called embodied solar equivalents (seJ) and later called "emergy" with nomenclature (seJ)	Odum and Odum (1983)
	Embodied solar equivalents per dollar calculated for different nations	seJ/$ in USA economy = 2.2E12 seJ/1984$	seJ/$	
1987–2000	Further refinements of total energy driving global processes, embodied solar energy renamed to EMERGY	Solar emergy/joule of coal energy ~40 000 solar emjoules/joule (seJ/J) called "Transformity"	seJ/J = transformity	Odum (1996)
	Emergy money ratio based on sum of renewable and non-renewable emergy driving economy divided by GNP	Dollar equivalents of emergy are called "emdollars" emergy per dollar in 2000 ~1.0 E12 seJ/$	seJ/g = specific emergy seJ/$ = emergy/unit money	
2000–present	Emergy driving the biosphere reevaluated as 15.83 E24 seJ/year raising all previously calculated transformities by the ratio of 15.83/9.44 = 1.68	Solar emergy per joule of coal energy ~6.7 E 4 seJ/J	seJ/J = transformity; seJ/g = specific emergy	Odum et al. (2000)
	Emergy per dollar calculation does not change. Driving energies increased 1.67 times	Emergy per dollar in USA in 2000 ~ 1.67 E12 seJ/$	seJ/$ = emergy/unit money	

to ''transformity" about the same time. In an appendix to his book Environmental Accounting (Odum, 1996), Odum provided a table listing a chronology of nomenclature and emergy conversions. The table provides insight into the development of the emergy concept and is worth presenting here in slightly different format and with some additions (Table 1).

Between 1983 and today, the emergy methodology has undergone continued transformations. It has continued to mature as each new research project presented new "theoretical wrinkles" and as they were explored dissected, and discussed. Always concepts and theories were explored out-load at our "Systems Seminar" at the University of Florida that meets every Thursday and has for the past 30 some odd years. It was during these sessions where the entire body of concepts and theories were first introduced, discussed, amplified, recycled, and evolved. In many respects, the development of emergy has been a dialog between Odum and his colleagues and students on Thursday afternoons. Thus, the emergy method developed in a way similar to the information cycle posited by Odum (Fig. 1), as necessary to maintain existing, and generate new information through a process of natural selection. First, newly generated information is selected, tested, and extracted, then copied and shared, and finally through use, completed the cycle where it acts through reinforcement to generate new information. This cycling of information is necessary to avoid its loss due to second-law depreciation as well as a requirement of new information generation.

4. Emergy and transformity

With his first attempts at defining emergy, and continuing until his death, Odum used the concept of an energy hierarchy (Fig. 2) as a means of explaining the work of nature and society that results in energy transformations. When viewed in totality, the systems of nature and society are interconnected in webs of energy flow. His concept was that all energy transformations of the geo-biosphere could be arranged in an ordered series to form an energy hierarchy with many joules of sunlight required to make a joule of organic matter, many joules of organic matter to make a joule of fuel, several joules of fuel required to make a joule of electric power, and so on.

The maturing of the emergy methodology resulted in rigorous definitions of terms and nomenclature as well as the refinement of the methodology of calculating transformities. Given next are definitions of most important terms used in the emergy methodology.

Emergy is the availability of energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service. The unit of emergy is the *emjoule*, a unit referring to the available energy of one kind consumed in transformations. For example, sunlight, fuel, electricity, and human service can be put on a common basis by expressing them all in the emjoules of solar energy that is required to produce each. In this case, the value is a unit of *solar emergy* expressed in *solar emjoules* (abbreviated

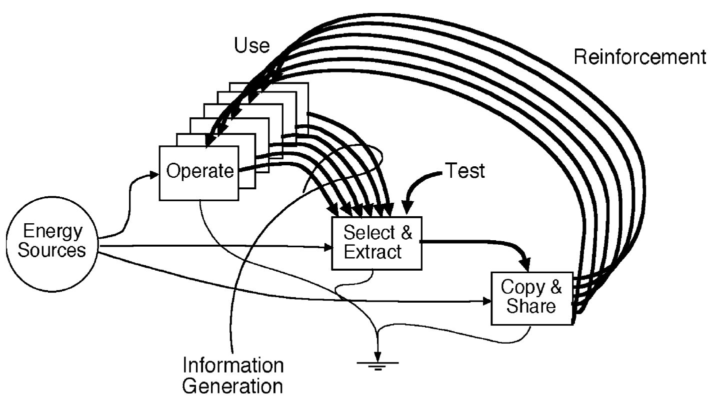

Fig. 1. Diagram illustrating the cycle of generation, selection, sharing, and loop reinforcement through use necessary to maintain and generate new information. (after Odum, 1996).

