Emergy Analysis and Environmental Accounting

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Glossary

emdollar (or EM$) A measure of the money that circulates in an economy as the result of some process. In practice, to obtain the emdollar value of an emergy flow or storage, the emergy is multiplied by the ratio of total emergy to gross domestic product for the national economy.

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 the equivalent solar energy required to generate it. Sometimes it is referred to 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 Emergy per unit time (sej/time)

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

nonrenewable 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.

production Production measured in emergy is the sum of all emergy inputs to a process.

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.

transformity The ratio obtained by dividing the total emergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of emergy/energy (sej/J). A transformity for a product is calculated by summing all of the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different forms to emergy of the same form.

This article presents a brief review of the concepts of energy hierarchy and definitions of emergy and related quantities. Tables of data are given on global emergy flows from which emergy and transformities of most products and processes of the biosphere are calculated. Then tables of transformities for many products are provided. Finally, several case studies of evaluations of energy technologies are given. In a summary discussion emergy analysis (EMA) and embodied energy analysis (EEA) are compared describing the strengths and weaknesses of each approach related to the evaluation of energy systems.

1. INTRODUCTION

1.1 Energy and the Emergy Hierarchy

Emergy is a universal measure of the work of nature and society made on a common basis. The work of nature and society results in energy transformations that when viewed in totality are interconnected in webs of energy flow. All energy transformations of the geobiosphere can be arranged in an ordered series to form an energy hierarchy. For example, many joules of sunlight are required to make a joule of organic matter, many joules of organic matter to make a joule of fuel, several joules of fuel are required to make a joule of electric power, and so on. Since different kinds of energy are not equal in their contribution to processes, work is made comparable by expressing each form of energy in units of one form. To accomplish this, the available energy of different forms of energy is evaluated by means of the energy of one type previously required to produce it. This quantity of one type of energy previously used is called emergy (spelled with an "m").

1.2 Definitions

The following paragraphs contain definitions and a brief explanation of emergy concepts. A more complete introduction can be found in H. T. Odum's 1996 text, *Environmental Accounting: Emergy and Environmental Decision Making*.

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 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 are calculated based on the emergy required to produce them. There are three main types of unit emergy values as follows:

- Transformity is one example of a unit emergy value and is defined as the emergy per unit of available energy (exergy). 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 is the unit emergy value of matter defined as the emergy per mass, 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 work was required to concentrate them, both spatially and chemically.
- Emergy per unit money is a unit emergy value 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. This emergy/money ratio is useful for evaluating service inputs given in money units where an average wage rate is appropriate.

Emergy accompanying a flow of something (energy, matter, information, etc.) is easily calculated if the unit emergy value is known. The flow expressed in its usual units is multiplied by the emergy per unit of that flow. For example, the flow of fuels in joules per time can be multiplied by the transformity of that fuel (emergy per unit energy in solar emjoules/joule), or the mass of a material input can be multiplied by its specific emergy (emergy per unit mass in solar emjoules/gram). The emergy of a storage is readily calculated by multiplying the storage quantity in its usual units by the emergy per unit.

Unit emergy values are a kind of efficiency measure, since they relate all the inputs to an output. The lower the transformity or specific emergy, the more efficient the conversion. It follows from the second law that there are some minimum unit emergy values for processes, which are consistent with maximum power operations. While there is no way to calculate them directly, the lowest transformity found in long-operating systems is used as an approximation. When estimating a theoretical potential of some system, it is appropriate to use the best (lowest) transformity known.

Empower is a flow of emergy (i.e., emergy per time). Emergy flows are usually expressed in units of solar empower (solar emjoules per time).

1.3 Emergy Evaluation Procedure

Emergy accounting uses the thermodynamic basis of all forms of energy, materials, and human services but converts them into equivalents of one form of energy. Emergy accounting is organized as a top-down approach where first a system diagram of the process is drawn to organize the evaluation and account for all inputs and outflows. Tables of the actual flows of materials, labor, and energy are constructed from the diagram and all flows are evaluated. 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 system being evaluated with those of the environment and larger economy within which it is embedded and that allow the prediction of economic viability, carrying capacity, or fitness.

This evaluation process has been termed emergy synthesis. Synthesis is the act of combining elements into coherent wholes. 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, context driven, and cannot be fully understood or utilized outside of systems. 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.

1.3.1 Left-Right Energy Systems Diagram

Systems diagrams are used to show the inputs that are evaluated and summed to obtain the emergy of a resulting flow or storage. 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. Components and flows within diagrams are arranged from left to right reflecting more available energy flow on the left, decreasing to the right with each successive energy transformation. For example, abundant solar energy is utilized in successive transformations in ecological, agricultural, and technoeconomic subsystems to support a small amount of high-quality energy of humans, their government, and information. A simple diagram of the global system including humans is shown in Fig. 1. The left-to-right organization also corresponds to increasing scale of territory and turnover time. As illustrated in Fig. 1, every energy transformation box has more than one input, including larger energy flows from the left, lesser amounts from units in parallel, and small but important controlling energies feeding back from the right.

1.3.2 Preparation of an Emergy Evaluation Table

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 summed for 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.

Separate tables are constructed for evaluations of flows and storage. Tables are usually constructed in the same format, as given by the column headings and format shown in Table I.

- 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 emergy per unit used for calculations, expressed in solar emergy joules per unit. Sometimes, inputs are expressed in grams, hours, or dollars, therefore an appropriate conversion ratio is used (sej/hr; sej/g; sej/$).
- Column 6 is the solar emergy of a given flow, calculated as raw input times the transformity (column 3 times column 5).
- Column 7 is the emdollar value of a given item for a given year. This is obtained by dividing the emergy in Column 6 by the emergy-to-money ratio (EMR) for the country and selected year of the evaluation (units are sej/$). The EMR is calculated independently. The resulting values in this column express the amount of economic activity that can be supported by a given emergy flow or storage.

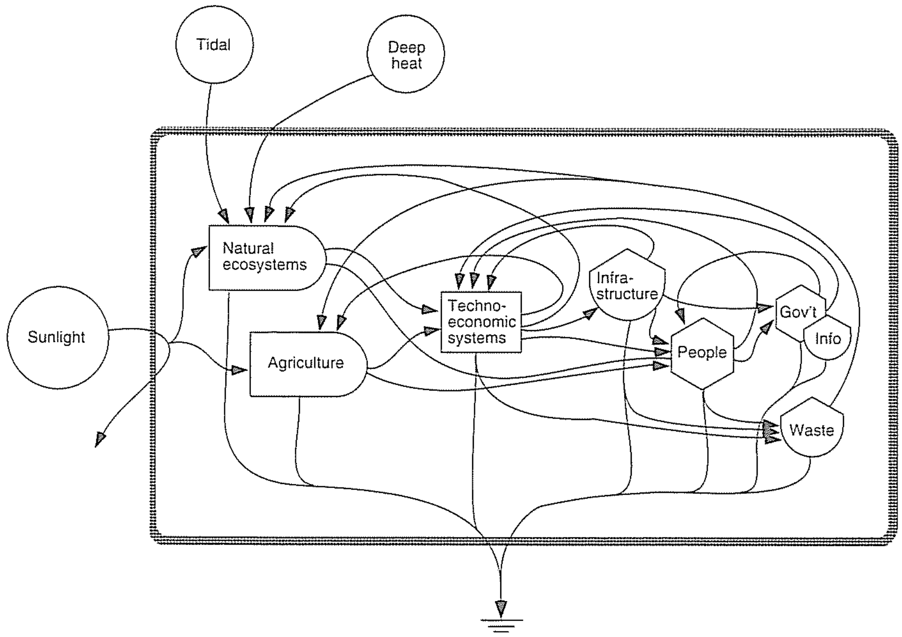


FIGURE 1 Successive energy transformations supporting human civilization. Large energy flows from the right support smaller and smaller amounts of high-quality energy. With each succeeding energy transformation, some energy is degraded some is passed on to the next level (to the left) and some is fed back in control actions. Explanations of symbols may be found in Odum (1996).

TABLE I

Example Emergy Evaluation Table

1	2	3	4	5	6	7
Note	Item	Data	Units	Emergy/unit (sej/unit)	Solar emergy (E + 15 sej/year)	emS Value (1998 emS/year)
1.	First item	xx.x	sej/year	xxx.x	xxx.x	xxx.x
2.	Second item	xx.x	g/year	xxx.x	xxx.x	xxx.x
..						
..						
n.	nth item	xx.x	sej/year	xxx.x	xxx.x	xxx.x
O.	Output	xx.xx	sej or g/year	xxx.x	$\sum_{n}^{1} Em$	xxx.x

1.3.3 Emergy of Storages

When calculating the emergy of stored quantities (storages)—for instance, wood biomass in a forest ecosystem or buildings in a city—it is necessary to sum the emergy of each of the inputs for the time of its contribution. Input emergy inflows are multiplied by the time it takes to accumulate the storage and exported yield, if any.

1.3.4 Evaluations Based on Averaged Inputs

Apparently all systems pulse with time intervals and pulse strength that increase with scale. To evaluate a process on one scale of time and space usually means using averages for each of the inputs from smaller scales where pulses are of high frequency. For example, for an evaluation of phenomena on the scale of human economy, yearly averages are often appropriate. On this scale average solar energy and average tidal energy are used. For calculations of global processes over a longer scale of time, an average of inputs from the deep earth may be used. Thus, for many purposes emergy evaluations are made with averaged inputs. The result is emergy evaluation as if the system was in a steady state. If the table is an evaluation of a storage, the result is in solar emjoules. If the table is an evaluation of a product flow, the result is in solar emjoules per time (or empower).

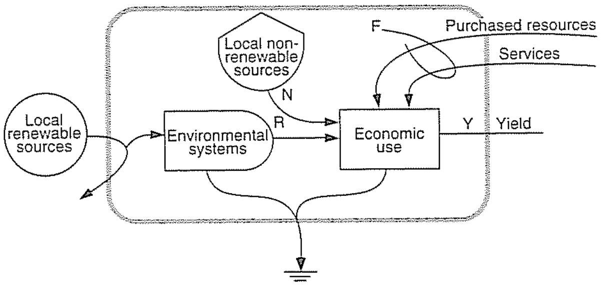
Dynamic emergy evaluations of storages and flows are also used. When a storage is growing, decreasing, or oscillating, its stored emergy contents and transformity are changing as well. Where a system is adequately represented by a dynamic model, an algorithm can be added to the model which calculates a time sequence of emergy and transformity. A simulation model of this type produces a running calculation according to the emergy definition, summing the inputs to storages, multiplying these by their unit emergy, and subtracting emergy removals.

1.3.5 Calculating Unit Emergy Values

After a table is prepared that evaluates all the inputs, unit emergy values of products can be calculated. The output or product (row “O” in Table I) is evaluated first in units of energy, exergy, or mass. Then the input emergy is summed and unit emergy value for the product calculated by dividing the emergy by the units of the output. The unit values that result are useful for other emergy evaluations. Thus, any emergy evaluation generates new emergy unit values.

1.3.6 Performance Indicators

The systems diagram in Fig. 2 shows nonrenewable 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 process to take place and include human service and purchased nonrenewable energy and material brought in from elsewhere (fuels, minerals, electricity, machinery, fertilizer, etc.). Several ratios, or indices are given in Fig. 1 that are used to evaluate the global performance of a process as follows:



Yield (Y) = R + N + F
Emergy yield ratio = Y/F
Emergy investment ratio = F/(R + N)
Environmental loading ratio = (F + N)/R
Empower density = (R + N + F)/area

FIGURE 2 Emergy indices used as performance indicators.

