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EMERGY, EMPOWER AND THE ECO-EXERGY TO EMPOWER RATIO: A RECONCILIATION OF H.T. ODUM WITH PRIGOGINE?

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ABSTRACT

This paper presents the theory behind and the possible uses of the ratio of eco-exergy to empower. This orientor originates from the comparison of S.E. Jørgensen's and H.T. Odum's approaches to ecosystems theory. The former proposed as orientor the maximization of stored eco-exergy, that is the extension of the thermodynamic function exergy of ecosystems. The latter, the maximization of empower, is the flow of emergy (solar energy directly and indirectly required to obtain a certain item). The use of the ratio of eco-exergy to empower enables one to understand what is the order that the two maximization criteria follow during the evolution of an ecosystem. A possible analogy between the maximization of eco-exergy to empower ratio and the minimization of specific dissipation is discussed. The use of this orientor for the comparison of the same system at different times or of different systems provides a possible holistic measure of the effects of the use of a certain pattern of inputs in a system. This can help comparisons within the framework of life cycle assessment.

Keywords: eco-exergy, eco-exergy to empower ratio, emergy, orientors.

1 INTRODUCTION

Ecosystem theories, at least the thermodynamically oriented ones, can be seen as having four points of origin (with some overlapping): on one hand, we have Lotka's *maximum power principle* [1] and information theory [2]. The different mixing of these two 'ingredients' has produced a number of concepts which have several aspects that are similar and some others that are complementary (for a complete survey of the characteristics of the orientors please refer to [3]).

On the other hand, these concepts can be seen as originating from two other viewpoints: that of graphs and networks and that of dissipative structures [4]. Systems can be treated and analyzed as networks using already existing and well-established techniques. Alternatively, they may be viewed as dissipative structures that exist at the expense of energy and as a consequence of building energy into structure. This entails changes in the energy expended from high quality, low entropy forms to lower quality, intermediate entropy forms, finally ending up as the highest entropy form, heat. In this case, thermodynamic efficiencies can be examined using the methods for optimized functioning.

Fath *et al.* [3] showed that 10 extremal principles involving orientors (power, storage, empower, emergy, ascendency, dissipation, cycling, residence time, specific dissipation, and empower/exergy ratio) can be unified by ecological network notation. In their fundamental paper, they also try to give a general principle encompassing all the aspects of the orientors: 'Get as much as you can (maximize input and first-passage flow), hold on to it for as long as you can (maximize retention time), and if you must let it go, then try to get it back (maximize cycling)' [3]. They conclude that the *resumé* of these three aspects is in the specific dissipation minimization, with the dimensions of time $[T^{-1}]$.

Furthermore, Fath *et al.* [5] demonstrated how specific entropy production, dissipation, eco-exergy storage, energy throughflow, and retention time behave during different growth and development stages: only the principles of maximization of energy throughflow and of maximization of eco-exergy storage are applicable during all four stages. The movement away from thermodynamic equilibrium, and the subsequent increase in organization during ecosystem growth and development, is a result of system components and configurations that maximize the flux of useful energy and the amount of stored exergy. Fath *et al.* [5] also show empirical data and theoretical models supporting these conclusions.

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2 EMERGY AND EMPOWER

'*Emergy* is the available energy (i.e. exergy) of one kind previously used up directly and indirectly to make a service or product. Its unit is the emjoule [(ej)]' [6] and its physical dimensions are those of energy (ML^2T^{-2}) of some specific kind, even though it is not a state function, since it strictly depends on the process. Considering that, basically, all the processes in the biosphere are driven by solar energy, it is natural to assume this as a common denominator and use the solar emergy (ML^2T^{-2} solar), measured in solar emjoules (sej), which is defined as the solar exergy required (directly or indirectly) to make a product.

(Solar) emergy measures the convergence of source energies at system boundaries into processes or products produced within the system interior. This is sometimes referred to as 'energy memory' [6].