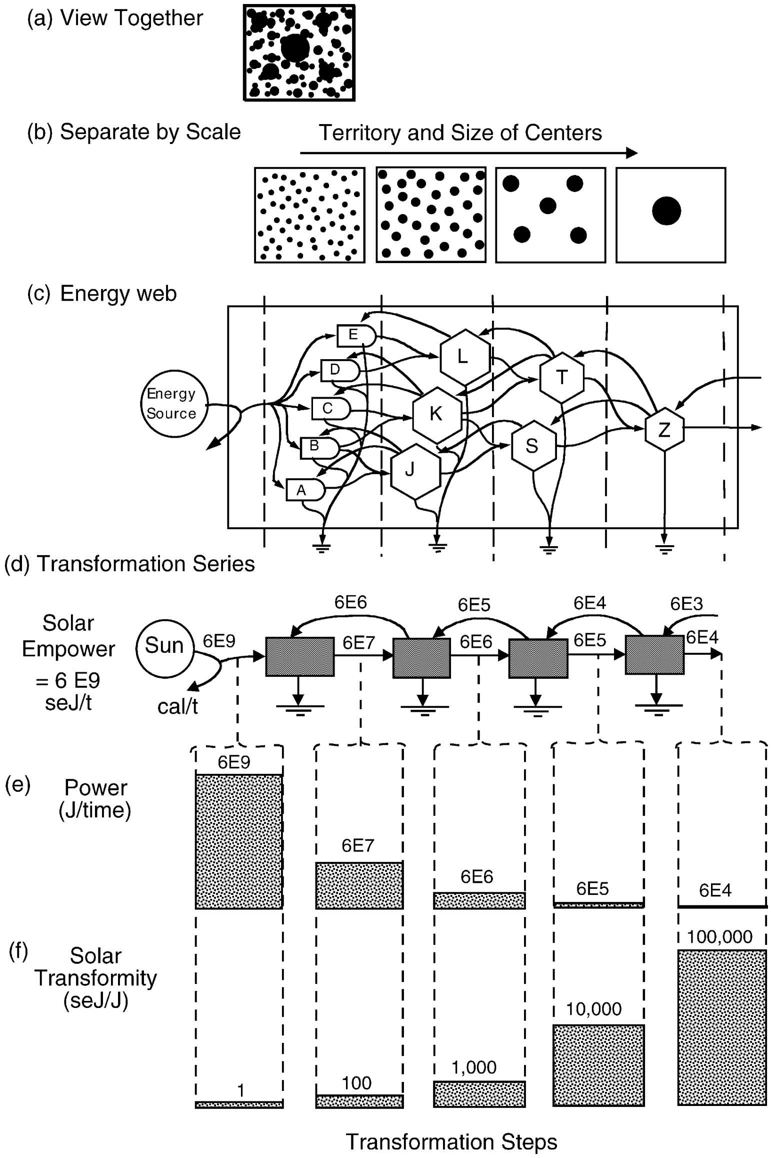

Fig. 2. Concepts of energy transformation hierarchy. (a) All units view together; (b) units separated by scale; (c) the units as a web of energy flows; (d) units shown as a transformation series with values of energy flow on pathways; (e) useful power flowing between transformations; and (f) transformities.

seJ). Although other units have been used, such as coal emjoules or electrical emjoules, in most cases all emergy data are given in solar emjoules.

Unit emergy values (emergy intensities) are calculated based on the emergy required to generate one unit of output. There are several important types of emergy intensities, as follows:

Transformity, defined as the emergy input per unit of available energy (exergy) output. For example, if 4000 solar emjoules are required to generate a joule of wood, then the solar transformity of that wood is 4000 solar emjoules per joule (abbreviated seJ/J). Solar energy is the largest but most dispersed energy input to the earth. *The* *solar transformity of the sunlight absorbed by the earth is 1.0 by definition.*

Specific emergy, defined as the emergy per unit mass output, and usually expressed as solar emergy per gram (seJ/g). Solids may be evaluated best with data on emergy per unit mass for its concentration. Because energy is required to concentrate materials, the unit emergy value of any substance increases with concentration. Elements and compounds not abundant in nature therefore have higher emergy/mass ratios when found in concentrated form, since more environmental work was required to concentrate them, both spatially and chemically.

Emergy per unit money, defined as the emergy supporting the generation of one unit of economic product (expressed as currency). It is used to convert money payments into emergy units. Since money is paid to people for their services and not to the environment, the contribution to a process represented by monetary payments is the emergy that people purchase with the money. The amount of resources that money buys depends on the amount of emergy supporting the economy and the amount of money circulating. An average emergy/money ratio in solar emjoules/$ can be calculated by dividing the total emergy use of a state or nation by its gross economic product. It varies by country and has been shown to decrease each year, which is one index of inflation. This emergy/money ratio is useful for evaluating service inputs given in money units where an average wage rate is appropriate.