Emergy yield ratio. The ratio of the total emergy (local and imported) driving a process or system to the emergy imported. The ratio is a measure of the potential contribution of the process to the main economy, due to the exploitation of local resources.

Environmental loading ratio. The ratio of nonrenewable and imported emergy use to renewable emergy use. It is an indicator of the pressure of a transformation process on the environment and can be considered a measure of ecosystem stress due to a production (transformation activity).

Emergy sustainability index. The ratio of the emergy yield ratio to the environmental loading ratio. It measures the potential contribution of a resource or process to the economy per unit of environmental loading.

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

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 emergy density are also calculated separately by dividing the total renewable emergy by area and the total nonrenewable emergy by area, respectively.

Several other ratios are sometimes calculated depending on the type and scale of the systems being evaluated.

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

Emprice. The emprice of a commodity is the emergy one receives for the money spent. Its units are sej/$.

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 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.

1.3.7 Understanding Emergy Indicators: What They Indicate

Lengthy discussion of the performance indicators were given in a previous publication by the authors titled "Emergy Based Indices and Ratios to Evaluate Sustainability—Monitoring Economies and Technology towards Environmentally Sound Innovation." Additional background and further discussion follows.

Transformity only measures how much emergy it takes to generate one unit of output, regardless of whether or not the input is renewable. It is a measure of efficiency on the global spatial and timescale of the biosphere. It indicates the hierarchical position of an item in the thermodynamic scale of the biosphere and can be regarded as a quality factor from the point of view of biosphere dynamics.

The $ELR = (N + F)/R$ is designed to compare the amount of nonrenewable and purchased emergy $(N + F)$ to the amount of locally renewable emergy (R). In the absence of investments from outside, the renewable emergy that is locally available would have driven the growth of a mature ecosystem consistent with the constraints imposed by the environment and would be characterized by an $ELR = 0$. Instead, the nonrenewable imported emergy drives a different site development, whose distance from the natural ecosystem can be indicated by the ratio $(N + F)/R$. The higher this ratio, the bigger the distance of the development from the natural process that could have developed locally. In some ways, the ELR is a measure of the disturbance to the local environmental dynamics, generated by the development driven from outside. The ELR is clearly able to make a difference between nonrenewable and renewable resources, thus complementing the information that is provided by the transformity (Brown and Ulgiati, 1997). From past experience gained in previous case studies investigated, it appears that low ELRs (around two or less) are indicative of relatively low environmental impacts (or processes that can use large areas of a local environment to "dilute impacts"). ELRs between three and ten are indicative of moderate environmental impacts, while ELRs ranging from ten up to extremely high values indicate much higher environmental impacts due to large flows of concentrated nonrenewable emergy in a relatively small local environment.

The emergy yield ratio, $EYR = (R + N + F)/F$, is a measure of the ability of a process to exploit and make available local resources by investing outside resources. It provides a look at the process from a different perspective, its openness. It provides a measure of the appropriation of local resources by a process, which can be read as a potential additional contribution to the economy, gained by investing resources already available. The lowest possible value of the EYR is 1, which indicates that a process delivers the same amount of emergy that was provided to drive it, and that it is unable to usefully exploit any local resource. Therefore, processes whose EYR is 1 or only slightly higher do not provide significant net emergy to the economy and only transform resources that are already available from previous processes. In so doing, they act as consumer processes more than creating new opportunities for system's growth. Primary energy sources (crude oil, coal, natural gas, uranium) usually show EYRs greater than 5, since they are exploited by means of a small input from the economy and return much greater emergy flows, which have been generated by previous geologic and ecological activities that accumulated these resources over past millennia. Secondary energy sources and primary materials like cement and steel show EYRs in the range from 2 to 5, indicating moderate contribution to the economy.

If the ELR (nonrenewable versus renewable emergy flows) and EYR (outside versus local emergy flows) are combined, a sustainability index is created—that is, an aggregated measure of the potential contribution to the larger system (EYR) per unit of loading imposed on the local system (ELR). This indicator, called emergy index of sustainability (EIS) is usefully applicable to measure openness and loading changes occurring over time in both technological processes and economies. In principle, the lowest possible value of the EIS is zero (when $EYR = 0$ and $ELR < \infty$ or when $EYR \neq 0$ and $ELR \rightarrow \infty$), while the theoretical upper limit $(\rightarrow \infty)$ is only possible for untouched, mature ecosystems. According to the results of several case studies investigated, EIS's lower than 1 appear to be indicative of consumer products or processes and those greater than 1 indicative of products that have net contributions to society without heavily affecting its environmental equilibrium. As it relates to economies, an EIS lower than 1 is indicative of highly developed consumer-oriented systems, EISs between 1 and 10 have been calculated for what have been termed "developing economies," while EISs greater than 10 indicate economies that have not yet significantly started any industrial development.

Finally, the emergy density, ED, measures the amount of emergy invested on one unit of land and suggest land be a limiting factor to any kind of development or process. Higher EDs characterize city centers, information centers such as governmental buildings, universities, and research institutions, and industrial clusters, while lower EDs are calculated for rural areas and natural environments.

2. *EMERGY EVALUATION OF THE BIOSPHERE AND ITS PROCESSES*

Figure 3 shows an aggregated system diagram of the energy transformation network of the biosphere arranged with decreasing energy from left to right. In Fig. 3, all the components interact and are required by the others. As a result, the total emergy driving the biosphere (the sum of solar, tidal, and deep heat) is required by all processes within, and thus the emergy assigned to each of the internal pathways is the same. After millions of years of self-organization, the transformations of the driving energies by the atmosphere, ocean, and land are organized simultaneously to interact and contribute mutual reinforcements. Therefore, the energy flow of each jointly necessary process is the sum of the emergy from the three sources.

TABLE II

Annual Emergy Contributions to Global Processes (after Odum et al., 2000)*

Input	Units	Inflow units/year	Emergy/unit sej/unit	Empower E24 sej/year
Solar insolation,	J[a]	3.93 E24	1.0	3.93
Deep earth heat,	J[b]	6.72 E20	1.20 E4	8.06
Tidal energy,	J[c]	0.52 E20	7.39 E4	3.84
Total		—	—	15.83

Abbreviations: sej = solar emjoules; E24 means multiplied by 10^{24}.

*Not including nonrenewable resources.

[a] Sunlight: solar constant 2 gcal/cm^2/min = 2 Langley per minute; 70% absorbed; earth cross section facing sun 1.27 E14 m^2.

[b] Heat release by crustal radioactivity 1.98 E20 J/year plus 4.74 E20 J/year heat flowing up from the mantle (Sclater *et al.*, 1980). Solar transformity 1.2 E4 sej/J based on an emergy equation for crustal heat as the sum of emergy from earth heat, solar input to earth cycles, and tide (Odum, 2000a).

[c] Tidal contribution to oceanic geopotential flux is 0.52 E20 J/year (Miller, 1966). Solar transformity of 7.4 E4 sej/J is based on an emergy equation for oceanic geopotential as the sum of emergy from earth heat, solar input to the ocean, and tide following Campbell (1998) (Odum, 2000a).

2.1 Annual Budget of Emergy Flow (Empower) Supporting the Geobiosphere

An emergy evaluation table of the main inputs to the geobiosphere of the earth (omitting, for the moment, the emergy use from nonrenewable resources) is given in Table II. The annual budget of emergy flow (empower) supporting the geobiosphere (atmosphere, ocean, and earth crust) includes solar energy, tidal energy, and heat energy from the deep earth. Other inputs from space, such as the high-energy radiation of solar flares, cosmic rays, meteorites, and stellar dust, are not evaluated. All of these vary with oscillations and pulses, and their emergy values vary with their intensities.

Total emergy contributions to the geobiosphere are about 15.83 E24 sej/year based on a reevaluation

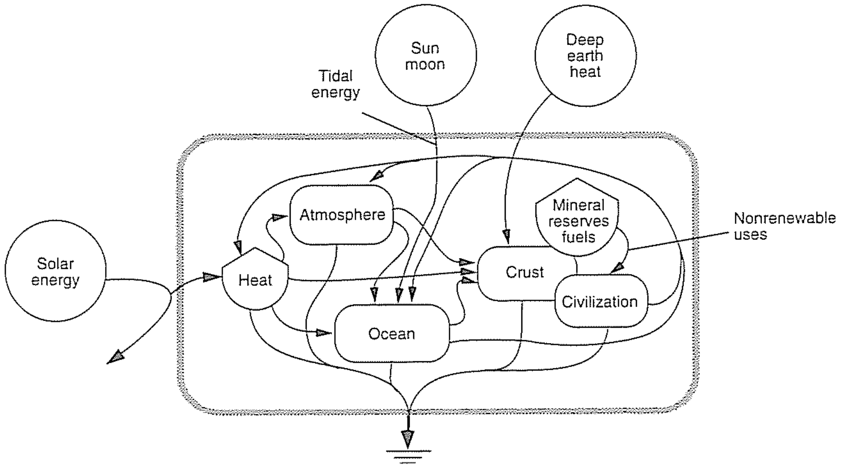


FIGURE 3 Energy transformation network of the biosphere. The interconnected pathways of energy flow, inputs, and all main components are necessary to all the other components and processes.

and subsequent recalculation of energy contributions done in the year 2000. Prior to that date, the total emergy contribution to the geobiosphere that was used in calculating unit emergy values was 9.44 E24 sej/year. The increase in global emergy reference base to 15.83 E24 sej/year changes all the unit emergy values that directly and indirectly were derived from the value of global annual empower. Thus, unit emergy values calculated prior to that year are multiplied by 1.68 (the ratio of 15.83/9.44).

2.2 Average Emergy Unit Values for Main Global Processes

Table III calculates unit emergy values for some main flows of the earth. The total emergy input to the geobiosphere in solar emergy (15.83 E24 sej/yr from Table II) is divided by each of the global product's ordinary measure (number of joules or grams). The unit values that result are useful for other emergy evaluations where global averages can be used.

2.3 Temporary Emergy Inputs to the Geobiosphere

In the 19th and 20th centuries, the production and consumption processes of human civilization using the large emergy in the geologic stores of fuels and minerals reached a scale with global impact. Because these storages are being used much faster than they are being generated in geologic cycles, they are often called nonrenewable resources. They are actually very slowly renewed resources. Table IV summarizes these additional components of the global emergy budget.

At present, the emergy contribution through the human civilization to the geobiosphere from the slowly renewed resources is greater than the inputs from renewable sources. A symptom of this surge of temporary emergy inflow is the carbon-dioxide accumulation in the atmosphere that causes greenhouse effects that change the pattern and intensity of weather.

It is important to note that the unit emergy values given in Table III are average values for global processes. It is well understood that there is no single

TABLE III

Emergy of Products of the Global Energy System (after Odum et al., 2000)

Product and units	Emergy* E24 sej/year	Production units/year	Emergy/unit sej/unit
Global latent heat, J[a]	15.83	1.26 E24	12.6 sej/J
Global wind circulation, J[b]	15.83	6.45 E21	2.5 E3 sej/J
Global precipitation on land, g[c]	15.83	1.09 E20	1.5 E5 sej/g
Global precipitation on land, J[d]	15.83	5.19 E20	3.1 E4 sej/J
Average river flow, g[e]	15.83	3.96 E19	4.0 E5 sej/g
Average river geopotential, J[f]	15.83	3.4 E20	4.7 E4 sej/J
Average river chem. energy, J[g]	15.83	1.96 E20	8.1 E4 sej/J
Average waves at the shore, J[h]	15.83	3.1 E20	5.1 E4 sej/J
Average ocean current, J[i]	15.83	8.6 E17	1.8 E7 sej/J

*Main empower of inputs to the geobiospheric system from Table II not including nonrenewable consumption (fossil fuel and mineral use).

