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Emergy-based indices and ratios to evaluate the sustainable use of resources

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Abstract

By means of a systemic analysis of the relationships among components of an ecosystem's web, the flows of energy and other resources converging to produce the output (biomass, biodiversity, assets, etc.) can be evaluated on a common basis, i.e. the content of *solar equivalent energy* (emergy). Indices and ratios based on the emergy flows can be calculated and used to evaluate the behaviour of the whole system. In this paper, one of these indices, the emergy yield ratio η (total yield emergy per unit of emergy invested) is evaluated and suggestions made to modify it to account for present and future environmental damages due to the use of a given resource. The meaning of this index, with and without the proposed modification, is stressed illustrating the long-term effects of environmental pollution as well as some key uncertainty factors that are very often not taken into account. Odum, 1993

Keywords: Emergy-based indices; Systemic analysis; Ecosystem web; Biomass; Biodiversity; Solar equivalent energy

1. Introduction

Ecological engineering is concerned with the interface of environment and human society. Quantitative understanding of the relationships between human dominated systems and the biosphere is the realm of emergy analysis (Odum, 1988). This method of analysis may be a useful tool for evaluating appropriate investments in ecological engineering projects by providing new information and lending insight regarding the advisability and net benefits (i.e. sustainability) from proposed projects. Waste recycling or clean up, for instance requires an emergy

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investment, lowering net emergy available for other uses in the economy. Thus a measure of sustainability is whether a proposed project uses more total emergy than it yields. When comparisons are made between traditional engineering solutions (technological) and ecological engineering solutions to problems, emergy analysis may provide a more complete accounting, since it can evaluate both economic and environmental systems.

Emergy analysis differs from economic analysis because instead of using the dollar value of goods, services, and resources, a measure of resource quality is used. Emergy analysis is a method of energy analysis that accounts for the direct and indirect use of energy in producing a commodity, resource, fuel, or service, in energy of one type, usually solar energy. The solar emergy in a resource, product, or service is the sum of the solar energies required to make it. In evaluating the emergy used to make a product or that invested in an ecological engineering project, the total emergy inputs are summed, including both fossil fuel energies and environmental energies (like sunlight, rain, tides, etc.). Emergy can be conceptualized as energy memory (Scienceman, 1987, 1989), since it is a measure of all of the energy previously required to produce a given product or process.

When processes are evaluated, all inputs are expressed on a common basis, i.e. solar emergy, since all energy does not have the equivalent ability to cause work. The common basis facilitates comparison with alternative processes or investments of energy. During analysis of a process of project, several ratios are calculated that help to predict best alternatives and those that are most likely to succeed. One ratio, the emergy yield ratio, might be used to evaluate ecological engineering projects. The emergy yield ratio is the ratio of yield from a process to the costs of obtaining the yield where costs (inputs) and yields are evaluated in emergy terms. The emergy yield ratio may be a measure of sustainability.

In this paper a critical evaluation of the emergy yield ratio is given, suggesting that there is a need to include future environmental disordering, recycling, and/or clean up. To minimize confusion with emergy yield ratios calculated for fuel resources, the new ratio might be called "end use" emergy yield ratio in contrast to the ratio that is calculated for sources without regard to negative effects, which we have titled "emergy yield ratio of a source."

2. Concepts and definitions

By definition, the solar emergy B_k of the flow k coming from a given process is:

$$B_k = \Sigma_i Tr_i E_i \quad i = 1,...,n \tag{1}$$

where E_i is the actual energy content of the i-th independent input flow to the process itself (Fig. 1a), and Tr_i is the solar transformity of the i-th input flow, defined (Fig. 1b) as follows:

$$Tr_i = B_i / E_i \tag{2}$$

In Eq. (2), B_i is the total solar emergy driving the i-th process. This circular definition is made operational by putting Tr_s, the solar transformity of direct solar energy, equal to 1.

