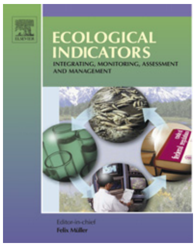
ECOLOGICAL INDICATORS 9 (2009) 959–970

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecolind



Sustainable biomass production: A comparison between Gross Energy Requirement and Emergy Synthesis methods

Pier Paolo Franzese [a,*], Törbjorn Rydberg [b], Giovanni Fulvio Russo [a], Sergio Ulgiati [a]

[a] Department of Environmental Sciences, Parthenope University of Naples, Centro Direzionale – Isola C4, 80143 Naples, Italy
[b] Department of Urban and Rural Development, Swedish University of Agricultural Sciences, Uppsala, Sweden

ARTICLE INFO

Article history:
Received 10 May 2008
Received in revised form
5 November 2008
Accepted 12 November 2008

Keywords:
Energy analysis
Gross Energy Requirement
Emergy Synthesis
Biomass

ABSTRACT

In this paper two methods for energy analysis and environmental accounting (Gross Energy Requirement and Emergy Synthesis) are critically discussed in order to explore their ability to provide a comprehensive evaluation of the performance and environmental sustainability of human-dominated production processes. In order to allow a quantitative comparison, two cropping systems, namely 1 ha of corn production in Italy, and 1 ha of willow production in Sweden, are investigated by means of the parallel application of both methods. The case studies are carried out by performing a quantitative inventory of both natural and economic input flows to the investigated cropping systems. Such input flows are then converted into embodied energy (MJ) as well as emergy (seJ) units. Finally, performance indicators representative for each method are calculated. Results provided by the two methods and their respective theoretical features are compared and discussed in order to point out limits and potentialities of both approaches. The study shows that the two methods account for different – although complementary – categories of input flows, use different conversion factors, and answer to different questions and concerns. Gross Energy Requirement focuses on fossil fuel use and is capable to support the development of more efficient use of commercial energy. Emergy Synthesis uses broader spatial and time frames and accounts for both natural and economic resources. In so doing, it takes into consideration different forms of energy, materials, human labor and economic services on a common basis, offering larger potentiality to explore the sustainable interplay of environment and economy.

1. Introduction

The exponential growth of human population and activities over the last two centuries has produced a huge increase of agricultural and industrial production. This trend was driven by the so-called "energy transition", namely by two main innovations: (1) the massive use of fossil resources (coal, oil and natural gas), and (2) replacement of human labor by machines. Energy use and efficiency became a crucial issue in the attempt of maximising the production of goods and services (Smil, 1991). The effort towards industrial growth disregarded for long time the environmental load placed by the increased use of fossil energy. Despite the still large available supply, there is no doubt that a gradual decline of availability of fossil energy will occur over the next decades (Hubbert, 1956, 1968; Campbell and Laherrére, 1998; Hall and Cleveland, 1981), forcing societies to major restructuring and innovation towards a low-energy economy (Odum and Odum, 2001).

As pointed out by Brown and Herendeen (1996), the implications of fossil fuel supply have promoted energy use

---

* Corresponding author. Tel.: +39 081 5476528; fax: +39 081 5476515.
E-mail address: pierpaolo.franzese@uniparthenope.it (P.P. Franzese).

1470-160X/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecolind.2008.11.004

as an indicator of performance and environmental impact. Previous attempts to explore energy use in human-dominated ecosystems gave rise to very different approaches, some of which based on direct and indirect fossil energy use (Slesser, 1978; Biondi et al., 1989, among others), energy related economic aspects (Costanza et al., 1997), and environmental concerns (Odum, 1996; Kay et al., 2001; Patterson, 2002).

It is recognized that different energy evaluation methods provide different perspectives and sometimes hardly comparable results (Brown and Herendeen, 1996; Hau and Bakshi, 2004; Sciubba and Ulgiati, 2005).

We focus in this paper on two energy evaluation methods (G.E.R.—Gross Energy Requirement; E.S.—Emergy Synthesis) in order to stress merits and bottlenecks of both approaches, highlighting the most appropriate application of each method.

G.E.R. (sometimes also referred to as Embodied Energy Analysis) was widely applied to perform energy evaluation of human-dominated processes by taking into account their direct and indirect use of fossil energy (IFIAS, 1974; Slesser, 1978; Samperi et al., 1989; Biondi et al., 1989; Smil, 1991; Brown et al., 1996; Herendeen, 1998a,b; Fluck and Direlle Baird, 1980; Fluck, 1992).

E.S. was also widely applied over the last 30 years to explore direct and indirect environmental support to human-dominated ecosystems (Odum, 1988, 1994, 1996; Odum et al., 1999; Brown and Ulgiati, 2004a,b).

The main difference with G.E.R. is that E.S. also accounts for inputs such as free environmental resources and services (Brown and Ulgiati, 2004a), economic services and human labor, and information (Ulgiati et al., 2007).

The aim of this paper is to point out similarities in the calculation procedures as well as differences between the theoretical features of the two energy-based evaluation methods by jointly applying them to two cropping systems. The two methods, based on different theoretical foundations, allow different insights on the use of energy and resources as well as a complementary picture of a system's performance at difference scales. Such a picture may provide support to environmental decision-making and energy policy development.

2. Materials and methods

2.1. Gross Energy Requirement (G.E.R.)

According to the International Federation of Institutes for Advanced Study (IFIAS), energy analysis has been defined as the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service (IFIAS, 1974). Until now, energy analysis was applied according to the IFIAS conventions, which were mainly aimed at quantifying the availability and use of stocks of fossil fuels (sometimes also referred to as "commercial energy", i.e. fossil and fossil-equivalent energy). In this framework, G.E.R. accounts for the amount of commercial energy that is required directly and indirectly by the process of making a good or service (Herendeen, 1998a,b). More specifically, it focuses on fuels and electricity, fertilizers and other chemicals, machinery, and assets supplied to a process in terms of the oil equivalent energy required to produce them. The G.E.R. is expressed in energy units per physical unit of good or service delivered (for instance, MJ per kg of steel).

G.E.R. of a product is concerned with the depletion of fossil energy, and therefore all process inputs of material and energy which do not require the use of fossil and fossil equivalent resources are not accounted for. Resources provided for free by the environment such as topsoil and spring water, are not accounted for by G.E.R. method. Human labor and economic services are also not included in most evaluations.

G.E.R. method deals with the idea that only fossil fuels can be subject to scarcity, while natural renewable resources are unlimitedly available and therefore not to be accounted for within the energy balance (Biondi et al., 1989).