[a] Global latent heat = latent heat of evapotranspiration 1020 mm/year (1020 mm/year) (1000 g/m^2/mm) (0.58 kcal/g) (4186 J/kcal) (5.1 E14 m^2) = 1.26 E24 J/year.

[b] Global wind circulation, 0.4 watts/m^2 (Wiin-Nielsen and Chen, 1993) (0.4 J/m^2/sec) (3.15 E7 sec/year) (5.12 E14 m^2/earth) = 6.45 E21 J/year.

[c] Global precipitation on land = 1.09 E11 m^3/year (Ryabchikov, 1975) (1.09 E14 m^3) (1 E6 kg/m^3) = 1.09 E20 g/year.

[d] Chemical potential energy of rainwater relative to seawater salinity (1.09 E20 g/year) (4.94 J Gibbs free energy/g) = 5.19 E20 J/year.

[e] Global runoff, 39.6 E3 km^3/year (Todd, 1970) (39.6 E12 m^3/year) (1 E6 g/m^3) = 3.96 E19 g/year.

[f] Average river geopotential work; average elevation of land = 875 m (39.6 E12 m^3/year) (1000 kg/m^3) (9.8 m/sec^2) (875 m) = 3.4 E20 J/year.

[g] Chemical potential energy of river water relative to seawater salinity (3.96 E19 g/year) (4.94 J Gibbs free energy/g) = 1.96 E20 J/year.

[h] Average wave energy reaching shores, (Kinsman, 1965) (1.68 E8 kcal/m/year) (4.39 E8 m shore front)(4186 J/kcal) = 3.1 E20 J/year.

[i] Average ocean current: 5 cm/sec (Oort *et al.*, 1989); 2-year turnover time (0.5) (1.37 E21 kg water) (0.050 m/sec) (0.050 m/sec)/(2 year) = 8.56 E17 J/year.

TABLE IV

Annual Emergy Contributions to Global Processes Including Use of Resource Reserves (after Brown and Ulgiati, 1999)

Inputs and Units	Inflow (J/year)	Emergy/unit* (sej/unit)	Empower E24 sej/year
Renewable inputs[a]	—	—	15.8
Nonrenewable energies released by society			
Oil, J[b]	1.38 E20	9.06 E4	12.5
Natural gas (oil eq.), J[c]	7.89 E19	8.05 E4	6.4
Coal (oil eq.), J[d]	1.09 E20	6.71 E4	7.3
Nuclear power, J[e]	8.60 E18	3.35 E5	2.9
Wood, J[f]	5.86 E19	1.84 E4	1.1
Soils, J[g]	1.38 E19	1.24 E5	1.7
Phosphate, J[h]	4.77 E16	1.29 E7	0.6
Limestone, J[i]	7.33 E16	2.72 E6	0.2
Metal ores, g[j]	9.93 E14	1.68 E9	1.7
Total nonrenewable empower			34.3
Total global empower			50.1

Abbreviations: sej = solar emjoules; E3 means multiplied by 10^3; t = metric ton; oil eq. = oil equivalents.

*Values of solar emergy/unit from Odum (1996) and modified to reflect a global resource base of 15.83 E24 sej/year.

[a] Renewable Inputs: Total of solar, tidal, and deep heat empower inputs from Odum (1996).

[b] Total oil production = 3.3 E9 Mt oil equivalent (British Petroleum, 1997) Energy flux = (3.3 E9 t oil eq.) (4.186 E10 J/t oil eq.) = 1.38 E20 J/year oil equivalent.

[c] Total natural gas production = 2.093 E9 m^3 (British Petroleum, 1997) Energy flux = (2.093 E12 m^3) (3.77 E7 J m^3) = 7.89 E19 J/year.

[d] Total soft coal production = 1.224 E9 t/year (British Petroleum, 1997) Total hard coal production = 3.297 E9 t/year (British Petroleum, 1997) Energy flux = (1.224 E9 t/year) (13.9 E9 J/t) + (3.297 E9 t/year)(27.9 E9 J/t) = 1.09 E20 J/year.

[e] Total nuclear power production = 2.39 E12 kwh/year (British Petroleum, 1997); Energy flux = (2.39 E12 kwh/year)(3.6 E6 J/kwh) = 8.6 E18 J/year electrical equivalent.

[f] Annual net loss of forest area = 11.27 E6 ha/year (Brown et al., 1997) Biomass = 40 kg m^2; 30% moisture (Lieth and Whitaker, 1975) Energy flux = (11.27 E6 ha/year) (1 E4 m^2/ha) (40 kg m^2)(1.3 E7 J/kg)(0.7) = 5.86 E19 J/year.

[g] Total soil erosion = 6.1 E10 t/year (Oldeman, 1994; Mannion, 1995) Assume soil loss 10 t/ha/year and 6.1 E9 ha agricultural land = 6.1 E16/g/year (assume 1.0% organic matter), 5.4 kcal/g Energy flux = (6.1 E16 g)(.01) (5.4 kcal/g)(4186 J/kcal) = 1.38 E19 J/year.

[h] Total global phosphate production = 137 E6 t/year (USDI, 1996) Gibbs free energy of phosphate rock = 3.48 E2 J/g Energy flux = (137 E12 g)(3.48 E2 J/g) = 4.77 E16 J/year.

[i] Total limestone production = 120 E6 t/year (USDI, 1996) Gibbs free energy of phosphate rock = 611 J/g Energy flux = (120 E12 g)(6.11 E2 J/g) = 7.33 E16 J/year.

[j] Total global production of metals 1994: Al, Cu, Pb, Fe, Zn (World Resources Institute, 1996): 992.9 E6 t/year = 992.9 E12 g/year.

unit emergy value for any given product, since no two processes are alike. This also holds for the processes of the biosphere. For instance, there are many transformities for rain depending on location and even time of year. Precipitation varies with altitude, is affected by mountains, and depends on the weather systems in complex ways. The evaluations in Table III are for the whole earth with 70% ocean. If the land is regarded as a higher level in the hierarchical organization of the geobiosphere, then rain over the land represents a convergence of oceanic resources as well as those of the continents, and calculation of continental rain transformity includes all geobiosphere driving energy (see rows 3 and 4 in Table III). As a result, continental rainfall has a higher transformity compared to the global average. To carry this idea even farther, the rainfall in any particular location may have a higher or lower transformity depending on the source area and intensity of the solar energy driving the cycles that produce it.

3. *UNIT EMERGY VALUES FOR FUELS AND SOME COMMON PRODUCTS*

Unit emergy values result from emergy evaluations. Several tables of unit emergy values for some common materials and energy sources follow. In Table V, unit emergy values are given for primary nonrenewable energy sources along with the emergy yield ratio (EYR). In some cases, the EYR is based on only one

TABLE V

Unit Emergy Values for Primary Nonrenewable Energy Sources (After Odum, 1996, Updated)

Item	Transformity (Sej/J)	Sej/g	EYR
Plantation pine (*in situ*)	1.1 E4	9.4 E7	2.8
Peat	3.2 E4	6.7 E8	3.0
Lignite	6.2 E4		6.8
Coal	6.7 E4		8–10.5
Rainforest wood (chipped, trans.)	6.9 E4	4.1 E8	2.2
Natural gas	8.1 E4		6.8–10.3
Crude oil	9.1 E4		3.2–11.1
Liquid motor fuel	1.1 E5		2.6–9.0
Electricity	3.4 E5		—

TABLE VI

Unit Emergy Values for Some Common Products (After Odum, 1996, Updated)

Item	Transformity (Sej/J)	Specific emergy (Sej/g)
Corn stalks	6.6 E4	
Rice, high energy[a]	7.4 E4	1.4 E9
Cotton	1.4 E5	
Sugar (sugarcane)[b]	1.5 E5	
Corn	1.6 E5	2.4 E9
Butter	2.2 E6	
Ammonia fertilizer	3.1 E6	
Mutton	5.7 E6	
Silk	6.7 E6	
Wool	7.4 E6	
Phosphate fertilizer	1.7 E7	
Shrimp (aquaculture)	2.2 E7	
Steel[b]	8.7 E7	7.8 E9

[a] After Brown and McKlanahan (1996).

[b] After Odum and Odum (1983).

evaluation for instance plantation pine. In other cases, several evaluations have been done of the same primary energy but from different sources and presumably different technology, so a range of values are given. For instance, the range of values for natural gas (6.8 to 10.3) represent the difference between offshore natural gas (6.8) and on natural gas produce in the Texas field on shore (10.3). Obviously each primary energy source has a range of values depending on source and technology. By using data from typical production facilities (and actually operating facilities), the unit emergy values represent average conditions and can be used for evaluations when actual unit values are not known. If it is known that conditions where an evaluation is being conducted are quite different than the averages suggested here, then detailed evaluations of sources should be conducted.

Table VI lists the unit emergy values for some common products in the order of their transformity. Only a few products are given here, while many more evaluations leading to unit emergy values have been conducted and are presented in a set of emergy folios, published by the Center for Environmental Policy at the University of Florida (www.ees.ufl.edu/cep).

Calculations of emergy production and storage provide a quantitative basis for making choices about environment and economy. The unit energy values done previously aid new evaluations, since they may save time and energy of authors attempting other evaluations because they do not need to reevaluate all inputs from scratch. In light of this, a series of emergy folios have been published, and others planned, that provide data on emergy contents, the computations on which they were based, and comparisons (www.ees.ufl.edu/cep/emergydownloads.asp). To date there are five folios by as many authors, who take the initiative to make new calculations or assemble results from the extensive but dispersed literature in published papers, books, reports, theses, dissertations, and unpublished manuscripts. The tabulating of unit emergy values and their basis is the main purpose of the handbooks.

4. CASE STUDIES: EVALUATION OF ENERGY CONVERSION SYSTEMS

Several case studies of conversion systems are evaluated using embodied energy analysis and emergy analyses (hereafter EEA and EMA, respectively). The results from case studies are discussed jointly in the following sections of this article. Comparisons are made to highlight synergisms that support each other and differences that require EMA be used for a deeper understanding of energy systems performance. Evaluations of the case studies resulted from a joint research project between the authors with funding from the Italian Energy Agency (ENEA).