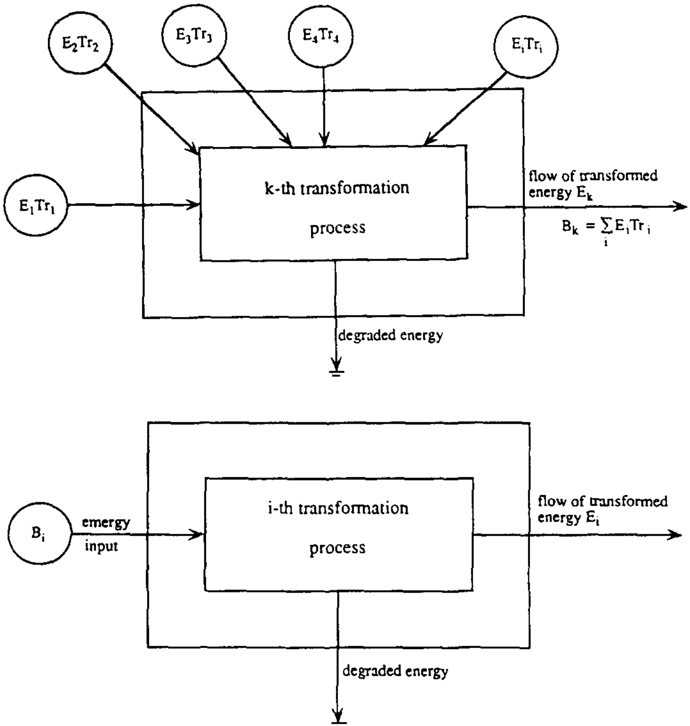


Fig. 1. (a) Total solar emergy driving a system. By definition, the emergy of the output is the sum of all the emergy inputs. (b) Definition of solar transformity, as the ratio of the total emergy input by the actual energy content of the output.

Thus, when a process is directly driven by solar energy, the transformity clearly appears as a measure of the convergence of solar energy to originate the product flow. When a set of transformities Tr_i has been calculated for a certain number of flows or products originated by direct solar energy, it is possible to evaluate the indirect solar energy requirement of other processes where the input flows are known, according to Eq. (1). Finally, the solar transformity of a given process k can be calculated from Eqs. (1) and (2):

$$Tr_k = B_k/E_k = \Sigma_i Tr_i E_i/E_k \tag{3}$$

where E_k is the actual energy content of the product k.

Solar emergy is usually measured in solar emergy joules (sej), while solar transformity is measured in solar emergy joules per joule of product (sej/J).

3. Natural and man-made processes

Natural systems and those under human control differ in the source of controlling energies (those of biosphere origin in the former, and those of human release and origin in the latter). In processes under human control, the same energy flow or product can originate from different processes, and have many different transformities according to the specific time, location and technological development. The same is not true for natural systems, where it is a common rule that processes in a given environment, operating under natural selection, develop organizations that achieve maximum performance. The result is an optimum value of the transformity, selected by a long trend to achieve the present throughput and operating efficiency.

The optimum transformity is that one which corresponds to the thermodynamic efficiency resulting from the ecosystem's self-organization activity, for the specific process under study. This is, generally speaking, not the highest efficiency theoretically possible: usually natural systems sacrifice efficiency for maximum power output (Lotka, 1922a, Lotka, 1922b; Odum and Pinkerton, 1955) relative to the whole system. This issue is often referred to as the Maximum Power Principle (Lotka, 1922a,b) or the Maximum Emergy Principle (Odum, 1988).

Maximum power is often not achieved at any point in time for individual self organizational processes. This is especially true for human dominated systems where many choices lead to differing optimization strategies that in the short run do not maximize power. However, through such choices an optimum system configuration may be achieved in the long run, that does maximize power. In the trend of human societies towards the most effective behaviour in resources use, transformities may vary, being time, technology and location specific, so that they should be carefully handled. When the exact origin of a resource or energy is not known or when an energy represents an aggregation of many individual production processes (e.g. electricity) an average value between those available is very often the best choice.

It is possible to calculate corresponding transformities for energy fluxes or material products not directly related to solar energy flow; this is the case of geothermal energy driving geological processes, or minerals from underground storages. Transformities have been calculated for most flows of energy and material storages in the biosphere in order to express flows or products in terms of solar emergy (Odum, 1995).