Emergy per unit labor, defined as the amount of emergy supporting one unit of labor directly supplied to a process. Laborers apply their work to the process, and in doing so, they indirectly invest in it the whole emergy that made their labor possible (food, training, transport, etc). This emergy intensity is generally expressed as emergy per time (seJ/year, seJ/h), but emergy per money earned (seJ/$) is also used. Indirect labor required to make and supply the inputs to a process is generally measured as dollar cost of services, so that its emergy intensity is calculated as seJ/$.

Empower is a flow of emergy (i.e., emergy/unit time). Emergy flows are usually expressed in units of solar empower (solar emjoules/time: seJ/s, seJ/year).

5. Disciplines and case studies

The emergy concept and the maximum empower principle (see Hall and Cia, Olsen and Campbell, this volume) constitute powerful concepts, definitions, and tools for investigation of systems at all scales, framing a system's behavior and sustainability within the biosphere's driving forces and evolutionary pattern.

More than an evaluation procedure aimed at just assigning numerical values to processes, flows, and products, the emergy method is a conceptual framework, a window through which systems are investigated under a donor-side perspective (i.e. the perspective of the environmental work required to support a system's dynamics). Based on the recognition that "value" has different meanings depending on the scale and perspective of the evaluation, the emergy method assigns values according to what it takes to drive a process and make products, under the constraints of maximum power selection. In Table 2, we list examples of fields of study and processes where Odum's emergy theories have been applied, in order to show the capability of the approach and its potential for further development. The Books of Proceedings of the first three Emergy Conferences (Brown et al., 2001, 2003, 2004) provide a significant set of theoretical and applied papers, for further reading.

6. Emergy and other evaluation procedures

Although Odum's investigations on energy issues started early in the Fifties, it was his seminal book "Environment, Power and Society" (Odum, 1971a) that actually originated the discipline of energy analysis and its uncountable applications to numerous disciplines, from environmental sciences to technological and economic fields of inquiry.

The recognition of the relevance of energy to the growth and dynamics of all complex systems with and without humans gave rise to a blooming of diverse analysis methods, based on accounting and interpreting matter and energy flows, at all scales. In the first

Table 2
Fields of study, emergy projects and references

Emergy and ecosystems (Odum et al., 1999)	
Self-organization (Odum, 1970, 1986, 1988)	
Aquatic ecosystems (Odum, 1967a; Odum, 1977b; Odum and Arding, 1991)	
Food webs and hierarchies (Brown and Bardi, 2001)	
Ecosystem health (Brown and Ulgiati, 2004)	
Forest ecosystems (Odum et al., 1995c; Doherty et al., 1995)	
Complexity (Odum, 1987a; Odum, 1994)	
Emergy and Information	
Diversity and information (Keitt, 1991; Odum, 1996)	
Culture, Education, University (Odum and Odum, 1980; Odum et al., 1995b)	
Emergy, Agriculture, agricultural products	
Food production, agriculture (Odum, 1967b, 1984b; Ulgiati et al., 1993)	
Emergy and energy sources and carriers	
Fossil fuels (Brown et al., 1993; Odum, 1996)	
Renewable and non-renewable electricity (Odum, 1983; Brown and Ulgiati, 2002)	
Hydrologic dams (Brown and McLanahan, 1992)	
Biofuels (Odum, 1980a; Odum and Odum, 1984)	
Hydrogen (Barbir, 1992)	
Emergy and the Economy	
National and international analyses (Odum and Odum, 1983; Odum, 1987b; Brown, 2003; Cialani et al., 2004)	
Trade (Odum, 1984a)	
Environmental accounting (Odum, 1996)	
Development policies (Odum, 1980b)	
Sustainability (Odum, 1973; Odum et al., 1976; Brown and Ulgiati, 1999)	
The prosperous way down (Odum and Odum, 2001)	
Emergy and cities	
Research on cities (Odum et al., 1995b)	
Taiwan spatial organization (Huang, 1998)	
Transportation modes (Bayley et al., 1977)	
Emergy and landscape development	
Empower density (Odum, 1996)	
Land development indicators (Brown and Vivas, 2004)	
Emergy in landforms (Kangas, 2002)	
Emergy and ecological engineering	
Restoration models (Prado-Jatar and Brown, 1997)	
Reclamation projects (Odum et al., 1981)	
Artificial ecosystems: wetlands, ponds... (Odum, 1977b; Odum, 1985)	
Emergy, material flows, and recycling	
Mining and mineral processing (Odum, 1996)	
Recycling pattern in human-dominated ecosystems (Brown and Buranakarn, 2003)	

Table 2 (*Continued*)