Summarizing, energy intensity factors used by the G.E.R. method to perform an energy analysis are calculated according to the following procedures:

1. Renewable resources that do not require the use of fossil energy to make them available are not accounted for (for instance, solar radiation, wind, rain, geothermal flow, etc.).
2. Renewable resources that require the use of fossil energy to make them available are only credited a G.E.R. equivalent to the fossil energy used up to such a purpose (for instance, this is the case of the forestry activities using oil powered machinery).
3. Non-renewable resources (like oil or coal) have a G.E.R. equivalent to the sum of their actual thermal energy content and the fossil energy used to make the resource available to the final user.
4. Human labor and economic services are not accounted for.

G.E.R. for the *i*th input to a process is calculated by multiplying the raw amount of that input by its energy intensity factor. Finally, the G.E.R. of the product *P* is calculated as

$$\text{G.E.R.}_{\text{prod}} = \sum_{i} \frac{\text{G.E.R.}_{i}}{P}$$

where *P* is expressed as gram or Joule.

2.2. Emergy Synthesis (E.S.)

Emergy Synthesis (Odum, 1988, 1996, 2007) is an energy evaluation method rooted in irreversible thermodynamics (Prigogine, 1947; De Groot and Mazur, 1962), and systems thinking (von Bertalanffy, 1968). It aims at calculating indicators of environmental performance that account for both natural and economic resources used up within ecosystem and human-dominated processes (Ulgiati et al., 1993; Brown and Ulgiati, 1999; Ulgiati, 2001; Lefroy and Rydberg, 2003; Cuadra and Rydberg, 2006; Rydberg and Haden, 2006).

According to the emergy theory different forms of energy, materials, human labor and economic services are all evaluated on the common basis of biosphere by converting them into equivalents of only one form of energy, the solar kind, expressed as solar equivalent Joule (seJ). To be more specific, emergy is defined as "the total amount of available energy of one kind (most often of the solar kind) that is used up directly or indirectly in a process to deliver an output product, flow, or service'' (Odum, 1996). Emergy accounting is a measure of the past and present environmental support to a process, and it allows to explore the interplay of natural ecosystem and human activities. The concept of self-organization provides a framework for understanding how systems utilize incoming emergy sources to develop new organizational states over time. Processes of energy transformation throughout the biosphere build order, degrade energy in the process, and cycle information in a network of hierarchically organized systems of ever-increasing spatial and temporal scales. Understanding this relationship between energy and the cycles of materials and information provides insight into the complex relations of society and biosphere (Brown and Ulgiati, 2004a,b).

The emergy method is deeply rooted in the concept of resource quality, i.e. the awareness that different energy forms have a different ability to do useful work even when their heat content is the same. Such an ability (or quality) is an intrinsic feature of the resource and derives from the characteristics of the process that generated the resource itself. This also applies to the different materials used in a process even when their masses are the same. The quality of a resource depends on its physical–chemical characteristics, which in turn depends on the work performed by nature to make it, via the complex pattern of natural process. Instead of only looking at what can be extracted out of a resource (exergy), the emergy evaluation method focuses on what it takes for biosphere to make and for societies to process a given resource. Odum (1988, 1994, 1996) pointed out that in all systems a greater amount of low-quality energy must be dissipated in order to generate a product containing a smaller amount of higher quality energy, in so generating an energy-based hierarchy of resources and products. The ratio of the available energy previously used up to make a product to the actual energy content of such a product provides a measure of the hierarchical position of the item within the thermodynamic scale of the biosphere (a kind of production cost of the item measured in ''biosphere currency'') Such a ratio is expressed as solar equivalent Joules per Joule (seJ/J) or per gram (seJ/g), termed transformity and specific emergy, respectively. The more energy previously used up, the higher the product's transformity, and the product therefore corresponds to a higher position in the energy hierarchy (Odum, 1996). As far as natural or economic dynamics select the optimum process capable of generating a given product, the amount of required input emergy decreases to the minimum emergy demand for its production. According to such a selection driven perspective, transformity translates into an energy scaling ratio to indicate quality and hierarchical position of different resources in the biosphere hierarchy.

2.2.1. *Labor and services*

The additional work provided by human activities in order to refine a raw resource adds up to its quality by making it more suitable to the final user. It is therefore clear that what makes a resource valuable is both the environmental and human work investment, according to the emergy donor-side perspective. Problem is that both environmental and human work have a cost that must be accounted for.

The importance of labor (activity directly applied to a process) and services (activities indirectly applied to a process from the larger scale of the economy) as key factors of production processes is crucial and most often disregarded. Labor and services carry knowledge and information, that are vital lymph to a production process. Many believe that information embodied in labor and societal infrastructures is a no-cost resource. This is because little attention is given to the characteristics of the information concept as well as to the way information is generated in natural and economic systems. For example, the information carried by DNA in living systems is no doubt generated and supported by direct and indirect solar emergy flows, which can be accounted for as the emergy flow of solar radiation and the emergy stored in the seeds. Similarly, the information carried by books, software, money, expertise, is also generated and supported by direct and indirect emergy flows at societal scale.

The problem is that the information content of a specific input, design, or tool is very difficult if not impossible to quantify as such. The large effort performed for information accounting since Shannon first introduced a quantitative expression of this concept did not lead to consensus on information measures, especially when complex systems (ecosystems, societies, culture) are involved (Shannon, 1948; Brillouin, 1962; Tribus and McIrvine, 1971). Instead, the amount of resources supporting the generation of information, i.e. how much it takes to support educated labor, generate innovation, make new technologies, construct infrastructures, test and spread new solutions and designs, can be quantified in emergy terms. For example, Odum (1989) explored the emergy needed to support a University system (i.e. to support undergraduate, graduate and PhD students as well as ongoing research activity), and calculated average values (order of magnitudes) of emergy intensities per hour or Joule of applied educated labor.

Societies invest emergy resources into generating and running the infrastructure that supports economy, production processes and more generally human activities. Such emergy investment is not directly involved into the individual production process, but indirectly provides the needed information and framework for it to occur. The starting point is to calculate the total emergy driving national economies for the generation of their Gross National Products (Huang and Shih, 1992; Cialani et al., 2005; Hagström and Nilsson, 2005; Sweeney et al., 2007; Lomas et al., 2007; among others). Nationwide data can be used to assess the emergy intensity of one unit of GDP generated (emergy intensity of currency, seJ/GDP). Since information in socio-economic systems is very often carried by currency and labor for human artefacts and designs, then emergy intensities of currency and labor can be used to convert hours of labor, money of earned income, and financial investments into information-related emergy inputs to a process. Therefore, money flows are strictly linked to the emergy invested at societal level, which in turn is linked to the individual process. The latter is supported directly by the emergy of specific input flows, and indirectly by the emergy supporting labor and societal infrastructures. Disregarding such an indirect supporting input (the amount of which is never a negligible fraction) leads to serious underestimating the real cost of a process/product. Although these quantitative estimates are still affected by many uncertainties, yet they provide an interesting first-order assessment of the share of labor and information within the total resource budget driving a system/process.