The total emergy flowing through a system during a certain period of time is called *empower*, with units sej/[time] [6] and physical dimensions ML^2T^{-3} as for power.

The basis of emergy analysis is the conversion of all the inputs to a process, both in the form of energies or materials, into the same function (emergy) by using a conversion factor called *transformity*. Transformity is the intensive correspondent of emergy, it is not a state function, and it is dimensionless, albeit it is usually expressed in *solar emjoules per joule* (sej/J), reflecting the fact that the numerator is formed by a sum of solar emergies (therefore of a consistent quality), while the denominator is exergy of whatever form (that of the product of the process).

When the transformities of homogeneous items are compared, transformity provides information about production efficiency: the higher the transformity, the lower the efficiency (more emergy is needed to produce the same amount of product). On the other hand, in general, the second law of thermodynamics requires that some energy must be dissipated into an unusable form during the transformation that creates each new level of control; consequently, the quantity of exergy in each new level must decrease. Instead, emergy, following a memorization rather than a conservation logic, remains constant or grows and therefore transformities increase. According to H.T. Odum 'energy flows of the universe are organized in an energy transformation hierarchy … the position in the energy hierarchy is measured with transformities' [6].

3 MAXIMUM EMPOWER

The maximum power principle by Lotka states that 'in every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system, so long as there is presented an unutilized residue of matter and available energy' [1].

According to the energy hierarchy concepts, transformations that survive the natural selection processes of self-organization reinforce their supporting network with a feedback of its energy output even though its energy flow is less. Commensurate reinforcement with less energy is possible because the systems concentrate outputs spatially and accumulate the products and deliver their feedback actions in pulses. In terms of Lotka's principle, each transformation that survives self-organization is organized to help maximize its power while reinforcing the network [7]. Odum refers to Lotka's principle as 'ambiguous', because it seems to imply that transformations at a lower scale are more important than those at a higher scale, as they carry more energy [6]. In fact, the acquisition of 1 MJ by a system in the form of a herbivore would be different with respect to the acquisition of the same 1 MJ in the form of grass: the former would imply, indirectly, an acquisition of around 10 MJ of energy in the form of grass. For this reason, Odum modified Lotka and, based on previous research carried out with Pinkerton [8], stated that 'if natural selection has been given time to operate, the higher the emergy flux necessary to sustain a system or a process, the higher is their hierarchical level and the usefulness that can be expected from them' [9] or 'prevailing systems are those whose designs maximize empower by reinforcing resource intake at the optimum efficiency' [6].

This is in agreement with the maximization of dissipation or of entropy production [3, 6, 10], but apparently contrasts with Prigogine's theorem of minimum entropy production [11], as always stated by H.T. Odum (personal communications).

There are basically two limitations to the maximum empower principle: one is already in Lotka's formulation – the principle holds as long as there is an abundance of resources; the other is in the fact that there must be a suitable span of time in which a natural selection must have taken place. This is often not the case when dealing with shorter runs and with systems involving relations between humans and natural systems.

4 EMERGY AND INFORMATION

Previous work has been done on the relation between energy and information in the transmission of messages [12] and the relation between emergy and information in biological systems of different dimensions [13, 14]. Tribus and McIrvine examined the relations between energy and information in the preparation, processing and distribution of information.

In his Crafoord prize lecture in Stockholm, Howard Odum stated that the emergy/information ratio is a measure of the information hierarchy: the higher the energy hierarchy of a system, the higher the ratio in sej/bit [13]. He also discussed the results of a comparison of four types of systems at different levels having the same number of bits of structural information. One thousand bits of molecular glucose, an algae, a forest and a science journal were examined. The production of the same quantity of information in different spatial scales requires quite different energy inputs. This gives a scale factor that cannot be obtained from simple energy analysis. The emergy/information ratio was greatest for the science journal, followed by the forest. On analyzing the energy to information ratio, an inverse result is obtained.

5 EXERGY AND ECO-EXERGY

The relation between emergy and information used by Odum gives a good indication of general character but has problems related to the Shannon's formula: the basic element of the 'alphabet' from which probability and information are calculated is arbitrary, so it is impossible to compare systems with a different set of possibilities.