4.1 Description of the Power Systems

4.1.1 Oil-Powered Thermal Plant

A conventional oil-powered thermal plant (Fig. 4) mainly consists of a fuel storage area, boilers for

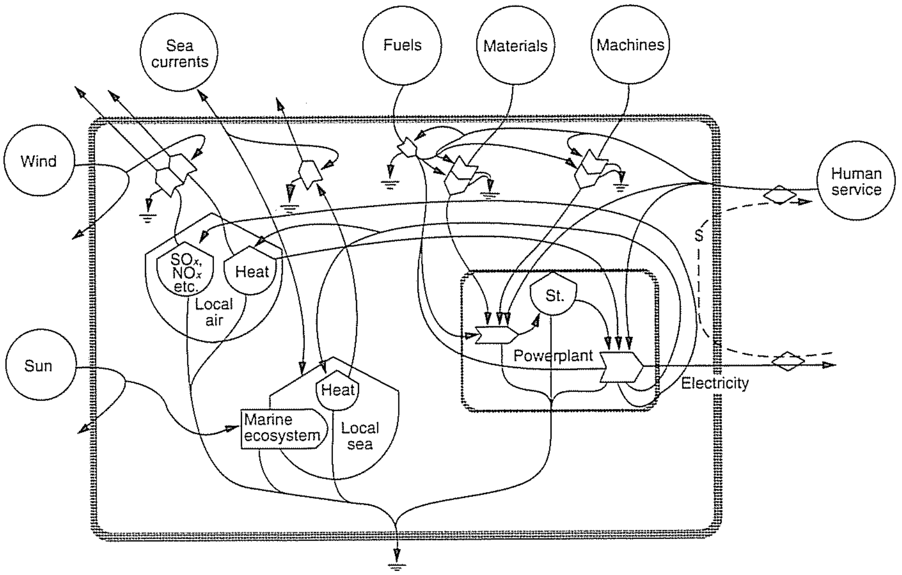


FIGURE 4 System diagram of a thermal power plant an its environment showing the use of nonrenewable energy as well as the use of the environment for cooling.

steam generation, steam turbines, electric generators, a set of electricity transformers from low to high voltage for easier transport to final users, one or more chimneys for the release of combustion gases to the atmosphere, and finally a set of heat exchangers and pumps to cool the plant off by means of river or sea water (44 m^3/s) and condense the steam. Filters and scrubbers for partial uptake of pollutants at the chimney mouth as well as fuel desulfurization devices are also used. The data for the evaluation were provided by the Italian National Electric Company (ENEL) and relate to the actual average performance of the Piombino 1280 MWe power plant (Tuscany, Italy). The plant consists of four 320 Mwe boiler-turbine-generator groups, cooled by the seawater from the nearby Mediterranean Sea. All inputs were listed and grouped according to their material components (steel, copper, etc.), then suitable energy and emergy intensity coefficients were used, according to previous studies available in the scientific literature. Labor and services are also accounted for in the emergy analysis only. Waste heat and chemicals released to the environment (seawater and atmosphere) were quantified and the amount of environmental services (cooling water, wind, etc.) needed for dispersal, dilution and abatement is calculated by means of the emergy accounting procedure. Fig. 4 shows the direct and indirect annual environmental flows supporting the construction of the plant structure (assuming a lifetime of 25 years) as well as its daily operation. The plant started to be fully operative in the year 1979, which means that it is not far from the end of its life cycle and may require a significant upgrade investment or final decommissioning and replacement by a more modern technology.

4.1.2 *Wind Turbine*

The investigated case study (Fig. 5) consists of a 2.5 MW wind powered field, composed with 10 single-blade, 250 kW, wind turbines M30-A, sited in southern Italy (Casone Romano). The wind field, installed in the year 1995 by the Riva Calzoni Company, is presently operated by ENEL. The distance between two generators is 150 m. Each turbine is located on the top of a 33 m support tower. Operating wind speeds are between 4 and 25 m/s. For wind speeds outside of these extremes, the turbine automatically stops. The wind field does not require any local labor for its daily activity and is directly managed from the operating company by means of remote control. The energy systems diagram of a wind power plant is shown in Fig. 5.

4.1.3 *Geothermal Plant*

To optimize the exploitation of the rich geothermal fields available in central Italy (Tuscany), the National Electric Company designed a 20 MW power module to be efficiently and cost-effectively installed in several sites of the geothermal area (Fig. 6). The main reason supporting the development of such a module is the need for the reduction of the time between the discovery of a new geothermal site and

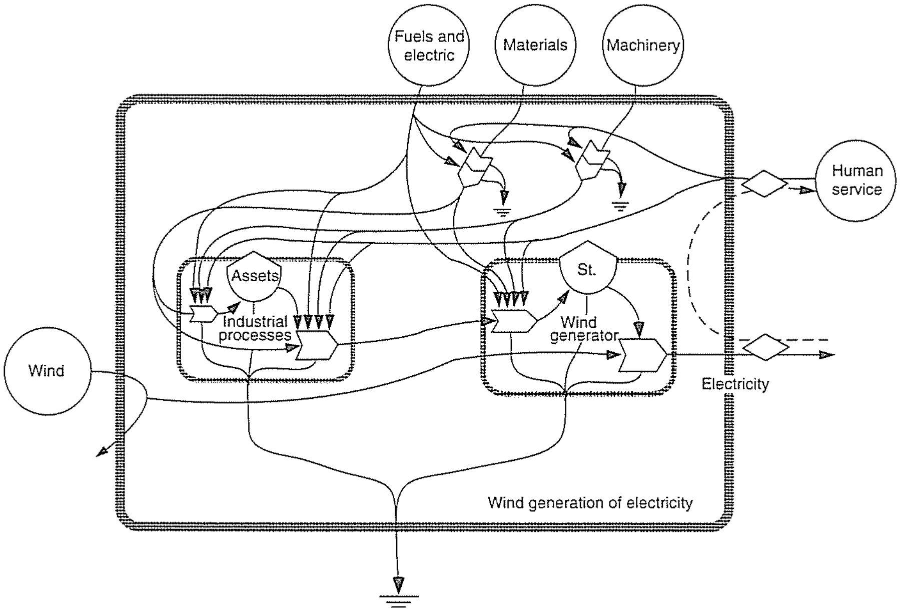


FIGURE 5 System diagram of wind power plant showing the industrial processes required to produce the generator and associated structure and the use of wind energy in the production of electricity.

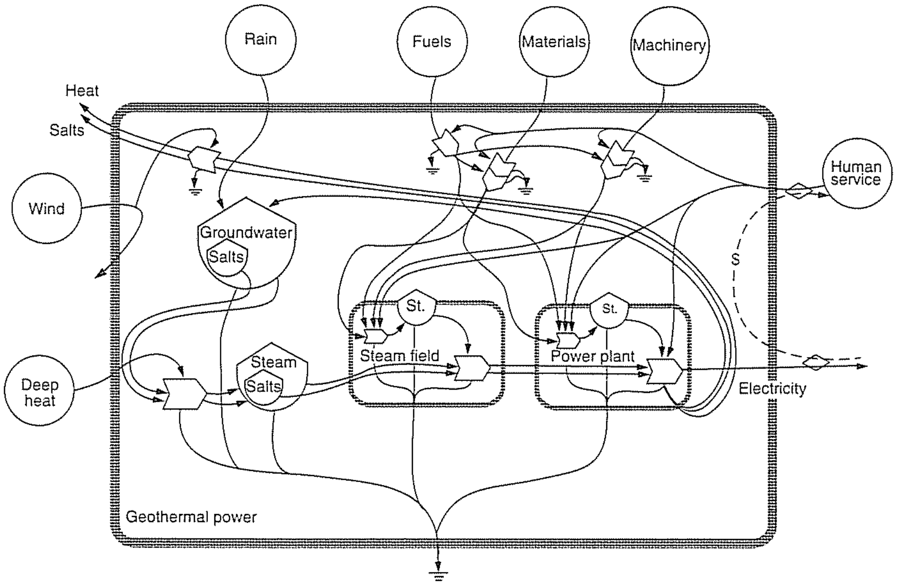


FIGURE 6 System diagram of a geothermal power plant showing the use of nonrenewable energies in developing the steam field and power plant, the use of geothermal steam, and release of heat and salts to the larger environment.

its actual exploitation. The module essentially consists of a turbine-generator group, receiving high-enthalpy fluids from nearby wells. A fraction of the extracted steam is then released to the atmosphere, through three cooling towers. The remaining fraction is, instead, condensed and reinjected into the underground reservoir to avoid their water depletion. The steam pipelines are made with steel and are insulated with rockwool and aluminum. Instead, the reinjection lines are made with glass fiber. The data used for the case study were provided by ENEL and relate the Cornia 2 power plant, sited close to Pisa and installed in the year 1994. No local labor is required. The plant is 24 hours per day distance-operated by the company's operative station sited in Larderello, the site where the first electric plant running on geothermal heat was installed in 1904.

Geothermal fluids carry and release significant amounts of hydrogen sulphide, carbon dioxide, radioactive radon, arsenic, mercury, nitrogen, and boron. This involves plant corrosion problems as well as pollution problems in the area. For this reason, several devices have been designed for the uptake and abatement of the most dangerous chemicals. The plant as well as the environmental and technological flows supporting its activity are described by the systems diagram drawn in Fig. 6.

4.1.4 Hydroelectric Plant

The case study (systems diagram shown in Fig. 7) concerns the reservoir-dam electric plant Pollino Nord, sited in southern Italy. Its activity started in the year 1973. The reservoir has a capacity of 1000 m^3 and is located at about 600 m above sea level. Water flows out of the dam through an iron pipeline reaching the turbines located downstream, at about 50 m above sea level. Two 51 MW turbines with vertical axis convert the water energy into electricity, generating a total actual electric power of about 85 MW. The plant started its activity in 1973. No labor is required for plant operation. It is distance-operated from the ENEL headquarters in Catanzaro (southern Italy).

4.1.5 Bioethanol Production

Figure 8 describes the main steps of the process: corn production, harvesting and transport to plant, and industrial processing. Corn is processed to ethanol and distillers dried grains with solubles (DDGS), to be used as animal feed. Agricultural residues were considered as a partial source of process heat (to substitute for some of the coal), so that a lower fossil energy input can be charged to the industrial phase. However, harvesting agricultural residues depletes the amount of nutrients in soil and requires significant energy expenditure for their replacement. Soil erosion is also accelerated, with significant consequences on soil fertility. Therefore, the fraction of agricultural residues that can be actually harvested is small and depends on a variety of parameters that are not easy to determine. The evaluation was conducted assuming that approximately 70% of agricultural residues were harvested, taking some of the above mentioned consequences (loss and replacement of nutrients in soil) into account. Corn production data refer to Italian agricultural standards, while corn-to-ethanol industrial conversion refers to average available conversion technologies.

4.1.6 Hydrogen from Steam Reforming of Natural Gas

Steam reforming of hydrocarbons (mainly natural gas) has been the most efficient, economical, and

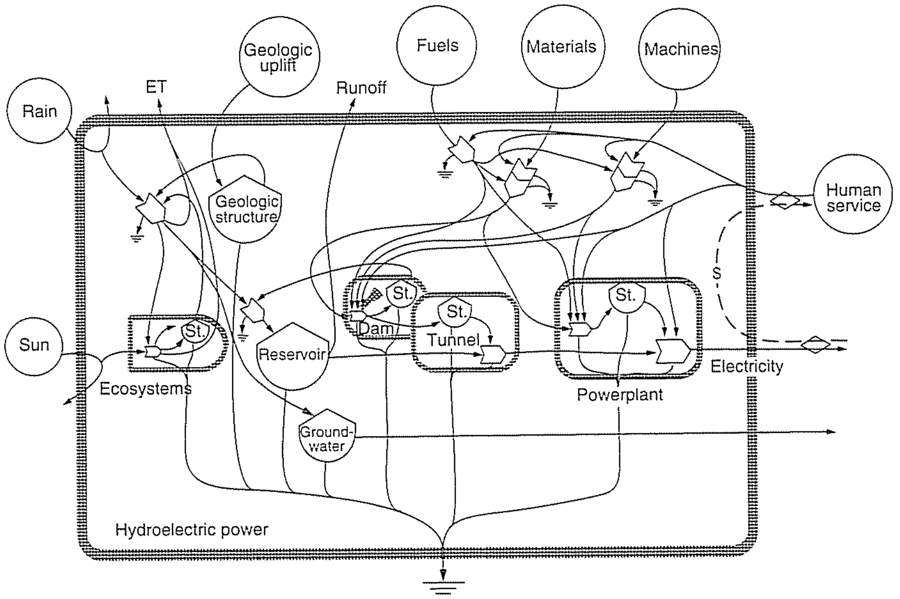


FIGURE 7 Systems diagram of a hydroelectric power plant showing the use of nonrenewable energy materials machines and human service in the construction operation and maintenance of the plant as well as the reliance of the system on geologic formation of the watershed and input of rain.