2.3. Case studies and calculation procedures

The energy and material requirements of two cropping systems in Italy and Sweden are used as the starting point of a thorough parallel and quantitative discussion of energy and emergy evaluations. The first cropping system refers to average data for 1 ha of corn (*Zea mays* L.) production in Italy (Ulgiati, 2001). The second cropping system refers to average data for 1 ha of willow (*Salix viminalix* L.) production in Sweden (Hagström, 2006). Raw data from these Authors were processed, integrated and standardized for better comparison.

Both energy evaluation methods follow a similar calculation procedure in order to generate performance indicators. In particular:

1. Identification of the spatial and temporal boundary of the investigated system. The same spatial and time boundaries (1 ha and 1 year) were used for both case studies.
2. Modelling of the investigated system by means of a symbolic energy language.
3. Inventory of the input flows in terms of mass or energy.
4. Conversion of input flows into energy (MJ) and emergy (seJ) units by means of appropriate conversion factors.
5. Calculation of the total energy and emergy used by the system.
6. Calculation of the energy and emergy intensities of the harvested products, expressed as MJ/kg (G.E.R.) or seJ/kg (specific emergy).

The purpose of the energy diagram, drawn according to a standardized energy systems language (Odum, 1994, 1996; Odum and Odum, 2000), is to show in a pictorial way what are the main process driving forces as well as the main interactions among system's components. By convention, driving forces and components are drawn from left to right in order of increasing quality (increasing transformity, in the case of emergy analysis) in order to provide a clear picture of the existing hierarchy within the system. The energy diagram is used as a basis for the quantitative inventory of input flows afterwards.

Fig. 1 shows a simplified systems diagram of a generic agricultural production process. Free environmental sources as well as human labor and economic services are also drawn in the diagram, although they are not accounted for by Gross Energy Requirements method.

Based on the energy diagram, tables of input flows to the cropping systems were constructed (Tables 1 and 2). Input raw amounts were multiplied by suitable energy and emergy intensity factors and converted into G.E.R. and emergy units (MJ and seJ). Energy and emergy flows were then summed into total energy and emergy amounts, that were in turn used to calculate the energy and emergy intensities of the final products.

3. Results and discussion

The yield of annual corn production was 7600 kg/ha, equivalent to a thermal energy content of 1.12×10^5 MJ/(ha yr) (Table 1). The annual yield of willow production was 8318 kg/ha, equivalent to a thermal energy content of 1.63×10^5 MJ/(ha yr) (Table 2).

The Gross Energy Requirement for the two cropping systems accounted for 2.93×10^4 and 8.36×10^3 MJ/(ha yr), respectively (Table 3). The total solar emergy required by the two cropping systems resulted into 8.20×10^{15} and 2.64×10^{15} seJ/(ha yr), respectively (Table 3).

These figures translate into energy intensities for corn and willow production equal to 0.26 MJ_{in}/MJ_{out} (3.85 MJ/kg) and 0.05 MJ_{in}/MJ_{out} (1.01 MJ/kg), respectively (Table 3). Energy intensity figures can be converted into an indicator of energy

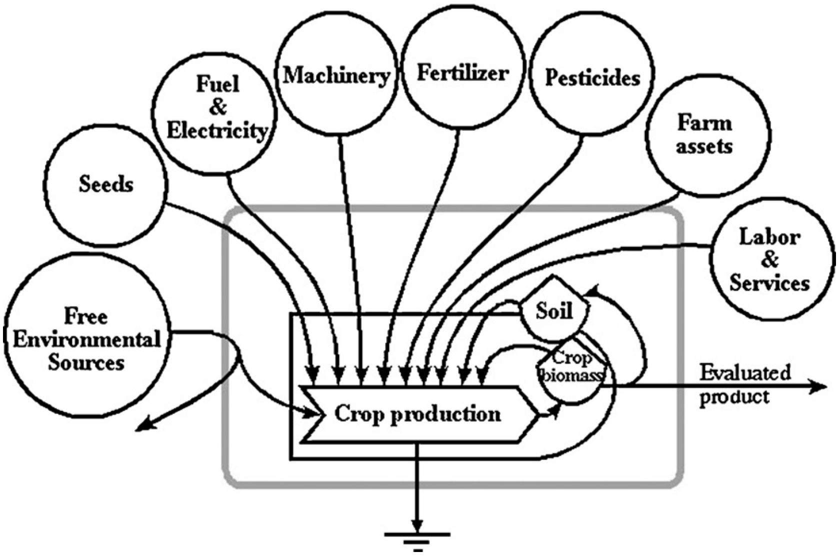


Fig. 1 – Simplified energy diagram showing the main driving forces of a crop production system.

Table 1 – Corn crop production in Italy: energy analysis and Emergy Synthesis (after Ulgiati, 2001).

Input		Energy analysis						Emergy Synthesis					
		Raw amount[a]	Unit	Energy intensity (MJ/unit)	Ref.	G.E.R. (MJ)	Energy (%)	Raw amount	Unit	Emergy intensity[b] (seJ/unit)	Ref.	Solar emergy[c] (seJ)	Emergy (%)
Local renewable resources													
1	Solar radiation	n.a.						5.53E+13	J	1.00E+00	[a]	5.53E+13	0.7%
2	Rain, chemical potential	n.a.						3.07E+10	J	3.05E+04	[b]	9.36E+14	11.4%
3	Geothermal flow	n.a.						2.00E+10	J	5.76E+04	[b]	1.15E+15	14.0%
Local non-renewable resources													
4	Net loss of topsoil	n.a.						3.24E+09	J	1.24E+05	[b]	4.02E+14	4.9%
5	Water, irrigation	n.a.						1.98E+09	J	6.87E+04	[c]	1.36E+14	1.7%
Imported resources													
6	Gasoline	3.00	kg	55.30	[1]	1.66E+02	0.6	1.22E+08	J	1.11E+05	[b]	1.35E+13	0.2%
7	Diesel	150.00	kg	51.50	[1]	7.73E+03	26.4	6.68E+09	J	1.11E+05	[b]	7.38E+14	9.0%
8	Lubricants	3.70	kg	83.70	[1]	3.10E+02	1.1	1.71E+08	J	1.11E+05	[b]	1.89E+13	0.2%
9	Electricity	555.60	kWh	10.50	[1]	5.83E+03	19.9	2.00E+09	J	2.51E+05	[d]	5.03E+14	6.1%
10	Machinery	13.60	kg	79.80	[1]	1.09E+03	3.7	1.36E+04	g	1.12E+10	[c]	1.53E+14	1.9%
11	Fertilizer, Nitrogen	169.00	kg	73.30	[1]	1.24E+04	42.3	1.69E+05	g	6.37E+09	[b]	1.08E+15	13.1%
12	Fertilizer, Phosphorus	82.00	kg	13.40	[1]	1.10E+03	3.8	8.20E+04	g	6.54E+09	[b]	5.36E+14	6.5%
13	Pesticides and Herbicides	5.40	kg	91.00	[1]	4.90E+02	1.7	5.38E+03	g	2.48E+10	[c]	1.33E+14	1.6%
14	Seeds	16.20	kg	10.00	[1]	1.62E+02	0.6	1.62E+04	g	5.87E+04	[f]	9.50E+08	0.0%
15	Labor	n.a.						1.30E−02	yr	6.54E+16	[e]	8.51E+14	10.4%
16	Services	n.a.						7.99E+02	$	3.12E+12	[e]	2.49E+15	30.4%
17	Harvest, fresh weight	7600	kg		[2]			7.60E+06	g		[2]		
18	Harvest, energy content	1.12E+05	MJ	0.26	[2]	2.93E+04	100	1.12E+11	J	7.34E+04	[2]	8.20E+15	100%