We can view emergy as the work that the biosphere has to do, in order to maintain a system far from equilibrium or in order to re-produce an item once it has been used. Emergy (and empower) is a donor-referenced concept rather than a receiver-referenced one. It is therefore necessary to compare it (or better its 'flow', empower) to a function of the state of the system that considers the information in the system, including the difference in size and quality of the components. Eco-exergy [15, 16] is a perfect candidate for this task.

Exergy is a thermodynamic potential that measures the distance of an open system from thermodynamic equilibrium, as a function of the gradients of the possible intensive physical and chemical variables. Eco-exergy is derived from exergy by means of approximations that make this function suitable for the description of the level of complexity of ecosystems. Eco-exergy (ex) for organisms can be calculated as:

$$\mathrm{ex} = \sum \beta_i \times c_i, \tag{1}$$

where β is a weighting factor related to the probability of forming the organism at the thermodynamic equilibrium [16]. In other words, it represents how much information an organism contains, starting from the genome size. Latest calculations of the β values are reported by Jørgensen *et al.* [17].

In this way, Eco-exergy measures the distance from thermodynamic equilibrium of a *living* organism, while in exergy this biological aspect is absent. Eco-exergy is a possible solution for the problem of distinguishing the dead deer from the living deer in [18]: eco-exergy is the suitable indicator for the living deer, exergy for the dead one.

6 THE RATIO OF ECO-EXERGY TO EMERGY FLOW

Bastianoni and Marchettini [19] introduced a relation between emergy flow and eco-exergy to indicate the solar emergy flow required by the ecosystem to produce or maintain a unit of organization or structure of a complex system. The choice of this ratio was made in order to maintain coherence with the definition of transformity and point out the differences: transformity is the emergy that contributes to a production system divided by the energy content of a product (or empower divided by power). The emergy flow to eco-exergy ratio instead represents an emergy flow divided by *the eco-exergy of the whole system* driven by this emergy flow. The unit of this ratio is sej/(J·time), while the dimensions are the reciprocal of time. We find the eco-exergy to empower ratio more meaningful since it would present the state of the system (as eco-exergy) per unit input (as emergy). Therefore the eco-exergy/empower ratio can be regarded as the efficiency of an ecosystem, even though it is not dimensionless (as efficiency usually is), as it has the dimension of time. Svirezhev (personal communication) found this fact to be normal, since this concept, in his opinion, resembles that of a *relaxation* time, i.e. the time necessary to recover from disturbances, so that the exergy to empower ratio should be related with concepts like resilience and resistance of an ecosystem.

This parameter indicates the quantity of external input necessary to maintain a structure far from equilibrium. The higher its value, the higher the efficiency of the system; if the eco-exergy/empower ratio tends to increase (apart from oscillations due to normal biological cycles), it means that natural selection makes the system follow a thermodynamic path that will bring the system to a higher organizational level.

As an efficiency indicator, the eco-exergy to empower ratio enlarges the viewpoint of a pure exergetic approach as described by Fath *et al.* [5], where the exergy degraded and the eco-exergy stored for various ecosystems are compared: using emergy it is recognised that solar radiation is the driving force of all the energy (and exergy) flows in the biosphere, which is important when important 'indirect' inputs (of solar energy) are also present in a process.

The eco-exergy to empower ratio has been applied to several aquatic ecosystems. To compare ecosystems different in size, we used empower and eco-exergy densities.

Table 1 shows empower and eco-exergy density values and the ratio of eco-exergy to empower. It was observed that the natural lake (Caprolace) had a higher eco-exergy/emergy ratio than the control and waste ponds, due to a higher eco-exergy density and a lower emergy density [19]. These observations were confirmed by the study of Lake Trasimeno [20]. Figheri Basin is an artificial ecosystem, but has many characteristics typical of natural systems. This depends partly on the long tradition of fish farming basins in the lagoon of Venice, which has 'selected' the best management strategies [21].