The total emergy driving a process becomes a measure of the self-organization activity of the planet converging energies to make that process possible. It is a measure of the environmental work necessary for providing a given resource. In other words, part of past and present work of ecosystems, geochemical cycles, and tidal momentum are required to make a resource available, be it the present oxygen stock in the atmosphere or the present stock of gold or oil deep in the planet. Giampietro and Pimentel (1991) developed a similar approach, introducing the Biosphere Space-Time Activity (BIOSTA) as a measure of environmental life-supporting work.

4. Emergy-based indices and ratios

Once the total number of input flows to a process have been identified and the total emergy driving the process has been calculated according to Eqs. (1), (2) and

(3), a set of indices and ratios can be accordingly introduced. These indices have been shown to be particularly useful when studying and comparing processes under human control, where a sustainable pattern is not guaranteed and choices have to be supported by the careful consideration of many different parameters. Some of these indices and ratios have been defined and discussed elsewhere (Odum and Odum, 1983; Brown and McClanahan, 1992; Doherty et al., 1992; Ulgiati et al., 1994; Odum, 1995). In the present paper, a critical evaluation of one of them, the emergy yield ratio η, is presented. This ratio, defined in the next section, can be used to compare different uses of the same resource or different processes yielding the same kind of output. It may lend insight into questions regarding sustainability and appropriate level of technological investment in ecological engineering projects.

5. Net emergy and emergy yield ratio

The theory that an emergy source should contribute to a system at least equal to the cost (emergy required) of obtaining it, is a consequence of the maximum emergy principle. For if the emergy cost is greater than its contributions, a system that uses emergy in this way is not competitive with one that gets more "net emergy" from its sources. The difference between the emergy costs of a source and its contribution is called its net emergy contribution. But what are these costs and how do they affect a systems performance and its competitive potential?

Fig. 2 illustrates the concept of net emergy often used to evaluate the potential contribution of an emergy source to the economy. An emergy source I, which often is the sum of a renewable part R and a nonrenewable part N, is transformed using a required input emergy from other sources (most often an energy feedback F from the economy). The emergy of I and F are summed to obtain the emergy yield Y. Net emergy is the difference between the investment F and the yield. However, the emergy costs of transforming a source are not the same as the disorder it may cause when used. In the context of a system, when a source is transformed, there is an increase in order, and an increase in disorder. Often the disorder created when a source is concentrated (i.e. digging for coal, cutting a forest) is taken into account when calculating net emergies, but the disorder created when it is used, is not.

Consider now the net emergy ϵ and the emergy yield ratio η of a given process, defined as follows:

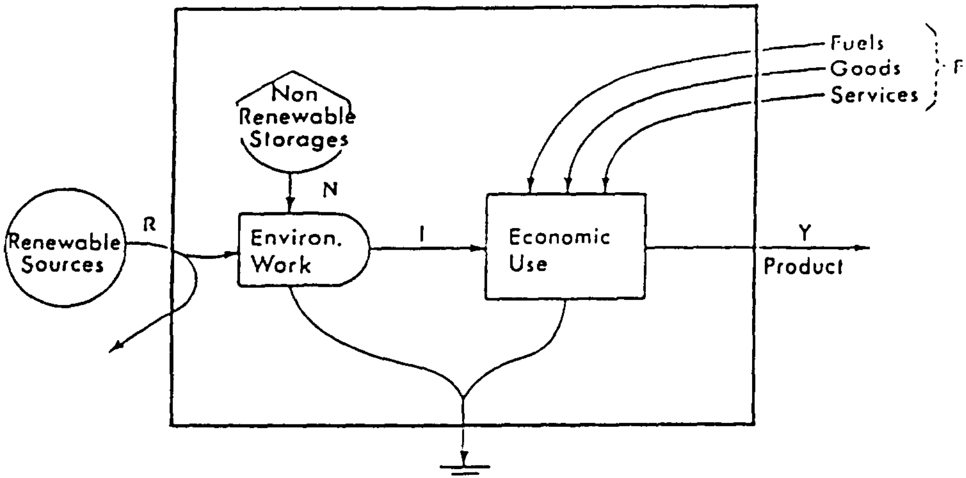
Net emergy $\epsilon = Y - F$ = yield Y minus feedback F;

Emergy yield ratio $\eta = Y/F$ = yield Y to feedback F ratio.

where Y is calculated as the sum of all independent inputs to the process, driving the production of the output:

$$Y = R + N + F.$$

It should be pointed out that there is a different time character in R compared



$$I = N + R$$

$$Y = I + F$$

$$\text{Net Emergy} = Y - F$$

$$\text{Emergy Yield Ratio} = Y/F$$

Fig. 2. Definition of net emergy ϵ and emergy yield ratio η.

to N and F. The flow R represents inputs coming from the present, i.e. inputs which are continuously formed at the same time that they are being used, while the emergy in N and F was used in the past, i.e. they represent the emergy needed over a long period of time to provide them. All these inputs are considered as a measure of the emergy cost of production of the output. All have been used up in the course of the process.