Note: input data to energy analysis are entered as kg and kWh, while they are converted to J and g in the emergy table. *References for energy intensity factors*: [1] Biondi *et al.*, 1989. [2] This study. *References for emergy intensity factors*: [a] By definition. [b] After Odum (1996). [c] After Brown and Arding (1991). [d] After Brown and Ulgiati (2004b). [e] After Cialani et al. (2005). [f] After Ulgiati (2001). [2] This study.

[a] n.a. = not accountable.

[b] The transformity values used in the table are all updated to the new emergy baseline for biosphere (total emergy driving the biosphere: 15.83×10^{24} seJ/yr; Brown and Ulgiati, 2004b).

[c] Total used emergy, as absolute and % values, is calculated without double counting of flows from the same source (solar radiation, rain, geothermal flow), according to the emergy algebra.

Table 2 – Willow crop production in Sweden: energy analysis and Emergy Synthesis (after Hagström, 2006).

Input		Energy analysis						Emergy Synthesis					
		Raw amount[a]	Unit	Energy intensity (MJ/unit)	Ref.	G.E.R. (MJ)	Energy (%)	Raw amount	Unit	Emergy intensity[b] (seJ/unit)	Ref.	Solar emergy[c] (seJ)	Emergy (%)
Local renewable resources													
1	Solar radiation	n.a.						2.57E+13	J	1.00E+00	[a]	2.57E+13	1.0
2	Wind, kinetic energy	n.a.						8.73E+10	J	2.51E+03	[b]	2.19E+14	8.3
3	Rain, evapo-transpired	n.a.						1.95E+10	J	3.05E+04	[b]	5.95E+14	22.5
Local non-renewable resources													
4	Net loss of topsoil	n.a.						2.95E+08	J	1.24E+05	[b]	3.65E+13	1.4
Imported resources													
5	Fuel, agriculture	12.63	kg	51.50	[1]	6.50E+02	7.78	5.62E+08	J	1.11E+05	[b]	6.22E+13	2.4
6	Fuel, harvesting and field transport	9.33	kg	51.50	[1]	4.80E+02	5.74	4.15E+08	J	1.11E+05	[b]	4.59E+13	1.7
7	Fuel, road transport	27.19	kg	51.50	[1]	1.40E+03	16.75	1.21E+09	J	1.11E+05	[b]	1.34E+14	5.1
8	Fuel, chipping	10.25	kg	51.50	[1]	5.28E+02	6.31	4.56E+08	J	1.11E+05	[b]	5.04E+13	1.9
9	Machinery, agriculture	1.14	kg	79.80	[1]	9.10E+01	1.09	1.14E+03	g	1.12E+10	[c]	1.28E+13	0.5
10	Machinery, harvesting and field transport	0.74	kg	79.80	[1]	5.91E+01	0.71	7.40E+02	g	1.12E+10	[c]	8.31E+12	0.3
11	Machinery, road transport	0.64	kg	79.80	[1]	5.11E+01	0.61	6.40E+02	g	1.12E+10	[c]	7.19E+12	0.3
12	Machinery, chipping	0.12	kg	79.80	[1]	9.58E+00	0.11	1.20E+02	g	1.12E+10	[c]	1.35E+12	0.1
13	Nitrogen	63.60	kg	73.30	[1]	4.66E+03	55.75	6.36E+04	g	7.71E+09	[b]	4.90E+14	18.6
14	Phosphorus	7.00	kg	13.40	[1]	9.38E+01	1.12	7.00E+03	g	2.98E+10	[b]	2.09E+14	7.9
15	Potassium	23.20	kg	9.20	[1]	2.13E+02	2.55	2.32E+04	g	2.92E+09	[b]	6.77E+13	2.6
16	Herbicides	1.12	kg	91.00	[1]	1.02E+02	1.22	1.12E+03	g	2.48E+10	[c]	2.78E+13	1.1
17	Willow cuttings	20.00	kg	1.05	[2]	2.10E+01	0.25	3.92E+08	J	1.58E+04	[2]	6.19E+12	0.2
18	Labor & Services, agriculture	n.a.						1.73E+03	SEK	2.65E+11	[g]	4.59E+14	17.4
19	Labor & Services, harvesting and field transport	n.a.						4.08E+02	SEK	2.65E+11	[g]	1.08E+14	4.1
20	Labor & Services, road transport	n.a.						9.87E+02	SEK	2.65E+11	[g]	2.61E+14	9.9
21	Labor & Services, chipping	n.a.						2.30E+02	SEK	2.65E+11	[g]	6.09E+13	2.3
22	Willow chips, dright matter	8318	kg		[2]			8.32E+06	g		[2]		
23	Willow chips, dright matter	1.63E+05	MJ	0.05	[2]	8.36E+03	100	1.63E+11	J	1.62E+04	[2]	2.64E+15	100

Note: input data to energy analysis are entered as kg, while they are converted to J and g in the emergy table. *References for energy intensity factors*: [1] Biondi et al. (1989). [2] This study. *References for emergy intensity factors*: [a] By definition. [b] After Odum (1996). [c] After Brown and Arding (1991). [g] After Hagström (2006). [2] This study.

[a] n.a. = not accountable.

[b] The transformity values used in the table are all updated to the new emergy baseline for biosphere (total emergy driving the biosphere: 15.83E24 seJ/yr; Brown and Ulgiati, 2004b).

[c] Total used emergy, as absolute and % values, is calculated without double counting of flows from the same source (solar radiation, rain, geothermal flow), according to the emergy algebra.

return on commercial energy investment (E.R.O.I.) equal to 3.82 and 19.50 MJ_{out}/MJ_{in}, respectively (Table 3).