The human contribution at Figheri Basin manifests as a higher emergy density (of the same order of magnitude as that of artificial systems) than in natural systems. However, there is a striking difference in eco-exergy density, with values of a higher order of magnitude than in any of the other systems used for comparison: man and nature are acting in synergy to enhance the performance of the ecosystem. The fact that Figheri Basin can be regarded as a rather stable ecosystem (i.e. quite regular in its behavior) makes this result even more interesting and significant.

The emergy flow to Iberà Lagoon has been underestimated due to lack of data about the release of nutrients from the surrounding rice farms. In a sense, this explains the highest value for the eco-exergy

Table 1: Empower density, eco-exergy density and eco-exergy to empower ratio for eight different ecosystems.

	Control pond	Waste pond	Caprolace Lagoon	Trasimeno Lake	Venice Lagoon	Figheri Basin	Iberá Lagoon	Galarza Lagoon
Empower density (sej/year l)	20.1×10^8	31.6×10^8	0.9×10^8	0.3×10^8	1.4×10^9	12.2×10^8	1.0×10^8	1.1×10^8
Eco-exergy density (J/l)	1.6×10^4	0.6×10^4	4.1×10^4	1.0×10^4	5.5×10^4	71.2×10^4	7.3×10^4	5.5×10^4
Eco-exergy/empower (10^{-5} J year/sej)	0.8	0.2	44.3	30.6	39.1	58.5	73	50.0

to empower ratio, while the ecosystem does not seem to be in ideal conditions [22]. Nonetheless, the important fact is that all natural systems that are better protected from human influence show very close figures. It seems that there is a tendency common to different ecosystems in different areas and of different characteristics to evolve towards similar thermodynamic efficiencies. Also, the latest results on the entire lagoon of Venice confirm the general trend, showing figures in the range of Trasimeno Lake and Caprolace Lagoon, in spite of the differences in the structure of the ecosystems and the huge inputs from the watershed.

In general, we can say that in natural systems, where selection has acted undisturbed for a long time, the ratio of eco-exergy to empower is higher and decreases with the introduction of artificial stress factors that make the emergy flow higher and lower the eco-exergy content of the ecosystem.

The fact that the eco-exergy to empower ratio is higher for 'older' ecosystems is consistent with the maximum eco-exergy principle, when emergy flow is considered constant. As a test example, we can refer to the experimental microcosm with phytoplankton used by Huisman [23]. In the experiments, light (taken as a limiting factor) was kept constant for a certain time, at different levels. The population followed a logistic-shape behavior with the climax state level increasing together with the incident light intensity [23].

Though this system is quite 'simple', it gives an idea of the pattern followed by emergy flow and eco-exergy. The maximum empower is verified by the fact that the steady state level of the population increases, albeit less and less, as a function of light intensity. At the same time, when light is kept constant (the only emergy flows to the system), the population tends to grow until it reaches the farthest possible point from thermodynamic equilibrium (maximum eco-exergy). Experiments were performed on different species of phytoplankton but with each one separated; therefore, the rise in eco-exergy is to be intended as a growth of biomass rather than a shift in species composition.

Based on this reasoning it seems that, close to the steady state (climax), the ratio of eco-exergy to emergy flow tends to increase, which means that in Fig. 1, showing eco-exergy as a function of emergy flow, the slope of the curve tends to rise. In this case the emergy flow is practically constant, while the system uses all the materials and energy available to reach a higher eco-exergy content. The system, once it reaches the climax, will remain in such a state for some time. At this point the system (and its eco-exergy) can grow only if further energy and/or materials are available (i.e. the emergy flow increases). At the beginning of such a phase the system would have obviously a lower eco-exergy to empower ratio.

In fact, in a system the eco-exergy versus empower plot seems to follow a 'stairs' function (see the solid lines in Fig. 1), where the horizontal lines indicate that the system has new energy and/or matter available, while the vertical lines mean that the system is reaching a higher level of organization due to the higher emergy available. Obviously the 'real' curve should be smoother as shown by the dotted lines in Fig. 1.