Emergy and thermodynamics	
Efficiency and Power (Odum and Pinkerton, 1955; Odum et al., 1995b)	
Maximum Empower Principle (Odum, 1975, 1983; Hall, 1995)	
Pulsing paradigm (Odum, 1982, 1995)	
Thermodynamic principles (Giannantoni, 2002, 2003)	
Systems modeling	
Energy systems language and modeling (Odum, 1971a,b, 1972b)	

two decades, since energy analysis has come to the attention of many scientists (1970s and 1980s), studies were devoted primarily to assessing and demonstrating the superiority of a given approach compared to others (see, for example, IFIAS, 1974 and Slesser, 1998). As the field matured and new scientific conceptualizations developed, (e.g. system thinking, hierarchical theory, non-linear dynamics, fractal geometry, complex systems analysis), it became increasingly clear that different approaches were very often required by the very nature of the problems being dealt with, in order to build a set of complementary descriptions, able to provide different assessments, narratives, or views on different space-time scales. This is why, depending on the goal of the investigation, a large number of analysts developed tools such as Embodied Energy Analysis, Exergy Analysis, Material Flow Accounting, Life Cycle Assessment, Ecological Footprint, and Societal Metabolism, among others, each method being able to answer specific questions about a system's performance.

Common features can be explicitly or implicitly found in the different methods for evaluation, including Odum's emergy. The latter, however, was intended to account for aspects, which are usually not accounted for by other evaluation methods. Non-emergy approaches most often evaluate only non-renewable resources, depending on what human technologies are able to extract from them (user-side quality). Furthermore, non-emergy approaches do not account for the free services that a system receives from the environment (e.g., the photosynthetic activity driven by the solar radiation, the dilution of pollutants by the wind, etc.), which are just as much a requirement for the productive process as are, e.g., fossil fuels nor do they have an accounting procedure for human labor, societal services, and information (i.e. for those flows, which carry negligible energy but are supported by a huge indirect flow of resources). Emergy includes all of this, perhaps not perfectly, but in a way to help us understand that there is a huge network of supporting energies necessary to support, e.g., any particular economic activity in our culture.

More specifically, by expanding the scope of energy studies to the biosphere's space and time scales, the emergy method is able to:

(i) Investigate systems that are outside of human activities (ecosystems, global biosphere processes).
(ii) Focus on the role of the environment in support of human-dominated processes, both on the resource supply side and on the sink side (dilution or uptake of pollutants).
(iii) Perform a donor-side quality assessment as a complement of generally used user-side assessments. This provides a measure of how much the system relies on the biosphere support.
(iv) Evaluate processes that are directly based on small flows of physical carriers, but are supported by huge indirect flows of resources, such as the creation and processing of information.
(v) Expand the time scale of the evaluation, to include the memory of resource flows converging to the system.
(vi) Assess the renewability of resources on the basis of both space and time convergence required to make them. The transformity quantifies this renewability in a continuous form, with higher values corresponding to higher convergence of environmental work and therefore lower renewability.
(vii) Evaluate in a quantitative way the (donor) quality of those resource flows and storages that have no market (such as fresh water, biodiversity, fertile topsoil) and cannot be evaluated in monetary terms.
(viii) Assess the environmental impact of processes based on matching of high quality and low quality resources.
(ix) Include in the evaluation the emergy supporting human labor and services.

All of these properties largely expand upon those of any other evaluation method, provide a powerful and comprehensive tool for the investigation of systems on the larger scales of the biosphere, and finally, help understanding the dynamic interaction between human-dominated processes and resources and services provided for free by nature.

7. The emergy conferences

The emergy method cannot escape undergoing the information cycle pointed out by H.T. Odum (Fig. 1). Since information is something that needs to be copied, shared, tested, and selected to avoid its loss due to second-law depreciation as well as to allow for new information to be generated, it is of fundamental importance that definitions and concepts, methods, and case studies using the emergy methodology are also disseminated, tested, and selected by emergy specialists and by all kinds of interested people, acting in the role of science's information-processing specialists. In doing so, errors are found and in time drop out, and those concepts and methods that work are reinforced through sharing and selecting.

For this reason, a series of biennial Emergy Synthesis Research Conferences was started in 1999, in order to gather emergy specialists together and provide the critical mass for shared information and theoretical evolution. The response to the calls of the organizing committee was stronger and more diverse than expected, indicating that the approach is by itself spreading and reaching research groups and disciplinary areas far from the original fields of application. In a way, this was a consequence of Odum's broad interests and scientific productivity, which allowed him to explore links and relations with areas outside systems ecology and thermodynamics; to embrace and synthesize economy, philosophy, social sciences, and policy.