Finally, the emergy intensities (transformities) resulted into 7.34×10^4 seJ/J for corn production (Table 3) and 1.62×10^4 seJ/J for willow production (Table 3).

It should be noted that the way Gross Energy Requirements and Emergy Synthesis account for input flows is different and affects the results significantly. In fact, G.E.R. accounts for non-renewable energy flows, the total of which is much less than the energy content of the products in both investigated systems. This is because the agricultural products store a fraction of solar radiation captured via photosynthesis in their chemical structure. Small it may be, in general it is larger than the ''commercial'' energy invested, thus generating a net energy return. The calculated high-energy gain (output energy/input energy) of cropping systems is the result of disregarding the energy input from nature, by only accounting for the investment made by human activity. Such a procedure for G.E.R., although incomplete in our opinion, may certainly suggest the need for and usefulness of a better use of fuels at the scale of the cropping system, but it is hardly useful to understand the extent of the interaction with surrounding environment and society. Emergy Synthesis includes the solar radiation driving the photosynthetic process as well as all other input flows provided for free by the environment (e.g. rain, deep heat, etc.). In addition, Emergy Synthesis also

Table 3 – Energy, mass and emergy indicators.

	Harvest (kg/(ha yr))	Harvest (MJ/(ha yr))	G.E.R. (MJ/(ha yr))	Energy intensity (MJ_{in}/MJ_{out})	Energy intensity (MJ/kg)	E.R.O.I. (MJ_{out}/MJ_{in})	Net energy ($MJ_{out} - MJ_{in}$)	Total emergy (seJ/(ha yr))	Solar transformity (seJ/J)	Specific emergy (seJ/kg)
Corn production	7600	1.12E+05	2.93E+04	0.26	3.85	3.82	8.25E+04	8.20E+15	7.34E+04	1.08E+12
Willow production	8318	1.63E+05	8.36E+03	0.05	1.01	19.50	1.55E+05	2.64E+15	1.62E+04	3.18E+11

Fig. 2 – (a) Breakdown of main categories of input emergy flows in corn production, Italy (after Ulgiati, 2001). (b) Breakdown of main categories of input emergy flows in willow production, Sweden (after Hagström, 2006).

accounts for inputs associated to the economic system, like human labor and economic services, all expressed in emergy units. Such a broader scope of emergy approach compared to G.E.R. generates very different ‘‘measures of cost’’ for the same product. For example, energy intensity for willow was found to be 1.01 MJ/kg (Table 3). This number reflects the fossil energy used to grow, harvest, transport, and chip the willow stems to make them available to the final user. On the contrary, the emergy intensity factor for chipped willow was found to be 3.18 × 10^{11} seJ/kg (Table 3), and it measures both the work of biosphere and that of humans in generating the final product. It clearly appears that the amount of input energy (including direct and indirect solar input) is about 315,000 times higher than indicated by G.E.R., and is generally not accounted for simply because it is outside of market dynamics. Such a result is not surprising if we consider the low efficiency of the photosynthetic process and the need for further environmental support to the global circulation processes providing environmental services (rain, wind, deep heat, among others), as indicated by the values of their transformities. What is the meaning of such a finding? The energy directly invested into the agricultural process is only the fuel in support to agricultural practices (irrigation, tractor). Some energy is indirectly invested into making the tools needed for production (fertilizers, machinery). Accounting for the energy cost of the energy applied (extraction, refining, transport, distribution infrastructure) we end up with the above indicated figure of 1.01 MJ/kg (embodied fossil energy). Let’s now assume that such an energy is raw oil. The transformity of raw oil (calculated without including labor and services) is in the order of magnitude 9.07 × 10^4 seJ/J (Odum et al., 2000), so that the above-embodied energy translates into an emergy intensity of about 9.10 × 10^{10} seJ/kg. Such a value multiplied by the total mass of product – 8318 kg willow – corresponds to 42% of total emergy input from Table 2. If renewable sources are added to the total, the figure becomes 1.67 × 10^{11} seJ/kg (24% of total emergy, Table 2). When the emergy of labor and services is finally added we reach an emergy intensity of 2.74 × 10^{11} seJ/kg (34%). A remaining fraction 4.40 × 10^{10} seJ/kg must be attributed to the emergy of raw minerals in machinery and fertilizers (iron, steel, copper, etc.), not accounted for in any of the previous items. Such figures clearly show the link between G.E.R. and emergy, consisting in accounting for all free environmental sources, minerals, labor and services in addition to the actual energy invested, thus making the picture much broader and complete.

Fig. 2a and b highlights the importance of non-commercial resource inflows in corn and willow production. When local renewable and non-renewable flows as well as labor and services are considered and expressed in emergy units, they account for about 61% and 58% of the total emergy use for corn and willow production, respectively. Disregarding their necessary contribution to the cropping systems leaves the analyst without crucial pieces of information. Moreover,

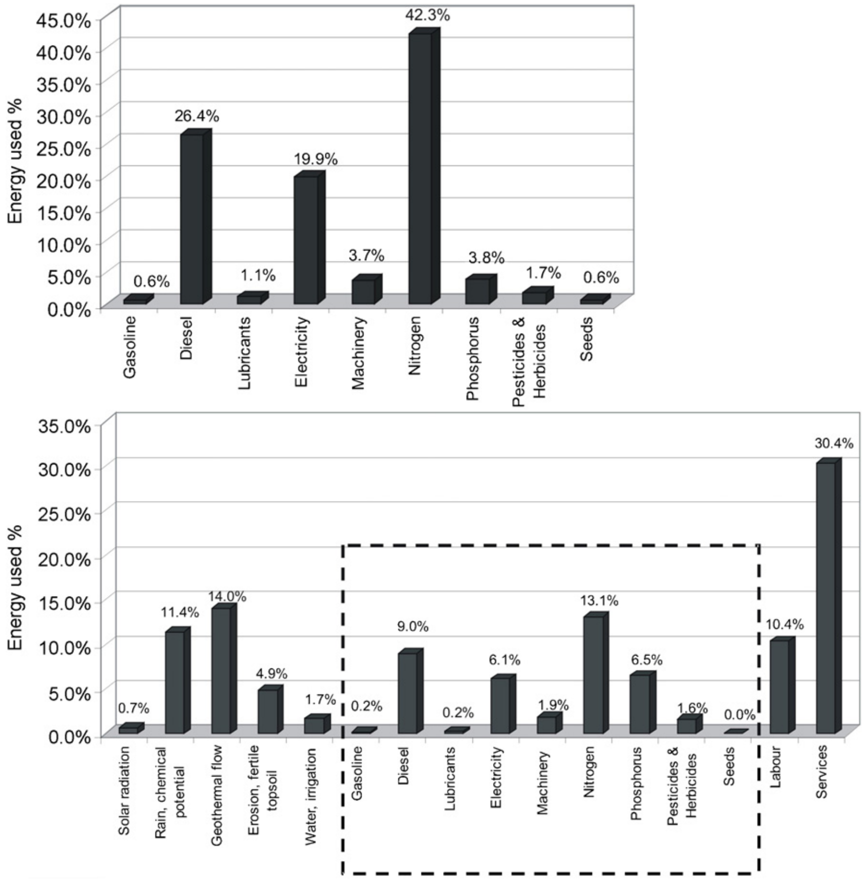


Fig. 3 – (a) Corn production in Italy: energy signature (after Ulgiati, 2001). (b) Corn production in Italy: *e*mergy signature (after Ulgiati, 2001). The dotted frame identifies the commercial items accounted by the G.E.R. method in (a).

