Exergy destruction as an ecological indicator: merits and limits

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- The study of Very Complex systems (“VLCS”) requires a holistic approach to analyse the entire system and all of the “external” and “internal” interactions that characterise it.
- The most sensible way to approach such problems is to consider the VCLS as an “extended” (in a sense to be specified later) thermodynamic system.
- The evaluation of the flows of matter and energy sustaining a territorial system and the knowledge of the transformations therein can be used to describe the rate of exploitation of the available natural resources.

The accepted meta-paradigm for the assessment of the state of the environment is the following:

a) environmental scientists, engineers, physicists, chemists and biologists have the role of defining, troubleshooting and calibrating a proper set of "decision parameters", called *ecological indicators* (EI)
b) National & International Agencies use these EI in their evaluations.

There is the clear necessity of defining an EI in such a way that it may convey at the same time some quantitative and qualitative information. This is not an easy task, and several EIs have been proposed that for one reason or another lack the necessary sharpness.

Scope and function of an ecological indicator

1. **What is an ecological indicator?**
2. **What are its desirable properties?**
3. **What is (are) its goal(s)?**

Definition of an Ecological Indicator

An EI is an aggregate, quantitative measure of the impact of a "community" on its surrounding environment.

This very broad definition is in no way ambiguous: the EI must be applicable to the bacterial colonies that generated our atmosphere 3.8 billions years ago as well as to the future manned Mars exploration stations.

The EI is by its own essence aggregate: it cannot be limited to a group of few individuals, whose impact is seldom noticeable for the environment.

The "impact" that is of essence for an EI is that produced on the "environment" that surrounds the community under examination: referring to "the flapping of the wings of a butterfly in the Amazons" we all must agree that a reasonable amount of determinism is necessary, and the "environment" of the butterfly is reasonably limited to the few hundred square meters of its ecological niche.

We see here that the definition suggests we treat the "community" and the "environment" as two separate but interacting systems.

Desirable properties of an Ecological Indicator

The properties of an EI sort of descend from the above definition:

1. ***An EI must be expressed by a -possibly simple- numeric expression that produces results that can be ordered in an unambiguous way (from "bad" to "good");***
2. ***An EI must be calculated on the basis of intrinsic properties of the "community" and of the "environment";***
3. ***The EI must be normalized in some sense (e.g., by expressing it as a ratio of the actual calculated value to an "average" value calculated for all similar communities that interact with that environment, or to an "ideal" measure of impact). This is important if we wish to compare not entirely similar communities;***
4. ***The EI must be calculated on the basis of an unambiguous, reproducible method under a well-defined set of fundamental assumptions;***
5. ***The EI must comply with the accepted laws of physics.***

Proper use of an Ecological Indicator

The only proper use of an EI is to measure the impact of a community on its environment.

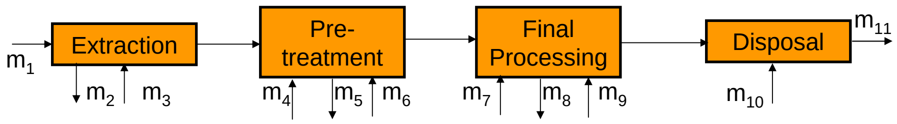
An EI ought not to be used to establish value rankings nor to provide direct guidance in ethical or social issues.

An EI can, and should, be used to assess an individual community (a societal sector, an industrial process, an economic strategy applied to a society or one of its parts) and, within these bounds, it may be used to compare alternative scenarios.

Limits of some existing Ecological Indicators

1) Material Throughput Analysis, MTA

Proposed in the '80es by a group of world Bank economists, and sometimes referred to as "Material Inventory Analysis".



The EI proper is a normalized mass flow rate of resources per person (or per unit) per year:

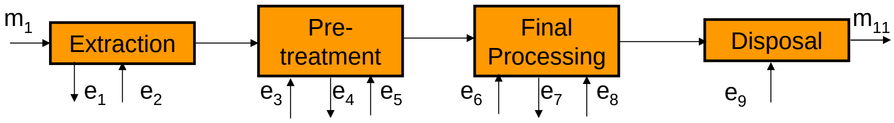
$$MTA = \frac{\sum (m_1 + ... + m_{10})}{m_{11}}$$

- **a) Simple**
- **b) S & Env**
- **c) Normalised**
- **d) Reproducible**
- **e) Laws of Physics**

MTA satisfies points a) through d) of the list of desirable properties given above.
It does not satisfy point e), (e.g. toxicity)

2) Embodied (or Cumulative) Energy Analysis, EEn

Formulated in the '60es by a group of US environmentalists (among others, Stephen Berry & Robert Herendeen) and based on the energy inventory of a commodity.