Held every two years in Gainesville on the University of Florida campus, the Emergy Synthesis Conference has grown steadily from about 35 participants in 1999 to over 90 participants in the January 2004 conference. The proceeding of the conference, published by the Center for Environmental Policy at the University of Florida (see Brown et al., 2001, 2003, 2004) has increased in size from a book of 26 papers resulting from the 1999 conference to 45 papers published in the 2004 proceedings. The conference is truly international bringing together scientists representing 18 countries from the continents of Asia, Australia, Europe, and North and South America.

8. Summary comments

The concept of energy quality has been most controversial. While quality has been recognized, somewhat, in the energy literature (Cleveland, 1992) where different forms of fossil energy are expressed in coal or oil equivalents, and some researchers have even expressed electricity in oil equivalents by using first law efficiencies, there has been wide-spread rejection of quality corrections of other forms of energy. The idea that a calorie of sunlight is not equivalent to a calorie of fossil fuel, or electricity strikes many as preposterous, since a calorie is a calorie is a calorie. Others have rejected the concept as being impossible since from their perspective, it is impossible to quantify the amount of sunlight that is required to produce a quantity of oil. Still others reject it because emergy does not appear to conform to first law accounting principles.

In retrospect, there is little debate that the systems H.T. Odum studied were as varied as the energy sources that drove them. All of them must have had an influence on his thinking and the development of the concepts and theories of emergy. The gigantic global gyres of tropical lows developing into hurricanes during his stint as meteorologist for the Air Force, the spring boil of Silver Springs, the ocean currents and waves on the Pacific atoll at Eniwetok, the freshwater inputs and gulf currents of the Texas coastline, or the rains and winds of the tropical rainforest in Puerto Rico must have had their influence on his thinking. In each case, Odum translated what he saw into systems of energy flow and began to speculate that different forms of energy had different abilities to do work ... in terms of not only amounts of work but also kind of work. He reasoned that a joule of sunlight was not the same as a joule of fossil fuel, or a joule of food, and that sunlight drives photosynthesis but cannot drive an automobile without significant efforts to concentrate it. These observations, the quantitative evaluations they fostered, and the resulting body of theories that are embodied in the emergy approach have been rejected by some and criticized by many. Yet, we believe that non-emergy specialists are very likely to find in the emergy approach the conceptual framework that is absolutely needed for a reliable investigation of the interplay of natural ecosystems and human-dominated systems and processes. The common thread is the ability to evaluate all forms of energy, materials, and human services on a common basis by converting them into equivalents of one form of energy, solar emergy, a measure of the past and present environmental support to any process occurring in the biosphere.

References

Barbir, F., 1992. Analysis and Modeling of Environmental and Economic Impacts of the Solar Hydrogen Energy System, Ph.D. Dissertation, Department of Mechanical Engineering, University of Miami, Florida, p. 176.

Bayley, S., Odum, H.T., Hanley, B., McDowell, C., 1977. Example of an Energy Evaluation of a Transportation Project, Center for Wetlands, University of Florida, Gainesville (CFW-77-01), p. 34.

Brown, M.T., 2003. Resource imperialism. emergy perspectives on sustainability, international trade and balancing the welfare of nations. In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A., Mayumi, K. (Eds.), Book of Proceedings of the International Workshop “Advances in Energy Studies. Reconsidering the Importance of Energy”, Porto Venere, Italy, 24–28 September 2002, SGE Publisher Padova, Italy, pp. 135–149.

Brown, M.T., Bardi, E., 2001. Emergy of Ecosystems. Folio No. 3 of Handbook of Emergy Evaluation, The Center for Environmental Policy, University of Florida, Gainesville, p. 93 (http://www.ees.ufl.edu/cep/).

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Res. Conserv. Recycling 38, 1–22.

Brown, M.T., McLanahan, T.R., 1992. Emergy Analysis Perspectives of Thailand and Mekong River Dam Proposals, Report to the Cousteau Society, Center for Wetlands and Water Resources, University of Florida, Gainesville, p. 60.

Brown, M.T., Ulgiati, S., 1999. Emergy evaluation of the biosphere and natural capital. AMBIO 28 (6), 486–493.

Brown, M.T., Ulgiati, S., 2002. Emergy evaluation and environmental loading of electricity production systems. J. Cleaner Prod. 10, 321–334.

Brown, M.T., Ulgiati, S., 2004. Emergy, transformity, and ecosystem health. In: Jorgensen, S.E. (Ed.), Handbook of Ecosystem Health, CRC Press, in press.

Brown M.T., Vivas M.B., 2004. A Landscape Development Intensity Index. Env. Monit. Assess. in press.

Brown, M.T., Brandt-Williams, S., Tilley, D., Ulgiati, S. (Eds.), 2001. Emergy Synthesis. Theory and Applications of the Emergy Methodology. Book of Proceedings of the First

International Emergy Research Conference, Gainesville, FL, 2–4 September, 1999, The Center for Environmental Policy, University of Florida, Gainesville, FL, p. 328.