Emergy accounting does not discount or compound emergy values over time. Because emergy is a measure of energy used, independent of monetary costs, it is not affected by inflation.

A new issue focused on in this paper is that, in addition to past expenditures of energy, investments from the future should also be evaluated and included, i.e. future emergy costs due to present use of emergy sources. As a consequence, different emergy indices based on past, present and future emergy costs can be calculated.

6. Evaluating investment costs

Consider now the process shown in Fig. 3. For the sake of concreteness, suppose the process is oil extraction and transformation. The first step of the process consists of investing emergy (F_1) from the economic system to extract the nonrenewable oil resource (N). Assuming that, in this case, the renewable emergy R is negligible, the yield Y_1 in emergy will be the sum of N and F_1 and the net emergy ϵ_1 of this step will be

$$\epsilon_1 = Y_1 - F_1 = N + F_1 - F_1 = N$$

while the emergy yield ratio will be

$$\eta_1 = Y_1 / F_1 = (N + F_1)/F_1$$

When crude oil is transformed the transformation steps (oil refining, transporting, etc.) require new emergy inputs (F_2) from the main economy (labor, machinery, information, etc.) so that the emergy yield (Y_2) after refining will be

$$Y_2 = Y_1 + F_2 = N + F_1 + F_2.$$

If steps I and II are considered together, the total feedback F will be:

$$F_{\text{tot}} = F_1 + F_2$$

and the overall net emergy will be

$$\epsilon_2 = Y_2 - F_{\text{tot}} = Y_2 - F_1 - F_2 = N + F_1 + F_2 - F_1 - F_2 = N = \epsilon_1.$$

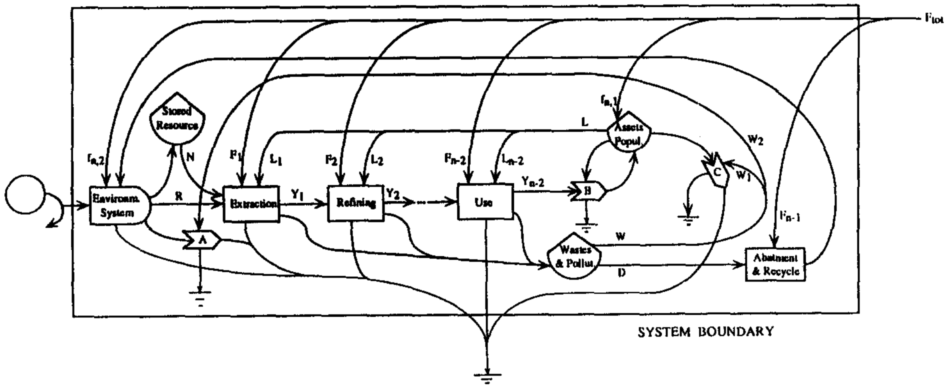


Fig. 3. Diagram of emergy investments (feedbacks), needed to exploit a given resource (e.g. oil). Feedbacks F_1 to $F_{n\text{-}2}$ are invested since the resource is extracted until it is used up. Uncontrolled wastes and pollutants $W = W_1 + W_2$ may affect and damage the natural environment and the system of human economy (assets and population), interacting in A and C. It will require an additional feedback $F_n = f_{n1} + f_{n2}$ to fix this damage and restore the previous state. An investment $F_{n\text{-}1}$ is also required to avoid the release of some pollutants and wastes D and dispose/recycle them in a way which is not noxious to the environment. The energy in the product from resource use $Y_{n\text{-}2}$ allows the autocatalytic growth of assets and population (interaction B), which feed back to all the steps of the process (L, L_1,..., mainly labor and information). If all the feedbacks F_{tot} are accounted for, the yield ratio $\eta_{n\text{-}2}$ becomes $\eta_n < \eta_{n\text{-}2}$, as described in the text.