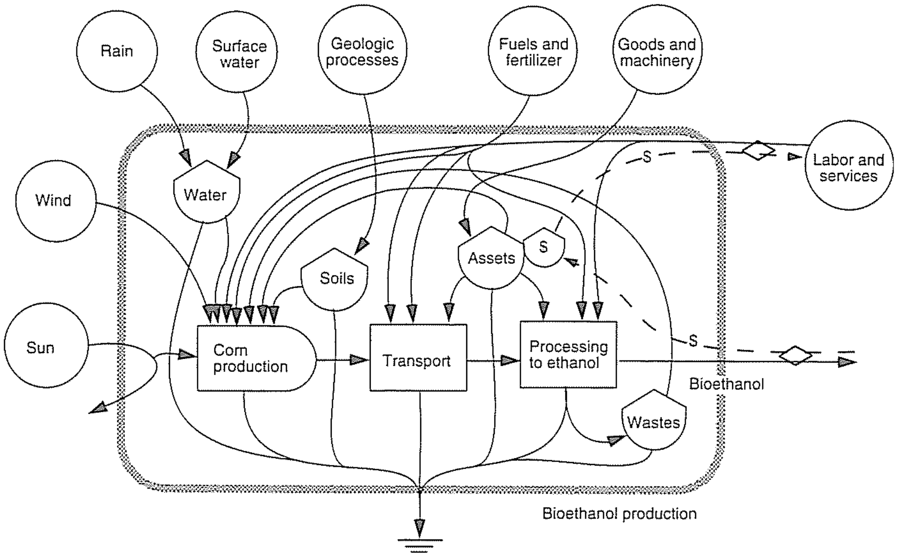


FIGURE 8 Systems diagram of bioethanol production showing the use of nonrenewable resources in the construction of the processing plant, transportation, and corn production as well as the environmental, renewable energies of sun, wind, and water.

widely used process for hydrogen production. An aggregated energy systems diagram of a conventional steam reforming process is shown in Fig. 9A. The feedstock (i.e. natural gas) is mixed with process steam and reacts over a nickel-based catalyst contained inside a system of alloyed steel tubes. To protect the catalyst, natural gas has to be desulfurized before being fed to the reformer. The following reactions take place in the reformer:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2.$$

The output of the reformer is fed to a series of shift reactors and a pressure swing adsorption unit, where hydrogen is separated and purified to over 99% purity. The reforming reaction is strongly endothermic and energy is supplied by combustion of natural gas or fuel oil. The reaction temperature is usually in the range 700 to 900°C.

4.1.7 Hydrogen from Water Electrolysis

Figure 9B shows an aggregated view of the hydrogen/water electrolysis process. Alkaline water electrolysis is a well-established industrial process in which electricity is used to split water into its component elements, generating hydrogen in a 1:1 molar ratio, with cell efficiencies in the order of 80 to 90%. The following reactions take place at the electrodes of an electrolysis cell (called an electrolyzer) filled with a suitable electrolyte (aqueous solution of KOH, NaOH, or NaCl) upon the application of a potential:

Cathode reaction: $2H_2O\ (l) + 2e^- \rightarrow H_2(g) + 2OH^-\ (aq)$

Anode reaction: $2OH^-(aq) \rightarrow \frac{1}{2}O_2(g) + H_2O(l)$

Overall cell reaction: $H_2O\ (l) \rightarrow H_2(g) + O_2\ (g)$

An electrolysis plant can operate over a wide range of capacity factors and is convenient for a wide range of operating capacities, which makes this process interesting for coupling with both renewable and nonrenewable energy sources. The needed electricity can be purchased from the grid (an interesting option in the case of excess electricity production from hydroelectric plants, for example) or produced on site. In this article, the electrolysis is assumed driven by the electricity generated by the oil-powered and wind-powered plants described earlier.

4.1.8 Ocean Thermal Energy Conversion (OTEC)

OTEC is an energy technology that converts indirect solar radiation to electric power (Fig. 10). OTEC systems use the ocean's natural thermal gradient—the fact that the ocean's layers of water have different temperatures—to drive a power-producing cycle. Commercial ocean thermal energy conversion plants must be located in an environment that is stable enough for efficient system operation. The temperature of the warm surface seawater must differ about 20°C (36°F) from that of the cold deep water that is no more than about 1000 meters (3280 feet) below the surface. The natural ocean thermal gradient necessary for OTEC operation is generally

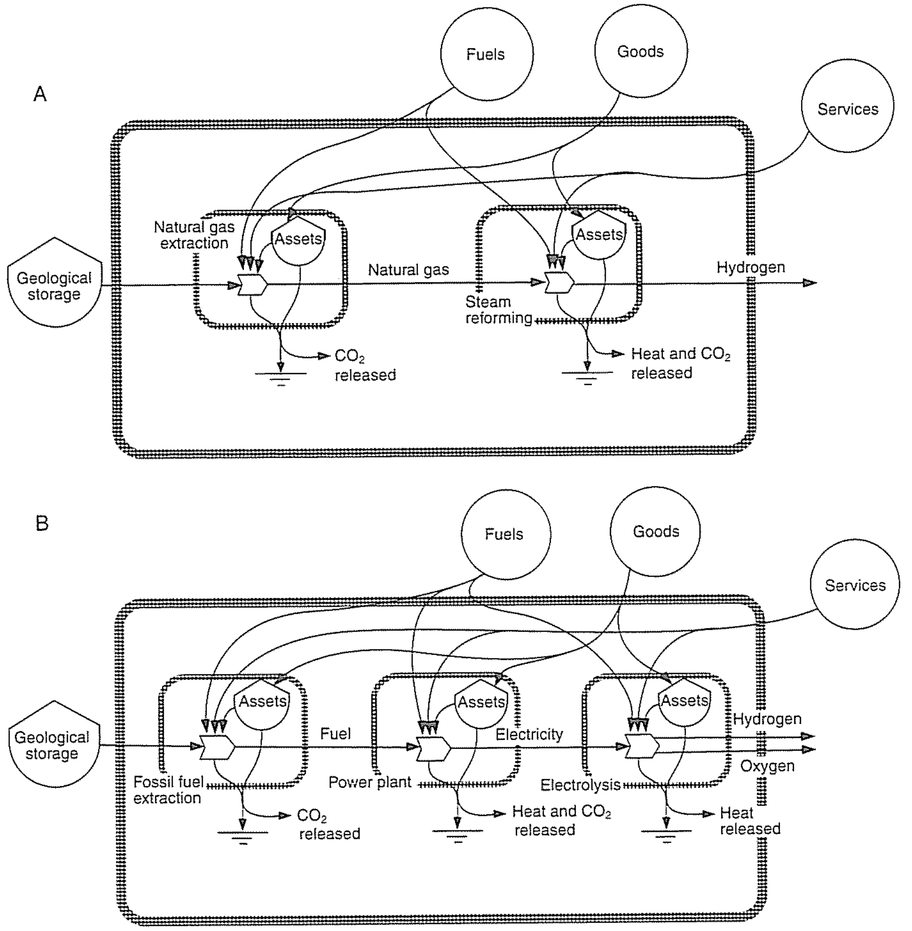


FIGURE 9 (A) Aggregated systems diagram of hydrogen production from steam reforming and (B) electrolysis.

found between latitudes 20 °N and 20° S. Within this tropical zone are portions of two industrial nations—the United States and Australia—as well as 29 territories and 66 developing nations. Of all these possible sites, tropical islands with growing power requirements and a dependence on expensive imported oil are the most likely areas for OTEC development. Electricity generated by plants fixed in one place can be delivered directly to a utility grid. A submersed cable would be required to transmit electricity from an anchored floating platform to land. Moving ships could manufacture transportable products such as methanol, hydrogen, or ammonia on board. The OTEC data for the evaluation are from Odum. He investigated the OTEC technology, performing both an energy and emergy assessment. His conclusions, based on emergy accounting, were that although OTEC shows a small net emergy yield it is unlikely to be competitive with fossil powered technologies for electricity, due to the excessive dilution of solar energy resulting into a very small heat gradient of marine water.

4.2 Methods

Apart from the OTEC plant, the case studies represent real plants, evaluated on the basis of the electricity actually generated and the fuel actually used. Therefore, calculated performance indicators may appear worse than those theoretically obtainable on the basis of nameplate power and efficiency, although the order of magnitude does not change significantly.

4.2.1 Data and Calculations

Unless specified differently, a lifetime of 25 years is assumed for each of the investigated plants or assets. Data used include construction materials, source energy, and labor in construction, as well as operation and maintenance, environmental inputs,

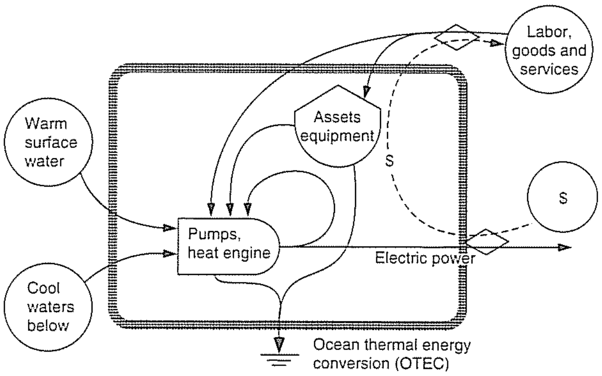


FIGURE 10 Aggregated systems diagram of ocean thermal energy conversion showing the use of labor, goods, and services (nonrenewable) and differential in surface and deep ocean water temperature.

and process outputs including electricity and pollutants. Input data for main plant components were kindly supplied by the companies producing and operating them.

All plants are analyzed using the same procedures as outlined earlier. Input data for each item (row) in the evaluation tables are the actual operational data of each plant and are converted into appropriate units using specific calculation procedures, most of which are described by Odum in his text *Environmental Accounting*. Input data to each investigated process are multiplied by suitable conversion coefficients (unit oil equivalents, g_{oil}/unit of item, for energy evaluation; transformities, sej/unit of item, for emergy evaluation), to yield energy and emergy values associated with each input item. Energy values (expressed as grams of oil equivalent) are then converted into grams of released carbon dioxide, by means of an average oil-to-carbon dioxide conversion coefficient derived from typical reaction stoichiometry. Energy, emergy, and CO_2 flows are then summed, yielding a total that is divided by the amount of the product of each plant to yield its energy cost, its transformity, and its associated carbon emissions. Finally, data are used to calculate several other energy-, emergy-, and carbon-flow indicators to obtain an overall picture of plant performance. All inputs to the electric production systems are expressed on a yearly basis. Fixed capital equipment, machinery, buildings, and so on are divided by their estimated useful life (10 to 30 years, depending on the case). Outputs are also expressed on an annual basis. CO_2 production is calculated for direct fuel combustion in thermal plants and estimated for goods and human services using multipliers of indirect energy consumption for their production. These multipliers are derived from a standardized comparison of literature in this field.

4.2.2 Performance Indicators

EEA typically evaluates energy sources and the outputs from process in their heat equivalents. Two indicators commonly used in EEA are calculated for all the investigated case studies. The first one is related to CO_2 production and global warming potential and is the amount of CO_2 released per megawatt of energy delivered. The second indicator is the output/input energy ratio (also called energy return on investment, EROI, according to Hall *et al.*). It is calculated as the ratio of heat equivalent energies of outputs and input flows and is considered as a measure of the first law energy efficiency of a process. The total input energy in this study is derived by multiplying all goods and materials consumed in the construction (divided by the average life span of the structure and equipment) and the annual maintenance of plants by energy equivalent multipliers, and adding the annual energy consumed directly and indirectly.

The output as electricity is converted to joules using the standard conversion of 3.6×10^6 J/kWh, while the masses of bioethanol and hydrogen are multiplied by their higher heating value (J/g). CO_2 releases are evaluated by multiplying the total input energy (sum of energy used directly and indirectly) by a standard stoichiometric conversion, 3.2 g CO_2/g oil equivalent. Renewable energy plants (wind, hydro, and geothermal) obviously do not burn fossil fuels directly, so their direct CO_2 emissions are lower (zero for the hydro and wind plants, but not negligible for the geothermal power plant due to underground CO_2 contained in the geothermal fluid extracted).