Brown, M.T., Campbell, D., Comar, V., Huang, S.L., Rydberg, T., Tilley, D.R., and Ulgiati, S. (Eds.), 2004. Emergy Synthesis. Theory and Applications of the Emergy Methodology, Part 3. Book of Proceedings of the Third International Emergy Research Conference, Gainesville, FL, 29–31 January, 2004. The Center for Environmental Policy, University of Florida, Gainesville, FL.

Brown, M.T., Odum, H.T., Tilley, D., and Ulgiati, S. (Eds.), 2003. Emergy Synthesis. Theory and Applications of the Emergy Methodology, Part 2. Book of Proceedings of the Second International Emergy Research Conference, Gainesville, FL, 20–22 September, 2001. The Center for Environmental Policy, University of Florida, Gainesville, FL.

Brown, M.T., Woithe, R.D., Montague, C.L., Odum, H.T., Odum, E.C., 1993. Emergy Analysis Perspectives of the Exxon Valdez Oil Spill in Prince William Sound, Alaska. Final Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville, FL, p. 114.

Cialani, C., Russi, D., Ulgiati, S., 2004. Investigating a 20-year national economic dynamics by means of emergy-based indicators. In: Brown, M.T., Campbell, D., Comar, V., Huang, S.L., Rydberg, T., Tilley, D.R., and Ulgiati, S. (Eds.), Emergy Synthesis. Theory and Applications of the Emergy Methodology, Part 3. Book of Proceedings of the Third International Emergy Research Conference, Gainesville, FL, 29–31 January, 2004. The Center for Environmental Policy, University of Florida, Gainesville, FL.

Cleveland, C.J., 1992. Energy quality and energy surplus in the extraction of fossil fuels in the US. Ecol. Econ. 6, 139–162.

Doherty, S.J., Odum, H.T., Nilsson, P.O., 1995. Systems Analysis of the Solar Emergy Basis for Forest Alternatives in Sweden. Final Report to the Swedish State Power Board, College of Forestry, Garpenberg, Sweden, p. 112.

Giannantoni C., 2002. The Maximum Em-Power Principle as the Basis for Thermodynamics of Quality. SGE Publisher, Padova, Italy, p. 185. ISBN 99-973101-87-6.

Giannantoni, C., 2003. The problem of the initial conditions and their physical meaning in linear differential equations of fractional order. Appl. Math. Comput. 141, 87–102.

Hall, C.A.S., Cleveland, C.J., and Kaufmann, R., 1986. Energy and Resource Quality. The Ecology of the Economic Process. John Wiley & Sons, NY, p 557.

Hall, C.A.S. (Ed.), 1995. Maximum Power. The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, p. 454.

Huang, S.L., 1998. Spatial hierarchy of urban energetic systems. In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A., Mayumi, K. (Eds.), Book of Proceedings of the International Workshop "Advances in Energy Studies. Energy Flows in Ecology and Economy", Porto Venere, Italy, 26–30 May 1998. MUSIS Publisher, Roma, Italy, pp. 499–514.

IFIAS, International Federation of Institutes for Advanced Study, 1974. In: Slesser, S.M. (Ed.), Energy Analysis Workshop on Methodology and Conventions, Stockholm.

Kangas, P.C., 2002. Emergy of Landforms. Folio No. 5 of Handbook of Emergy Evaluation. The Center for Environmental Policy, University of Florida, Gainesville, p. 93. (http://www.ees.ufl.edu/cep/).

Keitt, T.H., 1991. Hierarchical Organization of Energy and Information in a Tropical Rain Forest Ecosystem, M.S. Thesis, Environmental Engineering Sciences, University of Florida, Gainesville, p. 72.

Odum, H.T., 1967a. Biological circuits and the marine systems of Texas. In: Olson, T.A., Burgess, F.J. (Eds.), Pollution and Marine Ecology, Wiley-Interscience, New York, pp. 99–157.

Odum, H.T., 1967b. Energetics of Food Production. The World Food Problem, Report of the President's Science Advisory Committee, Panel on World Food Supply, Vol. 3, The Whitehouse, pp. 55–94.

Odum, H.T., 1970. Summary: an emerging view of the ecological system at El Verde. In: Odum, H.T., Pigeon, R.F. (Eds.), A Tropical Rainforest, Division of Technical Information, U.S. Atomic Energy Commission (TID2470), Chapter I-10, pp. I 191–I 289, p. 1660.

Odum, H.T., 1971a. Environment, Power and Society. John Wiley, NY, p. 336.

Odum, H.T., 1971b. An energy circuit language for ecological and social systems: its physical basis. In: Patten, B. (Ed.), Systems Analysis and Simulation in Ecology, Vol. 2, Academic Press, New York, pp. 139–211.