Especially in this latter version (dotted), this pattern of self-organization, suggested by eco-exergy/empower maximization, is also consistent with both maximum empower and maximum eco-exergy principles. In fact, for each of the couples' horizontal–vertical lines, both emergy flow and eco-exergy stored, as well as the eco-exergy to empower ratio, are maximized. Therefore, the three principles are basically consistent: they can all be valid at the same time. It is the order in which two of the principles are satisfied that is constrained: first, the maximum empower and then the maximum eco-exergy, while eco-exergy/empower remains valid. This is, in fact, quite intuitive: first, an ecosystem should find new sources of energy (or better emergy); only afterwards these available inputs can be used to build up new biomass, and/or complexity of the ecosystem itself (stored eco-exergy). This fact amplifies the role of the eco-exergy to empower ratio: when a system is relatively 'young', i.e. when acquiring new inputs, the ratio tends to be lower; on the other hand, when the system is

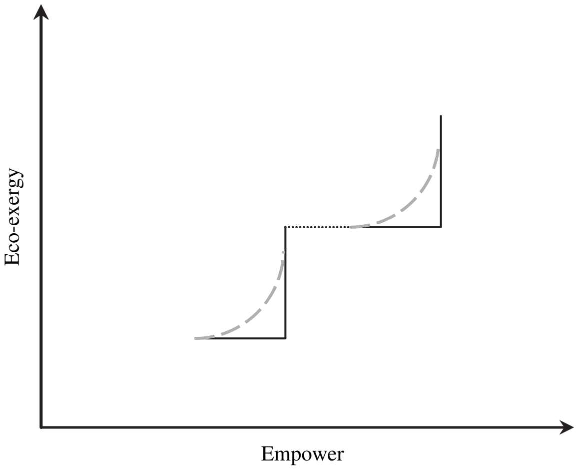

Figure 1: Theoretical development of eco-exergy versus empower.

developing with the available inputs, the eco-exergy to empower ratio tends to rise as the system tends to the climax stage. This result is consistent with that of Fath *et al.* [5] who have shown that eco-exergy storage in the various phases of ecosystem growth and development increases faster than exergy use.

This fact may be seen as a reconciliation of H.T. Odum's theories not only with the theories of S.E. Jørgensen but also with those of Y. Prigogine. Maximum (em)power can be achieved together with a maximum eco-exergy to empower ratio. But it can be shown that the last stages of development of an ecosystem is also consistent with Prigogine's minimal specific dissipation. In fact Fath *et al.* [3] refer to this principle as being slightly different from the maximization of eco-exergy to empower ratio: this is formally true, since they are represented by {Min TSE/TSS} and {Max TSS/TST}, respectively (TSS, total system storage; TSE, total system export; TST, total system throughput).

Nevertheless, it should be considered that in emergy, by definition, the export is the sum of the independent inflows (and throughflows), i.e. TSE is the result of the convergence of all the throughflows that contribute to the development of the system and therefore TST and TSE are exactly the same concept. The maximization of the eco-exergy to empower ratio is thus consistent with the minimization of specific dissipation.

7 THE RATIO OF ΔEx TO ΔEM

What happens to an ecosystem if there is a change in inputs? How would a system respond to this change with regard to its self-organization? In general terms we can ask ourselves, can we express the concept of 'pollution' by means of holistic measures? Also, this problem can be seen in terms of emergy flows and eco-exergy.

If we consider that the emergy flow to a system varies between two equal and contiguous intervals, these intervals must be significant for the system under study in order to annul the effect of periodical variations like daily and seasonal cycles. In effect, emergy analysis is almost always performed considering an interval of 1 year during which all the emergy inputs and energy outputs are accounted for in obtaining transformities. The variation of emergy flow is represented as ΔEM [24].