For the same amount of N obtained after the first step, a higher amount of F was invested. As a result N has changed: it was crude oil, at the beginning, while it is refined products after the second step. The amount of these refined products (either measured in grams or joules) is less than the original crude oil, but their usefulness to the economic system (in the form of fuels, lubricants, etc.) is higher.

If we now calculate the emergy yield ratio η for the two processes I (oil extraction) and II (oil extraction plus refining), we have:

$$\eta_1 = Y_1/F_1 = (N + F_1)/F_1 = N/F_1 + F_1/F_1 = N/F_1 + 1$$

and

$$\eta_2 = Y_2/F_{\text{tot}} = (Y_1 + F_2)/F_{\text{tot}} = (N + F_1 + F_2)/(F_1 + F_2) = N/(F_1 + F_2) + 1.$$

By considering a plurality of steps, it emerges that $\eta_1 > \eta_2 > \eta_3 > \ldots > \eta_{n-1} > \eta_n$, i.e. the higher the technological level of a resource processing, the lower the output per unit invested input, in emergy terms.

Consider now Y_2 in the form of a refined resource (for example, gasoline). The process of using this resource is represented as another step in Fig. 3, where an additional high quality input F_{n-2} in the form of machinery, labor, etc., is also required, in order to use the resource. The above reasoning also applies to this step: the emergy yield ratio η_{n-2} of the overall process from extracting to completely using up the resource will again be lower than the previous one. Yet, when a resource is used, a product Y_{n-2} is obtained (work, goods, kilometres of travel, etc.) together with some by-products W, which can be undesirable or even toxic. By-products may affect humans, the immediate environment within which the process takes place, as well as the whole biosphere, modifying its ability to self-organize and affecting its overall stability.

The number of possible (solid, gaseous, liquid) by-products is practically infinite and each of them may have a variety of consequences, depending upon their chemical activity, permanence time within the system, etc. Suppose that humans will be able to remove them from their environment, or even to prevent their release by means of adequate technologies. This will require some process of control, recycle or abatement (Fig. 3), driven by a further input F_{n-1} from the system, again reducing the net emergy yield η_{n-1}.

It's evident that we are facing a source of large uncertainty, due to the difficult analysis of the number of by-products and their toxicity as well as of the technologies for their removal. While F_1 to F_{n-2} could be evaluated with relative precision, it appears that the evaluation of F_{n-1} and of its impact on the overall yield ratio η_{n-1} could present a high degree of uncertainty. Yet, this should be taken into account when evaluating the real contribution (work potential) of a given resource to a system.

It seems impossible to hypothesize a complete control, disposal and recycle system for all pollutants. It appears reasonable that it may be possible to evaluate the emergy investment (F_{n-1}) needed to dispose or recycle a few of the wastes/by-products W (solid urban wastes, few chemical and gaseous wastes from industrial production, etc.), while the larger part will be released into the biosphere, without control.

Emission of pollutants into the biosphere and their physical and chemical interactions with other biosphere components (for example, the damage to the ozone layer by CFC) are likely to cause a large number of consequences in the self-organization ability of the biosphere. Undoubtably these are very hard to forecast, detect or measure. Again, a large uncertainty follows concerning the disorder that may be created by uncontrolled pollutants or heat emissions: for instance, (1) loss of human health, (2) loss of fertility of soils; (3) reduction of photosynthetic primary productivity; (4) loss of biodiversity; (5) changes in the global water cycle; (6) desertification of large areas, and so on. Maybe, from the viewpoint of the biosphere all these (or some of them) are minor problems in the long time scale. Yet, they appear to be dramatic changes in the short run, modifying the structure/functions of the global life support system and in turn affecting the net emergy yield from an energy source.

In general, it is not possible to avoid all emissions of wastes and pollutants with present technologies: some of them are very often released into the environment. An additional investment F_n will be required annually over the permanence time of the pollutant in the biosphere (turnover time), to fix the damage caused by a given pollutant. As a result of those considerations, we propose an emergy ratio that might be termed "Emergy Yield Ratio of End Use" in contrast to the ratio that is often calculated which we term "Emergy Yield Ratio of a Source."