Odum, H.T., 1972a. Unscientific Myopia: The Illusions of Plenty. A Review of the "Energy and Power" Issue of Scientific American. Landscape Architecture, pp. 246–248.

Odum, H.T., 1972b. Chemical cycles with energy circuit models. In: Dryssen, D., Jagner, D. (Eds.), Changing Chemistry of the Ocean, Nobel Symposium 20, Wiley, New York, pp. 223–257.

Odum, H.T., 1973. Energy, ecology and economics. Royal Swedish Academy of Science. AMBIO 2 (6), 220–227.

Odum, H.T., 1975. Combining energy laws and corollaries of the maximum power principle with visual system mathematics. In: Levin, S. (Ed.), Ecosystems: Analysis and Prediction. Proceedings of the Conference on Ecosystems at Alta, Utah. SIAM Institute for Mathematics and Society, Philadelphia, pp. 239–263.

Odum, H.T., 1976a. Energy quality and carrying capacity of the earth. Response at Prize Ceremony* Institute de la Vie* Paris. Trop. Ecol. 16 (1), 1–8.

Odum, H.T., 1976b. Energy analysis and net energy. In: Proceedings of NSF Workshop on Net Energy, Stanford, Cal. Institute for Energy Studies, Stanford Univ. and TRW, pp. 90–115.

Odum, H.T., 1977a. Energy analysis, energy quality and environment. In: Gilliland, M.W. (Ed.), Energy Analysis: A New Public Policy Tool, American Association for the Advancement of Science, Selected Symposium No. 9, Washington, DC, Westview Press, pp. 55–87, Odum, H.T., 1983. Systems Ecology. John Wiley, New York, p. 644.

Odum, H.T., 1977b. Value of wetlands as domestic ecosystems. In: Montanari, J.H., Jusler, J.A, (Eds.), National Wetland Protection Symposium, U.S. Fish and Wildlife Services, Dept. of the Interior, Reston, Va. (FWS/Obs-78/97).

Odum, H.T., 1980a. Biomass and Florida's Future: A Hearing before the Subcommittee on Energy Development and Applications of the Committee on Science and Technology of the U.S. House of Representatives, 96th Congress, Government Printing Office, Washington, DC, pp. 58–67

Odum, H.T., 1980b. Principle of environmental energy matching for estimating potential economic value: a rebuttal. Coastal Zone Manage. J. 5 (3), 239–243.

Odum, H.T., 1982. Pulsing, power and hierarchy. In: Mitsch, W.J., Ragade, R.K., Bosserman, R.W., Dillon, J.A., Jr. (Eds.), Energetics and Systems, Ann Arbor Science, Ann Arbor, Michigan, pp. 33–59,

Odum, H.T., 1983. Maximum power and efficiency: a rebuttal. Ecol. Model. 20, 71–82.

Odum, H.T., 1984a. Energy analysis of the environmental role in agriculture. In: Stanhill, G. (Ed.), Energy and Agriculture, Springer Verlag, Berlin, pp. 24–51, p. 192.

Odum, H.T., 1984b. Embodied energy, foreign trade, and welfare of nations. In: Jansson, A.M. (Ed.), Integrations of Economy and Ecology, an Outlook for the Eighties, Asko Laboratory, University of Stockholm, Sweden, pp. 185–200.

Odum, H.T., 1985. Water conservation and wetland values. In: Godfrey, P.J., Kaynor, E.R., Pelezrski, S., Benforado, J. (Eds.), Ecological Considerations in Wetlands Treatment of Municipal Wastewaters, Van Nostrand Reinhold, New York, pp. 98–111, p. 473.

Odum, H.T., 1986. Enmergy in ecosystems. In: Polunin, N. (Ed.), Environmental Monographs and Symposia, John Wiley, NY, pp. 337–369.

Odum, H.T., 1987a. Living with complexity. In: The Crafoord Prize in the Biosciences, 1987, Lectures, Royal Swedish Academy of Sciences, Stockholm, Sweden, pp. 19–85, p. 87.

Odum, H.T., 1987b. Models for national, international, and global systems policy. In: Braat, L.C., Van Lierop, W.F.J. (Eds.), Economic-Ecological Modeling, Elsevier Science Publishing, New York, Chapter 13, pp. 203–251, p. 329.

Odum, H.T., 1988. Self organization, transformity and information. Science 242, 1132–1139.

Odum, H.T., 1994. Ecological and General Systems: An Introduction to Systems Ecology, University Press of Colorado, Niwot, Revised Edition of Systems Ecology, 1983, Wiley, p. 644.

Odum, H.T., 1995. Self organization and maximum power, Chapter 28. In: Hall, C.S.A. (Ed.), Maximum Power, University Press of Colorado, Niwot, pp. 311–364 .

Odum H.T., 1996. Environmental Accounting. Emergy and Environmental Decision Making, John Wiley & Sons, NY.