EMA indices are calculated in a similar way. Each item in Table VII (bioethanol) and Table VIII (wind turbine) as well as in all the other tables related to the investigated case studies is multiplied by an appropriate transformity to get the emergy input from the item to the process. The total emergy (a measure of the total environmental support or ecological footprint to the process) is then calculated by summing all inputs according to the previously described emergy algebra. Finally, a new transformity for the process output is calculated by dividing the total emergy by the exergy (sometimes the mass) of the product. Further emergy-based indicators (emergy yield ratio, environmental loading ratio, emergy index of sustainability, emergy density) are also calculated.

4.3 Results and Discussion

Comparing EEA- and EMA-based performance indicators for each kind of energy conversion device makes it possible to ascertain what pieces of information can be obtained from each one of the two approaches and to better understand the space-time scale difference between them.

A careful reading of Tables VII to X provides a rich set of information. Tables VII and VIII are given as examples of how emergy calculations are performed. Table VII refers to bioethanol production from corn (Fig. 8), while Table VIII refers to a 2.5 MW wind electricity production field (Fig. 5). Tables IX and X provide a comparison among energy-, carbon-, and emergy- based indicators in all the conversion patterns investigated. Table IX refers to electricity generation, while Table X refers to selected energy carriers other than electricity. Conversion factors used and references are clearly listed in each table.

4.3.1 Energy and Emergy Evaluations

Emergy evaluations of bioethanol production from corn (Table VII) and electricity generation from wind (Table VIII) are given as examples for a clear description of the emergy approach. These two case studies do not focus on the best available technologies and it is possible that other wind turbines or biomass-to-ethanol processes exist showing better performances. These two cases are used as more or less average-technology case studies. The same rationale applies to the other case studies summarized in Tables IX and X but not shown in detail here.

Renewable flows to bioethanol production from corn (Table VII) account for about 15.3% of the total emergy driving the process. They can be identified as the rain driving the agricultural phase and the wind dispersing the pollutants that come out of the industrial step. Electricity and fuels (including coal) account for about 17.4%, goods and machinery for 42.6%, while labor and services represent 24.7% of the total emergy input. Goods and machinery are therefore the main emergy input to the process, due to the environmental support embodied in their manufacture from raw materials.

Environmental flows as well as labor and services are not included in the conventional energy accounting, therefore a comparison between EEA and EMA requires the percentages be calculated taking these flows out of the total emergy. In so doing, fuels and electricity come out to be respectively the 29% of total emergy and the 45% of total energy, while goods and machinery account for 71% of total emergy and 55% of total energy. This means that EEA overestimates the role of direct energy inputs and underestimates the role of energy flows embodied in goods and machinery. A similar calculation can be performed for the wind turbine by using data presented in Table VIII. As far as wind plant is concerned, it can be noted that wind emergy accounts for about 82% of the total emergy input, while labor and services (4%) and goods and machinery (14%) play a much smaller role. A comparison with energy data is less significant here, since no direct energy inputs are required. It is crystal clear that EMA offers a more comprehensive picture of the whole process by taking into account the hidden environmental flows that support a given process and by evaluating their role on the scale of the biosphere, where they are compared by means of a common measure of environmental quality.

4.3.2 Embodied Energy Performance Indicators

The EEA results are synoptically shown in Tables IX and X. The EROIs of electricity generation range from a low 0.30 of the oil-powered plant to a high 23.7 of the hydroelectric plant. The geothermal and wind conversions also show high energy returns (respectively 20.7 and 7.7), while the OTEC plant only shows an energy return equal to 3.8, due to the low thermal gradient between deep and surface water temperatures. Similarly, Table X shows EROIs in the range 0.24 to 6.1 for energy carriers different than electricity (bioethanol and hydrogen). As expected, the lower value refers to hydrogen production via electrolysis with electricity generated by an oil-powered, thermal plant similar to the one described in Table IX. Instead, the highest EROI is shown by hydrogen generated via electrolysis by means of wind-powered electricity.

The net CO_2 release shows similar patterns, with higher values when direct fossil fuel combustion is involved and lower values when renewable sources drive the process, as expected. In the latter case, only indirect emissions can be calculated, linked to fuel use for the production of components and for machinery construction and operation. The surprising high emission from geothermal electricity is due to the CO_2 content of geothermal fluids.

The better performance of processes driven by renewables is clearly due to the fact that the EROI compares only commercial energies (i.e., calculates the ratio of the thermal energy delivered to the fossil or fossil equivalent energy that is provided to the

TABLE VII

Emergy Analysis of Bioethanol Production

Item	Unit	Amount (unit/ha*year)	Unit emergy values (seJ/unit)	Ref. for UEV	Solar emergy (seJ/ha*year)
Agricultural phase (corn production)					
Renewable inputs					
Sunlight	J	5.50E+13	1.00E+00	[1]	5.50E+13
Rain water (chemical potential)	J	3.07E+10	3.06E+04	[2]	9.39E+14
Earth cycle	J	3.00E+10	1.02E+04	[2]	3.05E+14
Nonrenewable inputs					
Organic matter in topsoil used up	J	3.24E+09	1.24E+05	[2]	4.02E+14
Nitrogen fertilizer	g	1.69E+05	6.38E+09	[2]	1.08E+15
Phosphate fertilizer	g	8.20E+04	6.55E+09	[2]	5.37E+14
Insecticides, pesticides, and herbicides	g	5.38E+03	2.49E+10	[3]	1.34E+14
Diesel	J	6.67E+09	1.11E+05	[2]	7.40E+14
Lubricants	J	1.64E+08	1.11E+05	[2]	1.82E+13
Gasoline	J	3.00E+00	1.11E+05	[2]	3.33E+05
Water for irrigation	J	1.36E+09	6.89E+04	[3]	9.37E+13
Electricity for irrigation	J	2.00E+09	2.52E+05	[4]	5.04E+14
Agricultural machinery (mainly steel)	g	1.36E+04	1.13E+10	[3]	1.53E+14
Seeds	g	1.62E+04	5.88E+04	[7]	9.53E+08
Human labor	years	1.30E-02	6.32E+16	[6]	8.21E+14
Annual services	US $	8.90E+02	2.00E+12	[6]	1.78E+15
Additional inputs for harvest of 70% residues to be used as process energy					
Nitrogen in residues harvested	g	7.88E+04	6.38E+09	[2]	5.03E+14
Phosphate in residues harvested	g	1.82E+04	6.55E+09	[2]	1.19E+14
Diesel for residues	J	9.03E+03	1.11E+05	[2]	1.00E+09
Machinery for residues	g	2.59E+03	1.13E+10	[3]	2.92E+13
Labor for residues	years	1.39E-03	6.32E+16	[6]	8.78E+13
Additional services	$	8.90E+01	2.00E+12	[6]	1.78E+14
Industrial phase (conversion of corn to bioethanol)					
Renewable inputs for the dilution of airborne and waterborne pollutants					
Wind	J	2.20E+11	2.52E+03	[2]	5.54E+14
Nonrenewable inputs					
Diesel for transport	J	6.76E+08	1.11E+05	[2]	7.50E+13
Transport machinery (mainly steel)	g	1.22E+04	1.13E+10	[3]	1.37E+14
Plant machinery (mainly steel)	g	4.41E+04	1.13E+10	[3]	4.96E+14

continues

Table VII continued

Item	Unit	Amount (unit/ha*year)	Unit emergy values (seJ/unit)	Ref. for UEV	Solar emergy (seJ/ha*year)
Cement in plant construction	g	7.84E+04	3.48E+09	[5]	2.73E+14
Additional coal for hot water/steam generation	J	8.10E+07	6.72E+04	[2]	5.44E+12
Process electricity	J	1.41E+09	2.52E+05	[4]	3.55E+14
Process and cooling water	J	7.99E+07	6.89E+04	[3]	5.50E+12
Gasoline denaturant	J	4.89E+08	1.11E+05	[2]	5.42E+13
Ammonia	g	3.56E+01	6.38E+09	[2]	2.27E+11
Lime	g	9.27E+00	1.68E+09	[2]	1.56E+10
Electricity running the waste water treatment plant	J	4.35E+07	2.52E+05	[4]	1.10E+13
Labor	years	1.68E-03	6.32E+16	[6]	1.06E+14
Annual capital cost and services	US $	2.22E+02	2.00E+12	[6]	4.44E+14
Main product of industrial phase					
Ethanol produced, without services	J	5.65E+10	1.28E+05	[7]	7.22E+15
Ethanol produced, with services	J	5.65E+10	1.73E+05	[7]	9.78E+15

process). Energies that are not purchased, but instead are provided for free by nature (e.g., the solar energy driving the wind or the solar energy that drives the photosynthesis for corn production) are not accounted for by EEA and therefore are not reflected in the EROI or in the CO_2 release.

4.3.3 Emergy-Based Performance Indicators

A series of emergy performance indicators are given in Tables IX and X for selected energy conversion devices. Some of these processes, driven by intensive use of primary nonrenewable resources, are secondary energy conversions, while others (wind, hydro and geothermal) should be considered primary energy exploitation patterns. Their values can be usefully compared to those of the primary fuels (oil, coal, natural gas) shown in Table X. Electricity generation in Table IX shows transformities that are, as expected, process specific and range from the low value of about 1.1×10^5 seJ/J for hydro- and wind-electricity up to much higher values around 3.5×10^5 seJ/J for geothermal and oil-powered electricity. The role of labor and services in these processes can be quantified as about 5 to 10% of the transformity. This means that the main contributions to any electricity generation process are the driving forces of fuels or renewable sources, followed by the emergy associated with plant components. As a consequence, a significant lowering of the total emergy demand cannot be expected by simply moving the plant to countries with lower cost of labor, as has become very common with goods production. The OTEC plant combines very small inputs in the form of solar energy via the temperature gradient of the oceans and technological equipment and, instead, a significant input in the form of financial investment, labor, and services, to which a huge emergy is associated. This makes this plant too dependent on nonrenewable, purchased emergy inputs, very high compared to the locally available renewable flow. The transformity of OTEC electricity is around 1.7×10^5 seJ/J, but declines by more than one order of magnitude when labor and services are not accounted for.

Transformities of energy delivered in the form of energy carriers other than electricity (Table X) show similar orders of magnitude. Hydrogen from water electrolysis shows higher or lower transformities depending respectively on oil- or wind-generated electricity. Hydrogen from steam reforming of

TABLE VIII

*Emergy Accounting of Wind Electricity Production in Italy**

Item	Unit	Amount	Unit emergy value (seJ/unit)	Ref. for UEV	Solar emergy (seJ)
Direct renewable inputs					
Wind	J	4.85E+13	2.52E+03	[2]	1.22E+17
Nonrenewable and purchased inputs					
Concrete (basement)	g	5.62E+06	2.59E+09	[1]	1.45E+16
Iron (machinery)	g	2.65E+05	2.50E+09	[2]	6.63E+14
Steel (machinery)	g	8.61E+05	5.31E+09	[2]	4.57E+15
Pig iron (machinery)	g	1.56E+05	5.43E+09	[2]	8.47E+14
Copper	g	8.76E+04	3.36E+09	[3]	2.94E+14
Insulating and miscellaneous plastic material	g	1.01E+04	2.52E+09	[4]	2.55E+13
Lube oil	J	3.10E+09	1.11E+05	[5]	3.44E+14
Labor	years	8.33E-02	6.32E+16	[6]	5.26E+15
Services	US $	2.94E+01	2.00E+12	[6]	5.88E+13
Electricity generated					
Electricity, with labor and services	J	1.35E+12	1.11E+05	[7]	1.49E+17
Electricity, without labor and services	J	1.35E+12	1.06E+05	[7]	1.44E+17

*Data on a yearly basis; 2.5 MW plant sited at Casone Romano, Foggia, Italy.