emergy intensities provide the evaluation with built-in time and entropy factors in that they account for past ecosystems activity and trial-and-error patterns related to natural selection. In fact, evolution ‘‘tries’’ several different patterns, but only one is (or very few are) selected by natural selection (Lotka, 1922a,b, 1945) depending on its (their) ability to take advantage of the existing resources and conditions. The final result of the evolutionary pattern embodies the time needed as well as the resources degraded (entropy) to support the process.

Inclusion of time clearly emerges in the different meaning of the words ‘‘direct’’ and ‘‘indirect’’ used by the two methods to refer to input flows. Gross Energy Requirement method uses ‘‘direct’’ to indicate fossil fuels which are supplied while the process takes place, with ‘‘indirect’’ referring to energy investment for the manufacture of goods and machinery as well as for energy processing into the required form. Instead, the term ‘‘direct’’ in Emergy Synthesis only indicates solar radiation, while the other free renewable as well as non-renewable flows (rain, wind, topsoil, . . ., good, fuels, labor and services) are ‘‘indirect’’, in so that they are the result of a convergence of environmental work needed for their production and supply, even if they are directly supplied to the process while it takes place.

As a consequence of the above statements, the conversion of raw input flows to emergy units changes their relative importance (Figs. 3a, 3b, 4a and 4b) compared to G.E.R. results. It makes apparent that additional input flows and hidden

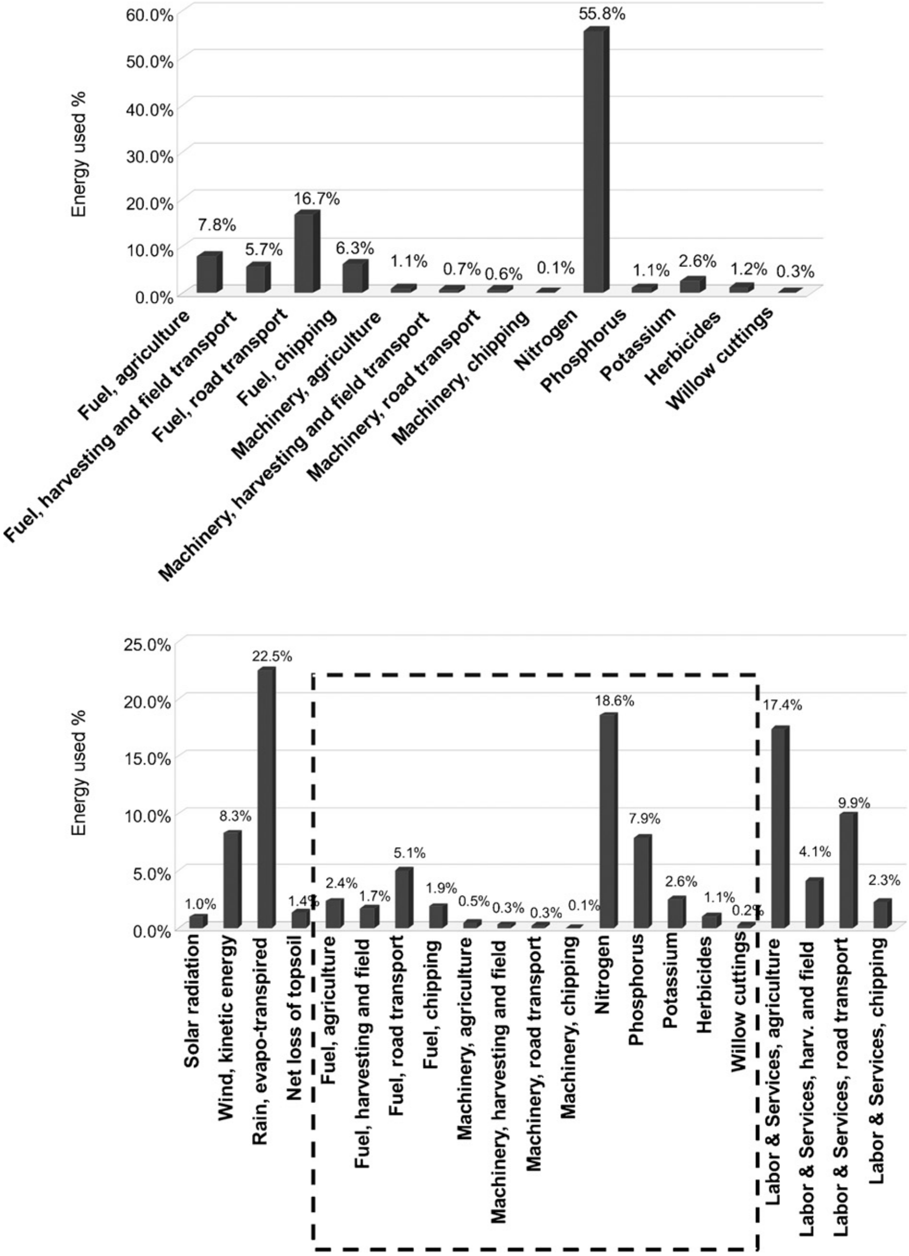


Fig. 4 – (a) Willow production in Sweden: energy signature (after Hagström, 2006). (b) Willow production in Sweden: *e*mergy signature (after Hagström, 2006). The dotted frame identifies the commercial items accounted by the G.E.R. method in (a).

contributions from past environmental processes are being included, significantly affecting the overall picture. For example, the bar diagram of energy flows in Fig. 3a shows a large dominance of the nitrogen fertilizer input, the energy cost of which (42.3% of the total) is much higher than the energy cost of diesel (26.4%) and phosphate fertilizer (3.8%), to mention only two important items. Instead, converting the same raw data into emergy units (Fig. 3b) lowers the relative importance of nitrogen to 13.1%, while phosphorous grows up to 6.5% and diesel drops to 9.0%. The decrease of nitrogen importance is certainly due to the additional presence of inputs not accounted for by the G.E.R. (local free renewable and non-renewable flows, labor and services). However, it should be also noted that some inputs have small intensities in energy terms but much higher emergy intensity factors. This is, for example, the case of phosphorous. The same applies to other input flows, such as diesel and electricity. Similar patterns were also found for willow production (Fig. 4a and b).