What will be the change in organization due to the change in the emergy input ΔEM? To answer this question, we have to be able to calculate the variation of the eco-exergy content of the system ΔEx.

We therefore introduce the quantity

$$\sigma = \frac{\Delta \mathrm{Ex}}{\Delta \mathrm{EM}}, \tag{2}$$

with the dimensions of J s sej^{-1}, representing the change of the level of organization (eco-exergy) of the system under study, when it is involved in a change in the emergy flow. It is a quantity that is specific to the inputs that are subtracted or added.

To explain what scenarios are possible, we can consider that if σ is positive the addition of emergy input gives rise to further organization, whereas a lowering of emergy has a negative effect on the system. On the other hand, when σ is negative, a higher emergy flow causes a decrease in organization or a lower quantity of one or more inputs causes increasing organization.

We can say that in both the latter cases the inputs (added or removed) can generally be regarded as pollutants: if we remove them, the system self-organizes; if we add them, the system is damaged. So we can have a definition of pollution based on two orientors, emergy and eco-exergy, that focus their attention not on particular aspects of a system, but on the system as a whole. The intensity of the ‘pollution’ is proportional to the absolute value of the slope of the segment connecting the origin to the point that describes the system, since a small increase (decrease) in emergy flow produces a large loss (gain) of organization.

The same reasoning can be applied to cases where σ is positive. The slope of the line connecting the point with the origin represents the benefit that a set of inputs – when added – is able to produce on a system.

The points on the diagram correspond to singular situations that can evolve over time. We have a succession of points, one for each subsequent interval, during which we can calculate the emergy flow. To clarify this point, we refer to what we previously said about the differences existing between emergy and eco-exergy also from a mathematical viewpoint.

Let us consider, t_0, t_1, …, t_{k-1}, t_k, t_{k+1}, …, a set of points on the axis of time, representing the extrema of the closed intervals in which we calculate the emergy flows to the system, $\mathrm{EM}([t_0, t_1])$, …, $\mathrm{EM}([t_{k-1}, t_k])$, $\mathrm{EM}([t_k, t_{k+1}])$, … . In correspondence to each point t_j we can also calculate the eco-exergy $\mathrm{Ex}(t_j)$.

The succession of points of the ratio $\Delta\mathrm{Ex}/\Delta\mathrm{EM}$ can be written as

$$\sigma_k = \frac{\mathrm{Ex}(t_{k+1}) - \mathrm{Ex}(t_k)}{\mathrm{EM}([t_k, t_{k+1}]) - \mathrm{EM}([t_{k-1}, t_k])}, \tag{3}$$

where σ_k is the ratio calculated considering the differences between the two flows of emergy during the intervals $[t_k, t_{k+1}]$ and $[t_{k-1}, t_k]$, and the value of the eco-exergy at the right extrema of these two intervals. In this way, we have a succession of σ_k points which represent the way the system responds to changing surrounding conditions. We can consider a succession starting from a point δ with a negative σ to a point with a positive value of σ. These would mean that the system is ‘learning’ how to use other available inputs and self-organize. On the other hand, a pattern of inputs that is initially positive for a system can become negative if there is a longer-term toxic effect.

As an example of the application of this concept, consider the change in the composition of rain that falls on a forest. If the rain becomes more acidic, its emergy content rises as does the emergy flow through the forest. On the other hand, the eco-exergy of the forest is likely to decrease because of the loss of biomass density and the consequent loss of biodiversity. In this case, σ would be negative at least until the acidity of the rain decreases again or the species in the forest learn how to survive in the modified environment or how to use a different input.

This framework has helpful in solving some shortcomings in the use of a pure life cycle assessment (LCA) approach [25]: as stated by Bakshi [26], in LCA there is a lack of a systematic and quantitative framework that does not allow comparisons of the environmental sustainability of processes, when we want to consider both the use of resources and the global effects of the outputs of a process. The use of emergy and exergy, and especially a wider use of the ratio of the variations of eco-exergy and empower, can be a step towards a thermodynamic foundation of LCA [26].

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