References for transformities (Tables VII and VIII):

[1] Brown and Buranakarn (2003).

[2] Bargigli and Ulgiati (2003).

[3] Lapp (1991).

[4] Average estimate based on selected case studies.

[5] Odum (1996).

[6] Ulgiati (2003).

[7] From calculation performed in this work.

natural gas shows a relatively low transformity. Unfortunately, only the value without services was calculated in the steam-reforming case study. However, since steam-reforming is a well-known technology, not particularly labor intensive, a dramatic increase of its transformity should not be expected when adding the emergy value of labor and services. The comparison with the transformities of primary sources in Table IV clearly shows that transformities depend on the length of the manufacturing chain. More process steps require more emergy inputs and may decrease the actual energy delivered at the end of the chain. Oil, coal, natural gas, hydro- and wind-electricity, and hydrogen from steam reforming all show transformities on the order of 10^4 seJ/J. However, when technologically heavy steps are added to further process the primary energy source, transformities grow by an order of magnitude to 10^5 seJ/J. It can be clearly understood that if bioethanol were used to generate electricity or if electricity from oil were used to refine metals, transformities would become even greater.

The other emergy indicators complement this picture, by showing low EYRs for oil-powered and OTEC electricity as well as for bioethanol and hydrogen from thermal electricity. Not surprisingly, all the other energy conversions have EYRs around 5. Similarly, high ELRs characterize oil-based patterns, as well as bioethanol and OTEC electricity, while very low ELRs (below 1) are shown by the processes relying to a larger degree on renewables. As a consequence, the aggregated sustainability measure expressed by the EIS ranges from a low 0.06 for oil-based processes up to a significantly high 25 for wind-based ones. Again, the OTEC plant shows a very low performance, quantified by an EIS lower than 0.01. However, let's recall that the evaluation of OTEC is based on a feasibility study and not on an actually existing plant.

4.3.4 Comparison of EEA and EMA Results

Results presented in Tables IX and X allow further considerations in addition to the already discussed features of the two approaches. Both EEA and EMA

TABLE X

Energy and Emergy-Based Indicators for Selected Nonelectric Energy Carriers

	Item	Unit	Bioethanol from corn[a]	Hydrogen from water electrolysis (oil powered)[b]	Hydrogen from water electrolysis (wind powered)[b]	Hydrogen from steam reforming of natural gas[c]
Energy indicators						
E_{out}	Total energy delivered per year	J/year	5.65E + 10	1.89E + 16	1.08E + 13	6.32E + 15
E_{in}	Total energy invested per year	J/year	3.77E + 10	7.84E + 16	1.77E + 12	8.18E + 15
GWP	CO_2 released/unit of energy delivered[d]	g/MJ	52.05	323.56	12.78	100.96
ER	Energy return on investment (energy output/input)		1.50	0.24	6.10	0.77
Emergy indicators						
R_1	Renewable input from the local scale	seJ/year	9.37E + 14	3.43E + 20	1.22E + 18	
R_2	Renewable input from the global scale[e]	seJ/year	1.08E + 15	1.73E + 21	0.00E + 00	
N	Locally nonrenewable input[f]	seJ/year	4.02E + 14	0.00E + 00	0.00E + 00	
F	Purchased plant inputs, including fuel	seJ/year	5.33E + 15	5.70E + 21	2.12E + 17	6.69E + 20
L	Labor and services[g]	seJ/year	3.65E + 15	5.48E + 20	6.85E + 16	
Y	Yield ($R_1 + R_2 + N + F$), without labor and services	seJ/year	7.75E + 15	7.77E + 21	1.43E + 18	6.69E + 20
Y_L	Yield ($R_1 + R_2 + N + F + L$), with labor and services	seJ/year	1.14E + 16	8.32E + 21	1.50E + 18	6.69E + 20
Indices (including services for fuel supply and plant manufacturing)						
Tr_1	Solar transformity of product, with labor and services	sej/J	2.02E + 05	4.40E + 05	1.39E + 05	
Tr_2	Solar transformity of product, w/out labor and services	sej/J	1.37E + 05	4.11E + 05	1.33E + 05	1.06E + 05
EYR	Emergy yield ratio, $EYE = (Y_s)/(F + L)$		1.27	1.33	5.36	
ELR	Environmental loading ratio, $ELR = (R_2 + N + F + L)/R_1$		11.16	23.26	0.23	
ED	Emergy density, $ED = (Y_L)$/area of plant	sej/m^2	1.12E + 12	4.33E + 15	2.13E + 12	
EIS	EYR/ELR		0.11	0.057	23.41	

[a] Ulgiati (2001), modified. Use of agricultural residues as source heat and an energy credit for coproducts (DDGS) accounted for.

[b] Calculated in this work. Performance coefficients for oil and wind powered electricity production from Table II. Water electrolysis performance characteristics from Bargigli *et al.* (2002).

[c] Bargigli *et al.* (2002). Only the step of hydrogen generation has been investigated, therefore emergy costs may be underestimated. Since this step has not direct environmental inputs, the environmental loading ratio and other indicators cannot be calculated.

[d] Global warming potential (GWP), includes direct CO_2 release from fuel combustion, indirect CO_2 release embodied in inputs, and (for geothermal plant only) CO_2 from underground water, released through the cooling towers.

[e] Indirect environmental inputs from the larger scale, needed to dilute heat and chemicals that are released by the plant.

[f] Includes only locally extracted fuel delivered to plant, as well as underground water and topsoil used up (if any).

[g] Labor accounts for hours actually worked in the investigated process. Services include human labor in all steps prior than plant use, quantified as the emergy associated to the monetary cost (cost of item, $, x country emergy/GNP ratio, seJ/$).

TABLE IX

Energy and Emergy-Based Indicators for Selected Electricity Power Plants

	Item	Unit	Oil plant (1280 MWe)[a]	Wind (2.5 MWe)[a]	Geothermal (20 MWe)[a]	OTEC 4.57 MWe[b]	Hydro (85 Mwe)[a]
Energy indicators							
E_{out}	Total electric energy delivered per year	J/year	2.35E + 16	1.35E + 13	3.28E + 14	1.19E + 14	3.94E + 14
E_{In}	Total energy invested per year	J/year	7.84E + 16	1.76E + 12	1.58E + 13	3.12E + 13	1.66E + 13
GWP	CO_2 released/unit of energy delivered[c]	g/MJ	260.22	10.17	182.32	20.43	3.29
ER	Energy return on investment (energy output/input)		0.30	7.67	20.76	3.82	23.73
Emergy indicators							
R_1	Renewable input from the local scale	seJ/year	3.43E + 20	1.22E + 18	5.63E + 19	1.13E + 17	2.84E + 19
R_2	Renewable input from the global scale[d]	seJ/year	1.72E + 21	0.00E + 00	2.64E + 19	0.00E + 00	0.00E + 00
N	Locally nonrenewable input[e]	seJ/year	0.00E + 00	0.00E + 00	7.74E + 18	0.00E + 00	7.47E + 18
F	Purchased plant inputs, including fuel	seJ/year	5.71E + 21	2.13E + 17	1.55E + 19	7.73E + 17	4.42E + 18
L	Labor and services[f]	seJ/year	5.36E + 20	5.33E + 16	4.17E + 18	1.95E + 19	3.73E + 18
Y	Yield ($R_1 + R_2 + N + F$), without labor and services	seJ/year	7.78E + 21	1.44E + 18	1.06E + 20	8.85E + 17	4.03E + 19
Y_L	Yield ($R_1 + R_2 + N + F + L$), with labor and services	seJ/year	8.32E + 21	1.49E + 18	1.10E + 20	2.04E + 19	4.40E + 19
Indices (including services for fuel supply and plant manufacturing							
Tr_1	Solar transformity of electricity, with labor and services	sej/J	3.54E + 05	1.10E + 05	3.35E + 05	1.71E + 05	1.12E + 05
Tr_2	Solar transformity of electricity, w/out labor and services	sej/J	3.31E + 05	1.06E + 05	3.23E + 05	7.44E + 03	1.02E + 05
EYR	Emergy yield ratio, $EYR = (Y_s)/(F + L)$		1.33	5.59	5.60	1.01	5.41
ELR	Environmental loading ratio, $ELR = (R_2 + N + F + L)/R_1$		23.26	0.22	0.96	180.00	0.55
ED	Emergy density, $ED = (Y_L)$/area of plant	sej/m^2	4.33E + 15	2.12E + 12	3.54E + 14	n.a.	2.84E + 13
EIS	EYR/ELR		0.057	25.64	5.87	0.006	9.84

n.a., not available.

[a] Brown and Ulgiati, 2002, modified.

[b] Data from H. T. Odum (2000b), partially modified by the authors.

[c] Global warning potential (GWP), includes direct CO_2 release from fuel combustion (if any), indirect CO_2 release embodied in inputs, and (for geothermal plant only) CO_2 from underground water, released through the cooling towers.

[d] Indirect environmental inputs from the larger scale, needed to dilute heat and chemicals that are released by the plant.

[e] Includes only locally extracted fuel delivered to plant, as well as underground water and topsoil used up (if any).

[f] Labor accounts for hours actually worked in the investigated process. Services include human labor in all steps prior than plant use, quantified as the emergy associated to the monetary cost (cost of item, \$, x country emergy/GNP ratio, seJ/\$).

calculate bad performance indicators for oil-based energy systems. EEA simply indicates that the ability of the investigated devices to operate the conversion chemical energy to work is low, as expected for any engine subject to the second law and the Carnot factor. EMA adds an indication of poor sustainability in both the global dynamics of the economy and the biosphere. The same consideration applies to the investigated bioethanol from corn. In this case, however, EEA indicates a small thermal energy return, which supports several claims of bioenergy supporters in favor of increased use of photosynthesis for energy. On the other hand, EMA jointly evaluates the environmental work diverted from its natural pattern in order to provide free renewable inputs, to replace fertile soil eroded by the intensive tilling, to supply fuels, goods and machinery, to support labor and services, and concludes that the global sustainability of this product is so low that it cannot be usefully pursued as an alternative energy source.

Much lower environmental work is required to deliver energy via hydro- and wind-powered turbines, which simply means that less environmental activity is diverted from its original patterns to provide electricity to the economy. This ensures that these technologies are not withdrawing too many resources from the global biosphere dynamics. Renewable energies (sun, wind, rain and deep heat) already have a role in nature's self-organization processes, so that diverting to much of them to support an economic process reduces their input to other natural processes. EEA assigns a more favorable energy return to hydro- than to wind-electricity, while EMA-based sustainability is much greater for wind conversion, due to equal EYRs and much lower ELR of wind compared to hydro.

Geothermal energy return is surprisingly high according to EEA, since the huge amount of deep heat (high-quality flow) is not accounted for as an input. EMA indicators still suggest a good performance for geothermal electricity, but the fact that a large fraction of high-quality deep heat is dispersed increases the transformity of the output. In addition, the load on the environment due to the release of chemicals extracted with the underground fluid increases the ELR and decreases the global EIS of the process. None of these considerations could be obtained by the traditional energy analysis.

A final remark about OTEC is also illuminating. The process was evaluated as a net energy supplier according to EEA, due to an energy return equal to 3.8. However, this favorable result cannot be obtained without supplying a significant amount of resources in the form of capital, labor, and services. These resources, generated by previous investment of primary emergy sources, decrease the global sustainability of the process to values that make its viability very unlikely, more than its actual feasibility.