The meaning of these findings is that G.E.R. provides useful information to the understanding of fossil fuels cost and optimization, while Emergy Synthesis comes into play when the concern is the relation of a process or system with the surrounding environment, from which resources come from and to which emissions and waste are returned. The sink aspect is dealt with in the emergy method by accounting for the environmental services (and emergy costs) needed for dilution, abatement and absorption of emissions (Ulgiati and Brown, 2002) and restoration of degraded ecosystems and manufacts (Ulgiati et al., 1995; Brown and Ulgiati, 2005). These two aspects (relations to source and sink) together with the concept of resource quality provide an important additional insight to the picture generated by G.E.R. Emergy Synthesis focuses on the global support a system receives from nature instead of limiting its focus to the consequences of fossil energy shortage. Both methods generate important information but referring to different questions: (a) G.E.R.: how can a system save commercial energy now? (b) G.E.R. and emergy jointly: how can a system be sustainable now and in the near future? (c) Emergy: how can a system reinforce its resource basis by proper matching of resource investment and resource withdrawal, in terms of quantity and quality, and therefore ensure global sustainability in the future?

Answering all the above questions (a), (b) and (c) is very important, but entails different space and time scales and, as a consequence, different kinds of action. Optimizing energy – a crucial step for the process to occur – only requires technical expertise to come into play, while matching a system or process needs with surrounding environment within a sustainability perspective requires a deep knowledge of ecological aspects (rate of topsoil erosion/formation, evapotranspiration, etc.), economic aspects (labor and services), competition for resource use and stakeholders involvement (e.g. cropping for food or fuel), all of which can be addressed by means of emergy accounting procedures.

4. Conclusion

We have shown that the two energy evaluation methods discussed in this paper account for different input items, utilize different conversion factors (energy intensity and transformity, respectively), are framed in different spatial and time scales, and answer to different questions and concerns.

Since the two methods are based on so different theoretical features, it is meaningless trying to assess the superiority of one approach over the other, while instead the analyst should be more concerned with the appropriate use of each method according to the goal of the investigation.

One of the main findings of our discussion is that the very specific focus on fossil fuels use makes the Gross Energy Requirements method capable to assist the evaluator in avoiding unjustified use of energy by decreasing thermodynamic losses. In so doing, the short-term success of the system/process is ensured and management costs are lowered. On the other hand, the broader spatial and time frames of Emergy Synthesis offer larger potentiality for resource policy-making as well as for addressing issues of sustainability and quality of environment–economy relations.

We recognize the relevance of fossil fuels when an intensive agricultural process is performed. Yet, as we are approaching a new era in which not only fossil fuels but also natural resources will be strongly affected by scarcity, we do believe that our view must be expanded in order to encompass a larger set of driving forces and constraints than previously acknowledged. If the ambition is to perform a more comprehensive environmental planning and natural resource management, the two methods should be used in a complementary way, in so providing insight into both the process (Gross Energy Requirements) and the global scale (Emergy Synthesis).

In conclusion, the concern for large scale issues and consequences is important because even if humans will be able to find an unlimited source of energy (be it nuclear, hydrogen, solar, etc.) so that there would not be any further concern for fossil fuels supply, it would still be necessary to explore how human activities relate to the dynamics of surrounding ecosystems, the availability of materials and the supply of environmental services by global biosphere activity.

REFERENCES

Biondi, P., Panaro, V., Pellizzi, G., 1989. Le richieste di energia del sistema agricolo italiano (in Italian). CNR, Consiglio Nazionale delle Ricerche, Progetto Finalizzato Energetica, Sottoprogetto Biomasse ed Agricoltura, Report LB-20, Roma, Italia, 389 pp.

Brillouin, L., 1962. Science and Information Theory. Academic Press, New York.

Brown, M.T., Arding, J., 1991. Transformities Working Paper. Center for Wetlands, University of Florida, Gainesville, USA.

Brown, M.T., Herendeen, R.A., 1996. Embodied Energy Analysis and EMERGY analysis: a comparative view. Ecological Economics 19, 219–235.

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

Brown, M.T., Ulgiati, S., 2004a. Energy quality, emergy, and transformity: H.T. Odum's contribution to quantifying and understanding systems. Ecological Modelling 178, 201–213.

Brown, M.T., Ulgiati, S., 2004b. Emergy analysis and environmental accounting. In: Cleveland, C. (Ed.), Encyclopedia of Energy. Academic Press, Elsevier, Oxford, UK, pp. 329–354.

Brown, M.T., Ulgiati, S., 2005. Emergy, transformity and ecosystem health. In: Jørgensen, S.E., Costanza, R., Xu, F.L. (Eds.), Handbook of Ecological Indicators for Assessment of Ecosystem Health. CRC Press, Boca Raton, FL, pp. 333–352.

Brown, L.H., Bernard, B.H., Bruce, A.H., 1996. Energy analysis of 108 industrial process. Fairmont Press, INC, pp. 314.

Campbell, C., Laherrére, J., 1998. The end of cheap oil. Sci. Am. (March), 60–65.

Cialani, C., Russi, D., Ulgiati, S., 2005. Investigating a 20-year national economic dynamics by means of emergy-based indicators. In: Brown, M.T., Campbell, D., Comar, V., Haung, S.L., Rydberg, T., Tilley, D., Ulgiati, S. (Eds.), Emergy Synthesis, vol. 3, pp. 401–416.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Cuadra, C., Rydberg, T., 2006. Emergy evaluation on the production, processing and export of coffee in Nicaragua. Ecological Modelling 196, 421–433.

De Groot, S.R., Mazur, P., 1962. Non-equilibrium Thermodynamics. North-Holland, Amsterdam.

Fluck, R., 1992. Energy in Farm Production, Energy in World Agriculture, vol. 6. Elsevier Science Publisher B.V., Amsterdam, 1992, ISBN 0-444-88681-8, pp. 359.

Fluck, R., Direlle Baird, C., 1980. Agricultural Energetics. AVI Publishing Company, Inc, Westport, Connecticut, 192 pp.

Hagström, P., 2006. Biomass Potential for Heat, Electricity and Vehicle Fuel in Sweden. Doctoral Thesis. SLU, Uppsala, Sweden, 224 pp. (ISSN 1652-6880 – ISBN 91-576-7060-9).

Hagström, P., Nilsson, P.O., 2005. Emergy evaluation of the Swedish economy since the 1950s. In: Brown, M.T., Bardi, E., Campbell, D., Comar, V., Huang, S.-L., Rydberg, T., Tilley, D., Ulgiati, S. (Eds.), Emergy Synthesis 3. Theory and Applications of the Emergy Methodology. Proceedings of the Third Biennial International Emergy Research Conference. Center for Environmental Policy, Department of Environmental Engineering Sciences, University of Florida, Gainesville, pp. 417–434.