Odum, H.T., Arding, J.E., 1991. Emergy Analysis of Shrimp Mariculture in Ecuador, Report to Coastal Studies Institute, University of Rhode Island, Narragansett, Center for Wetlands, University of Florida, Gainesville, p. 87.

Odum, E.C., Odum, H.T., 1980. Energy systems and environmental education. In: Bakshi, T.S., Naveh, Z. (Eds.), Environmental Education—Principles, Methods and Applications, Plenum Press, New York, pp. 213–231 .

Odum, H.T., Odum, E.C., (Eds.), 1983. Energy Analysis Overview of Nations, with sections by G. Bosch, L. Braat, W. Dunn, G. de R. Innes, J.R. Richardson, D.M. Scienceman, J.P. Sendzmir, D.J. Smith, and M.V. Thomas. Working Paper of the International Institute of Applied Systems Analysis, Laxenburg, Austria (WP-83-82), p. 469.

Odum, E.C., Odum, H.T., 1984. System of ethanol production from sugarcane in Brazil. Ciencia e Cultura 37 (11), 1849–1855.

Odum, H.T., Pinkerton, R.C., 1955. Time's speed regulator: the optimum efficiency for maximum power output in physical and biological systems. Am. Scientist 43, 331–343.

Odum, H.T., et al., 1976. Net energy Analysis of Alternatives for the United States. U.S. Energy Policy: Trends and Goals. Part V. Middle and Long-term Energy Policies and Alternatives. 94th Congress 2nd Session Committee Print. Prepared for the Subcommittee on Energy and Power of the Committee on Interstate and Foreign Commerce of the U.S. House of Representatives, 66-723, U.S. Govt. Printing Office, Washington, DC, pp. 254–304.

Odum, H.T., Kemp, W., Sell, M., Boynton, W., Lehman, M., 1978a. Energy analysis and the coupling of man and estuaries. Environ. Manage. 1, 297–315.

Odum, H.T., Gayle, T., Brown, M.T., Waldman, J., 1978b. Energy analysis of the University of Florida, Center for Wetlands, University of Florida, Gainesville, in preparation.

Odum, H.T., Kangas, P., Best, G.R., Rushton, B.T., Leibowitz, S., Butner, J.R., 1981. Studies on Phosphate Mining Reclamation and Energy, Center for Wetlands, University of Florida, Gainesville, p. 142.

Odum, H.T., Lavine, M.J., Wang, F.C., Miller, M.A. Alexander, J.F., Butler, T., 1983. Manual for Using Energy Analysis for Plant Siting, Report to the Nuclear Regulatory Commission, Washington, DC. Report No. NUREG/CR-2443, National Technical Information Service, Springfield, Va., p. 242.

Odum, E.C., Odum, H.T., Peterson, N.S., 1995a. Using simulation to introduce systems approach in education, Chapter 31. In: Hall, C.A.S. (Ed.), Maximum Power, University Press of Colorado, Niwot, pp. 346–352.

Odum, H. T., Brown, M. T., Whitefield, L. S., Woithe, R., and Doherty, S., 1995b. Zonal Organization of Cities and Environment: A Study of Energy System Basis for Urban Society. A Report to the Chiang Ching-Kuo Foundation for International Scholarly Exchange, Center for Environmental Policy, University of Florida, Gainesville, FL.

Odum, W.P., Odum, E.P., Odum, H.T., 1995c. Nature's pulsing paradigm. Estuaries 18 (4), 547–555.

Odum, H.T., Brown, M.T., Ulgiati, S., 1999. Ecosystems as energetic systems. In: Jorgensen, S.E., Muller, F. (Eds.), Handbook of Ecosystem Theories, CRC Press, New York, pp. 281–302.

Odum, H.T., Brown, M.T., Williams, S.B., 2000. Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios. Folio #1—Introduction and Global Budget. Center for Environmental Policy, Environmental

Odum H.T., Odum, E.C., 2001. A Prosperous Way Down: Principles and Policies, University Press of Colorado.

Prado-Jatar, M.A., Brown, M.T., 1997. Interface ecosystems with an oil spill in a Venezuelan tropical savannah. Ecol. Eng. 8, 49–78.

Slesser M., 1998. Text of a message from Prof. Malcom Slesser to the workshop participants. In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A., Mayumi, K. (Eds.), Advances in Energy Studies. Energy Flows in Ecology and Economy. Musis Publisher, Roma, Italy, pp. 625–627.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1993. Emergy analysis of italian agricultural system. the role of energy quality and environmental inputs. In: Bonati, L., Cosentino, U., Lasagni, M., Moro, G., Pitea D., Schiraldi, A. (Eds.), Trends in Ecological Physical Chemistry, Elsevier Science Publishers, Amsterdam, pp. 187–215.