4.3.5 EEA and EMA: Scale and Energy Quality

Emergy analysis and embodied energy analysis treat the conceptual issues of scale and quality of energy very differently. From these differences, significant discussion has arisen over the years (see, for instance, the article in *Ecological Economics* titled "Embodied Energy Analysis and Emergy Analysis: A Comparative View" by Brown and Herendeen). In the following discussion, two important issues are elucidated: temporal and spatial scale, and energy quality.

4.3.5.1 Issues of Scale It should be kept in mind that EEA and EMA have different windows of interest (although they also share several common features) and therefore are used to investigate different questions about a given process.

In particular, EEA provides a measure of the overall commercial (oil equivalent) energy invested to support a production process. Its outcome is the amount of oil equivalent energy required to drive a process or to generate a product. Its spatial scale is the actual scale of the process, although it may in principle include the spatial scale of the previous commercial processes from which the input flows came from (for instance, if a mineral from a faraway country is fed to the process, transport must also be accounted for). Its timescale is the time required to extract the raw materials and to actually make the product. In principle, time is only accounted for in order to calculate the fraction of embodied energy of assets and machinery that are used up in the process and that therefore should be assigned to the product. Since machinery and assets have little embodied energy relevance, this time and the related amount of assets are often disregarded by EEA analysts.

Instead, the outcome of EMA is a quantification of the environmental support provided by nature to a process, which may be or may be not under human control. The spatial scale of EMA is larger than the actual scale of the process, since the evaluation also includes free environmental flows from - the larger scale of the biosphere that are not accounted for in energy analysis. In a similar way, the EMA timescale is the total time it took to make a resource via all natural processes involved (generation of minerals, fossil fuels, topsoil, water storages, etc.):

embodied in the transformity of a resource is the global environmental input required over space and time to drive the geological and biosphere processes, which converge to build a resource storage or to support a resource flow. Emergy-based indicators therefore have a built-in memory of the process history—that is, the real "trial and error" pathway that was followed by environment and humans to generate the product, including those pathways discarded by natural selection for maximum power output. The latter sentence may not completely apply to short timescale of technological processes and human economies, but results can be managed in such a way as to take into account the further uncertainty related to patterns that are not yet optimized.

4.3.5.2 Issues of Quality 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 degrees of temperature. All energies can be converted to heat at 100% efficiency; thus, it is relatively easy and accurate to express energies in their heat equivalents. The basic units of energy are the amount of heat required to raise a given amount of water a given number of degrees of temperature. Thus, the calorie is the amount of heat required to raise 1 cm^3 of water 1°Celsius. A joule is equal to 4.187 calories.

Heat-equivalent 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. Human beings, then, become heat engines and the value of their services and information is nothing more than a few thousand calories per day. Obviously, not all energies are the same and methods of analysis need reflect this fact.

Different forms of energy have different abilities to do work, not only in terms of amounts of work but also in terms of kind of work. It is therefore 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. Sunlight drives photosynthesis. A system organized to use concentrated energies like fossil fuels cannot process a more dilute energy form like sunlight, joule for joule. 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 system as a whole energies should be converted to units that span this greater realm, accounting for multiple levels of system processes, ranging from the smallest scale to the largest scales of the biosphere, and accounting for processes other than heat engine technology. The ability of driving processes other than engine-like ones is a new quality aspect of resource flows, which is accounted for by emergy analysis.

Net energy evaluations of energy sources and transformation processes are designed to provide information concerning efficiency and potential yield under the engine-like point of view cited previously. This is something that energy analysis does appropriately. It is able to offer at least two different results:

1. As embodied energy analysis, it provides a measure of the commercial energy cost of a product (MJ or grams of oil equivalent per unit of product). When the product is energy, this measure is better expressed as EROI (joules of energy delivered per unit of energy provided to the process).
2. As exergy analysis at the process scale, it provides a measure of thermodynamic efficiency, indicates possible optimization patterns, and finally ranks the quality of the product from the user-side point of view.

Neither of these two energy analysis patterns is able to provide any significant insight into the quality of each input and output flow in the larger scale of the biosphere, as pointed out earlier. Neither of them takes into account the role of the environmental work supporting both ecosystems and human societies, in particular the role of unmonied inputs provided by nature to human economies. This is something that requires a scale expansion and a change of perspective, from local to global, i.e., the emergy approach.

5. SUMMARY

This article is a brief synopsis of the emergy accounting methodology. Emergy-based case studies of energy conversion systems are presented to allow both an increased understanding of how the method is applied as well as a critical comparisons with embodied energy analysis. Much like a short intensive course given in a limited time frame, this article has touched on what is most important. There is much literature explaining the theory and concepts of the emergy approach as well as applications of the method to a large number of case studies, ranging from ecosystems to socioeconomic systems, to evaluations of the biosphere, including energy processing, agriculture, industry, tourism, wastewater management, recycling patterns, generation and storage of culture and information, development of cities as emergy attractors, and scenarios for future societal development. References to emergy literature are given throughout. Starting on 1999, an international emergy conference takes place every other year. The books of proceedings of the first two emergy conferences provide a significant set of theoretical and applied papers for further reading. In all cases, 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.

SEE ALSO THE FOLLOWING ARTICLES

Earth's Energy Balance • Ecosystem Health: Energy Indicators • Ecosystems and Energy: History and Overview • Exergy • Exergy Analysis of Energy Systems • Global Energy Use: Status and Trends • Human Energetics • Thermodynamics, Laws of

Further Reading

Bargigli, S., Raugei, M., and Ulgiati, S. (2002). Thermodynamic and environmental profile of selected gaseous energy carriers. Comparing natural gas, syngas and hydrogen. *In* "ECOS 2002," Book of Proceedings of the 15th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems–Berlin (Germany), July 2–5 (G. Tsatsaronis, M. J. Moran, F. Cziesla, and T. Bruckner, Eds.), pp. 604–612.

Bargigli, S., Raugei, M., and Ulgiati, S. (2003). A multi-scale and multi-criteria analysis of aluminium "greenness." *J. Cleaner Production,* submitted.

Bargigli, S., and Ulgiati, S. (2003). Emergy and life-cycle assessment of steel production. *In* Proceedings of the Second Biennial Emergy Evaluation and Research Conference, Gainesville, FL.

British Petroleum (1997). "BP Statistical Review of World Energy, 1997." The British Petroleum Company, London.

Brown, L. R., Renner, M., and Flavin, C. (1997). "Vital Signs, 1997: The Environmental Trends That Are Shaping Our Future." W. W. Morton & Co., New York.

Brown, M. T., and Arding, J. (1991). Tranformities Working Paper, Center for Wetlands. University of Florida, Gainesville, FL.

Brown, M. T., Brandt-Williams, S., Tilley, D., and 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, September 2–4, 1999. The Center for Environmental Policy, University of Florida, Gainesville, FL.

Brown, M. T., and Buranakarn, V. (2003). Emergy indices and ratios for sustainable material cycles and recycle options. *Resources, Conservation and Recycling* 38, 1–22.

Brown, M. T., and Herendeen, R. A. (1996). Embodied energy analysis and emergy analysis: A comparative view. *Ecological Economics* 19, 219–235.

Brown, M. T., and McClanahan, T. (1996). Emergy Analysis Perspectives for Thailand and Mekong River Dam Proposals. *Ecological Modeling* 91, 105–130.

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

Brown, M. T., and Ulgiati, S. (1997). Emergy based indices and ratios to evaluate sustainability–Monitoring economies and technology towards environmentally sound innovation. *Ecological Engineering* 9, 51–69.

Brown, M. T., and Ulgiati, S. (1999). Emergy evaluation of the biosphere and natural capital. *Ambio* 28(6), 486–492.

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

Campbell, D. (1998). Emergy analysis of human carrying capacity and regional sustainability: An example using the state of Maine (Appendix). *Environmental Monitoring and Assessment* 51, 531–569.

Hall, C. A. S., Cleveland, C. J., and Kaufman, R. (1986). "Energy and Resource Quality: The Ecology of the Economic Process." Wiley/Interscience, New York.

Huang, S. –L., Lai, H. –Y., and Lee, C. –L. (2001). Energy hierarchy and urban landscape system. *Landscape and Urban Planning* 53, 145–161.

Kinsman, B. (1965). "Wind, Waves, Their Generation and Propagation on the Ocean Surface." Prentice-Hall, Englewood Cliffs, NJ.

Lapp, C. W. (1991). Emergy analysis of the nuclear power system in the United States. M. S. thesis, University of Florida, Department of Environmental Engineering Sciences, Gainesville, FL.

Mannion, A. M. (1995). "Agriculture and Environmental Change: Temporal and Spatial Dimensions." John Wiley & Sons, New York.

Miller, G. A. (1966). The flux of tidal energy out of the deep oceans. *J. Geophysical Res.* 71, 2485–2489.

Odum, H. T. (1996). "Environmental Accounting. Emergy and Environmental Decision Making." John Wiley & Sons, New York.

Odum, H. T. (2000a). Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios. Folio #2—Emergy of Global Processes. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville, FL.

Odum, H. T. (2000b). Emergy Evaluation of an OTEC Electrical Power System. *Energy* 25, 389–393.

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

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

Odum, H. T., Brown, M. T., and 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 Engineering Sciences. University of Florida, Gainesville, FL.

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

Odum, H. T., and Odum, E. C. (eds.). (1983). Energy Analysis Overview of Nations. Working Paper WP-83-82. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Oldeman, L. R. (1994). The global extent of soil degradation. *In* "Soil Resilience and Sustainable Land Use" (D. J. Greenland and I. Szabolcs, Eds.). CAB International, Wallington, United Kingdom.

Oort, A. H., Ascher, S. C., Levitus, S., and Peixoto, J. P. (1989). New estimates of the available potential energy in the World Ocean. *J. Geophysical Research* 94, 3187–3200.

Ryabchikov, A. (1975). "The Changing Face of the Earth." Translated by J. Williams. Progress, Moscow.

Scienceman, D. M. (1987). Energy and emergy. *In* "Environmental Economics" (G. Pillet and T. Murota, Eds.), pp. 257–276. Roland Leimgruber, Geneva, Switzerland.

Sclater, J. F., Taupart, G., and Galson, I. D. (1980). The heat flow through the oceanic and continental crust and the heat loss of the earth. *Rev. Geophys. Space Phys.* 18, 269–311.

Tabacco, A. M., Bargigli, S., Raugei, M., and Ulgiati, S. (2003). Life cycle, exergy and emergy assessment of metallic chromium production from ore. *In* "Advances in Energy Studies: Reconsidering the Importance of Energy" (S. Ulgiati, M. T. Brown, M. Giampietro, R. A. Herendeen, and K. Mayumi, Eds.). SGE, Padova, Italy.

Todd, D. K. (ed.). (1970). "The Water Encyclopedia," 2nd ed. Lewis, Chelsea, MI.

Ulgiati, S. (2001). A comprehensive energy and economic assessment of biofuels: When "green" is not enough. *Critical Reviews in Plant Sciences* 20, 71–106.

Ulgiati, S. (2003). "Emergy Analysis of Italy in the years 1984, 1989, 1991, 1995, and 2000." Unpublished manuscript, Energy and Environment Research Unit, Department of Chemistry, University of Siena, Italy (ulgiati@unisi.it).

USDI (1996). "Mineral Commodity Summaries, January 1997." U. S. Department of Interior, Washington, DC.

Wiin-Nielsen, A., and Chen, T. (1993). "Fundamentals of atmospheric energetics." Oxford Press, New York.

World Resources Institute (1996). "World resources 1996–97." Oxford University Press, Oxford.