In conclusion, the total feedback F_{tot} will be given by the sum of inputs F_1 to F_{n-2}, required to exploit and use the resource, and inputs F_{n-1} and F_n, required after the resource has been used. If all these investments are taken into account, the emergy yield ratio η_n will be

$$\begin{aligned}\eta_n = Y_n/F_{tot} &= (N + F_1 + F_2 + \dots + F_{n-2} + F_{n-1} + F_n)\\ &\quad /(F_1 + F_2 + \dots + F_{n-2} + F_{n-1} + F_n)\\ &= (N + \Sigma_i F_i)/\Sigma_i F_i = N/F_{tot} + 1 \quad i = 1,\dots,n\end{aligned}$$

which is again lower than the ratios previously calculated.

The previous formula for η_n can be further detailed as follows:

$$F_1 = \Sigma_j f_{1j}$$

where f_{1j} is a generic input invested in step I of the process. Analogous expressions F_2, F_3,...,can be written for steps II and III, and eventually other steps, until the exploited resource is used up. We may also write

$$F_{n-1} = \Sigma_j f_{(n-1)j}$$

$$F_n = \Sigma_j f_{nj}$$

where $f_{(n-1)j}$ and f_{nj} are respectively generic emergy investments for pollutant control, recycle or abatement and for repairing diseases and damages in human life and assets due to prolonged presence of uncontrolled pollutants, as described above; the sum should be extended to all (known) mechanisms and pollutants.

We are now able to write a general expression for End use Emergy Yield Ratio as follows ϵ_n:

$$\eta_n(N+\Sigma_i\Sigma_j f_{ij})/\Sigma_i\Sigma_j f_{ij} \quad i=1,\ldots,n; \quad j=1,\ldots,m_i \tag{4}$$

where the index i ranges over all of different steps requiring a feedback F_i and the index j ranges over the different components f_{ij} of a given feedback F_i.

7. Discussion

The minimum value η_n may have is 1. This happens when N can be considered negligible in comparison with F_{tot}. In this case, the emergy return equals the investment and the process does not contribute net emergy to the user. This may happen for technical reasons, for example when fuels and minerals are not very concentrated or when the use of a given resource is highly polluting.

Higher values for η_n are obtainable when the importance of the feedbacks (F_n) are reduced. If the process has no polluting emissions or it the emission rate is comparable with the recycling rate of the biosphere, so that no additional work is required to avoid emissions or to fix damages, the emergy yield ratio will be determined by the emergy content of the yield and the emergy invested by humans directly to exploit the resource. Improvements of yields obtained using up more nonrenewable resources for production or for pollutant disposal will also increase the feedbacks, without contributing to an increase of the overall η_n.

When actions for pollutants abatement and for saving the biosphere structure/functions are needed and accounted for, η_n is lower: thus it can be considered a suitable indicator of the sustainability of a process exploiting a given resource. The value η_n of the process under study will therefore fall within a range [1 to $\eta_{\max}$], the closer the ratio is to unity, the less sustainable the process.

Further details can be obtained by focusing our attention on the feedbacks. As we already pointed out, they can be divided in two categories: investments for resource processing and investments for pollutants processing. We are able to evaluate with appreciable precision the first category of investments, also taking into account variation due to changes in resource availability as well as technical improvements.

On the contrary, a larger uncertainty is embodied in the second category of investments, and it might be useful to account in greater detail for these last kinds of feedback. Investments, $F_{n\text{-}1}$, for abatement or recycle of emissions are process and technology specific; they also depend upon the degree of abatement or recycle necessary. Each $f_{(n\text{-}1)j}$ should be evaluated by considering apart the individual process of a specific pollutant or residue (for example, recycle of plastic wastes) and evaluating an emergy cost per kg of recycled matter. Thus, the $f_{(n\text{-}1)j}$ would have the form of the product of this cost c_j times the total mass m_j of wastes of that kind:

$$f_{(n-1)_j}=\chi_j m_j \tag{5a}$$

$$F_{n-1}=\Sigma_j\chi_j m_j. \tag{5b}$$

That environmental consequences of resource exploitation need be included in net emergy evaluations is made apparent by two recent incidents which received much world-wide attention: The Exxon Valdez oil spill and the Chernobyl nuclear accident. When the environmental losses and clean up costs of the Exxon Valdez spill were evaluated in emergy, they were over 90 times as great as the oil that was spilled (Brown et al., 1993). The emergy of spilled oil and environmental damages amounted to about 14.5 days of Alaskan Pipeline flow. While spills of this magnitude may not affect the net emergy of Alaskan oil, the clean up had dubious benefits. Nearly 5 times more fuel was used in clean up activities than was spilled.