Hall, C.A.S., Cleveland, C.J., 1981. Petroleum drilling and production in the United States: yield per effort and net energy analysis. Science 211, 576–579.

Hau, L.J., Bakshi, B.R., 2004. Promise and problems of emergy analysis. Ecological Modelling 178, 215–225.

Herendeen, R., 1998a. Ecological Numeracy: Quantitative Analysis of Environmental Issues. John Wiley and Sons, 360 pp.

Herendeen, R., 1998b. Embodied energy, embodied everything. . .now what? In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A. and Mayumi, K. (Eds.), Book of Proceedings of the International Workshop "Advances in Energy Studies. Energy Flows in the Ecology and Economy", Porto Venere, Italy, May 26/30, 1998, pp. 13–48.

Huang, S.-L., Shih, T.-H., 1992. The evolution and prospects of Taiwan's ecological economic system. In: Proceedings of The Second Summer Institute of the Pacific Regional Science Conference Organization.. Chinese Regional Science Assoc., Taipei, Taiwan.

Hubbert, M.K., 1956. Nuclear energy and the fossil fuels. In: Drilling and Production Practices, American Petroleum Institute, New York, pp. 7–25.

Hubbert, M.K., 1968. Energy resources. In: Resources and Man. Natl. Acad. Sci. W.H. Free-man, San Francisco, pp. 157–242.

IFIAS, 1974. Energy analysis. Workshop Report no. 6. Stockholm, 89 pp.

Kay, J., Allen, T., Fraser, R., Luvall, J., Ulanowicz, R., 2001. Can we use energy based indicators to characterize and measure the status of ecosystems, human, disturbed and natural? In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R., Mayumi, K. (Eds.), Proceedings of the International Workshop: Advances in Energy Studies: Exploring Supplies, Constraints and Strategies, Porto Venere, Italy, May 23–27, 2000, pp. 121–133.

Lefroy, E., Rydberg, T., 2003. Emergy evaluation of three cropping systems in southwestern Australia. Ecological Modelling 161, 195–211.

Lomas, P.L., Cialani, C., Ulgiati, S., 2007. Emergy analysis of Nations. Lessons learned from historical series. In: Brown M.T., Campbell D., Comar V., Haung S.L., Rydberg T., Tilley D., Ulgiati S. (Eds.), emergy synthesis 4. Theory and Applications of the Emergy Methodology. Center for Environmental Policy, University of Florida, Gainesville, USA, pp. 39.1–39.18 (ISBN: 0-9707325-3-8).

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

Lotka, A.J., 1922b. Natural selection as a physical principle. Proceedings of the National Academy of Sciences 8, 151–155.

Lotka, A.J., 1945. The law of evolution as a maximal principle. Human Biology 17, 167–194.

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

Odum, H.T., 1989. A systems overview of the university in society. In: Bjornson, R., Waldman, M. (Eds.), Rethinking Patterns of Knowledge. Papers in Comparative Studies No. 6. The Center for Comparative Studies in the Humanities, The Ohio State University, Columbus, Ohio.

Odum, H.T., 1994. Ecological and General Systems. University Press of Colorado, USA, 644 pp.

Odum, H.T., 1996. ENVIRONMENTAL ACCOUNTING. Emergy and Environmental Decision Making. John Wiley & Sons, New York, USA, 370 pp.

Odum, H.T., 2007. Environment, Power and Society for the Twenty-First Century: The Hierarchy of Energy. Columbia University Press, USA, 432 pp.

Odum, H.T., Odum, E.C., 2000. Modeling for all Scales. Academic Press, USA, 480 pp.

Odum, H.T., Odum, E.C., 2001. Prosperous Way Down: Principles and Policies. University Press of Colorado, USA, 348 pp.

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

Odum, H.T., Brown, M.T., Williams, S.B., 2000. Handbook of emergy evaluation: a compendium of data for emergy computation issued in a series of folios. Folio No.1 – Introduction and Global Budget. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville, 2000, p. 16, http://www.emergysystems.org/folios.php.

Patterson, M.G., 2002. Ecological production based pricing of biosphere processes. Ecological Economics 41, 457–478.

Prigogine, I., 1947. Study of thermodynamics of Irreversible Processes, 3rd ed. Wiley, New York.

Rydberg, T., Haden, A.C., 2006. Emergy evaluations of Denmark and Danish agriculture: assessing the influence of changing resource availability on the organization of agriculture and society. Agriculture, Ecosystems & Environment 117, 145–158.

Samperi, M., Napolitano, C., De Laurentis, D., Mariani, T., Pellicano, A.G., 1989. Bilanci energetici in Abruzzo (in Italian). Final Report for ENEA-CNR-'Energetics 2' Target Project, Contract No. 86.02622.59, 55 pp.

Sciubba, E., Ulgiati, S., 2005. Emergy and exergy analyses: complementary methods or irreducible ideological options? Energy - The International Journal 30, 1953–1988.

Shannon, C.E., 1948. A mathematical theory of communication. Bell System Technical Journal 27, 379–423.

Slesser, M., 1978. Energy in the Economy. Macmillan, London.

Smil, V., 1991. General Energetics: Energy in the Biosphere and Civilization. John Wiley and Sons, New York, USA, 369 pp.

Sweeney, S., Cohen, M., King, D., Brown, M.T., 2007. Creation of a global emergy database for standardized national emergy synthesis. In: Brown M.T., Campbell D., Comar V., Haung S.L., Rydberg T., Tilley D., Ulgiati S. (Eds.), emergy synthesis 4. Theory and Applications of the Emergy Methodology. Center for Environmental Policy, University of Florida, Gainesville, USA, pp. 23.1–23.18 (ISBN: 0-9707325-3-8).

Tribus, M., McIrvine, E.C., 1971. Energy and information. Scientific American 225 (3), 179–184.

Ulgiati, S., 2001. A comprehensive energy and economic assessment of biofuels: when "green" is not enough. Critical Reviews in Plant Sciences 20 (1), 71–106.

Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for the dilution and abatement of process emissions. The case of electricity production. The Journal of Cleaner Production 10, 335–348.

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

Ulgiati, S., Brown, M.T., Bastianoni, S., Marchettini, N., 1995. Emergy-based indices and ratios to evaluate the sustainable use of resources. Ecological Engineering 5, 519–531.

Ulgiati, S., Bargigli, S., Raugei, M., 2007. An emergy evaluation of complexity, information and technology, towards maximum power and zero emissions. Journal of Cleaner Production 15, 1359–1372.

von Bertalanffy, L., 1968. General System Theory. George Braziller, New York, NY, 295 pp.