Maybe of greater concern, and certainly of much greater impact, are the effects of the Chernobyl accident. Using data published to date, Lapp (1991) calculated the long-term emergy costs of 2520 km^2 of land permanently closed, 10000 km^2 partially "controlled", and 24060 km^2 periodically "controlled" and the 300 billion ruble price for clean up and restoration. Using Lapp's data the emergy costs and environmental damages ofthe Chernobyl accident are equal to the net output of 6 average U.S. nuclear power plants. While these are examples of two relatively isolated incidents they suggest that net emergy and emergy yeild ratios can be greatly influenced by the emergy costs for fixing environmental damages.

The cost for fixing the eventual damages to human health and assets F_n is proportional to the permanence time t_j of each pollutant; it also depends upon the yearly average damage from this pollutant (for example, increased speed of calcium carbonate degradation by acid precipitations in buildings and monuments, increased number of respiratory diseases induced by combustion products in the urban environment). Fixing each kind of damage has an emergy cost (increased availability of health services; more frequent maintenance of buildings and monuments restoration, etc.), which should be evaluated apart as the total cost per unit f_j (sej/person; sej/m^2 of restored building, etc) times the number of units D_j affected.

A possible expression for F_n is therefore

$$f_{nj} = \phi_j D_j \tag{6a}$$

$$F_n = \Sigma_j \phi_j D_j. \tag{6b}$$

We are finally able to write a more complete formula for the emergy yield ratio η_n:

$$\eta_n = \left(N + \Sigma_j f_{1j} + \ldots + \Sigma_j \chi_j m_j + \Sigma_j \phi_j D_j\right) / \left(\Sigma_j f_{1j} + \ldots + \Sigma_j \chi_j m_j + \Sigma_j \phi_j D_j\right).$$

The dependence of χ_j and ϕ_j upon the permanence time t_j can be underlined writing $\chi_j(t_j)$ and $\phi_j(t_j)$ in Eqs. (5) and (6).

Many emission parameters in this formula are affected by a large uncertainty. Some of this uncertainty may be removed when a specific emission is considered so that the number of variables are reduced. An approximate measure of the ratio could be calculated focusing on the by-products/pollutants/wastes that are produced in larger amounts, although we will not be able to reduce our uncertainty without a limit. In addition, the formula doesn't consider nonlinear interactions between pollutants and between pollutants and biosphere self-organization process, whose consequences are hard to evaluate.

8. Conclusions

The emergy contribution from a process to a system cannot be evaluated only on the basis of net emergy ϵ. The cost for providing the yield Y, is sometimes higher than expected, when production of disorder by resource use is considered. Hidden costs come from the need to avoid or fix the damages that a resource use can cause directly to users or to biosphere complex equilibria. Thus, we proposed an Emergy Yield Ratio that includes costs associated with a resource's use and not just its production. We term this "End Use Emergy Yield Ratio." Self-organizing systems (like forests, or the biosphere as a whole) developed over millenia an organizational structure where by-products are not pollutants but continuously circulate or are temporarily stored within the system's web. In the short run human societies have been able to develop processes of natural resource exploitation with little concern for by-product amounts and recycle. However, by-products from processes driven by humans are very often noxious to humankind itself or to biosphere equilibria, and may be reaching amounts and concentrations that are beyond the biospheres ability to recycle and abate naturally. Their abatement, recycle and disposal will increasingly require large emergy investments, thus reducing the apparent advantage of using some resources/processes. Uncertainties in evaluating the emergy yield ration of a given process are sometimes very large, especially when nonrenewable resources are used. Processes with highest uncertainties and/or lowest yeild ratios may not lead to sustainable patterns of exploitation.

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