The resulting indicator is called the *Embodied Energy* (EEn), is expressed in J/unit, and - according to its proponents- constitutes a direct measure of environmental impact:

$$EEn = \frac{\sum(e_1 + ... + e_9)}{m_{11}}$$

EEn satisfies points a) through d) of the list of desirable properties given above.

It does not satisfy point e), because it does not account for the different <u>quality</u> of the energy flows it includes in its bookkeeping: think of a society that uses 1000 kW of fossil electrical energy and 2000 kW of thermal energy at 400°K per person per year, compared to another that uses 2000 kW and 500 kW respectively: the environmental impact of the discharge of the second one is higher (because each kW of electricity is generated by converting approximately 2.5 thermal kW), but its EEn is lower.

a) Simple
b) S & Env
c) Normalised
d) Reproducible
e) Laws of Physics

3) *Emergy* ("*Energy Memory*") *Analysis*

Proposed by Howard Odum in the '70es.

This method, too, is an energy accounting, but is based on the fundamental assumption that the only input that matters is the solar radiation: all other flows, of matter and energy alike, are brought back to "equivalent solar joules" (Solar Emjoules, Sej) by a proper set of coefficients, called *transformities*.

Each transformity represents the amount of Sej equivalents that went into the "production" of the commodity under consideration; the emergy "spent" in environmental remediation processes can also be accounted for on the same basis.

The EI is the emergy content Em of the commodity.

Em satisfies points a) through d) of the list of desirable properties given above.

It does not satisfy point e) though, because it does not include any measure of the different quality of the energies it includes in its accounting.

a) Simple
b) S & Env
c) Normalised
d) Reproducible
e) Laws of Physics

Recently, there have been attempts to modify the method, by calculating the transformities on the basis of the exergy (and not the energy) of the incoming solar radiation.

The results are not very encouraging though, for two reasons:

1) The calculation of the transformities is difficult and is perforce based on very restrictive fundamental assumptions that may distort the results. For example, the transformity of oil in an underground field is ***estimated*** on the basis of an analysis of the geological processes that lead to its formation, and turns out to be 55400 Sej/J (Simone Bastianoni et al., 2005): it is clear that even a small error in this estimate is amplified as one proceeds downstream in the analysis, and may lead to a completely wrong value of the indicator Em for all products in which oil and its derivates are used.
2) The calculation of the transformities does not include entropy considerations in any way.

4) Exergy destruction as an ecological indicator?

The exergy destruction E_l in a process can be expressed as a function of the initial and final thermodynamic states of all participating media. Could El be used as an ecological indicator?

It clearly possesses all of the required properties defined in Section 2, and thus the question that remains to be answered is: does El measure the environmental impact of a process or of a series of processes that represent the "signature" of a specific community on the environment?

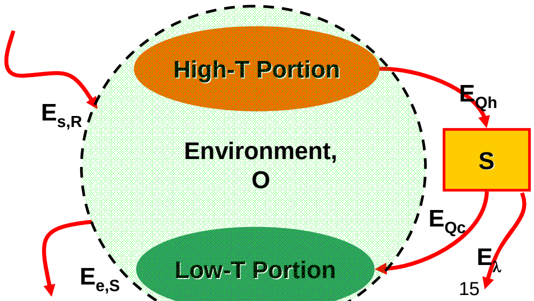
We can anticipate that the answer is negative, but to justify this conclusion we must analyze the problem in more detail.

4.1 - Thermal dissipation

$$e_\lambda = e_{Qh} - e_{Qc} = QT_O\left(\frac{T_h - T_c}{T_h T_c}\right)$$

With T_O=293°K, T_h=500°K and T_c=308°K, the above equation tells us that, for every kW of thermal input, 0.365 kW (or 36.5%) are destroyed in this thermal cascade.

El is a correct indicator of the adverse ecological impact of transferring energy from high to low temperatures.



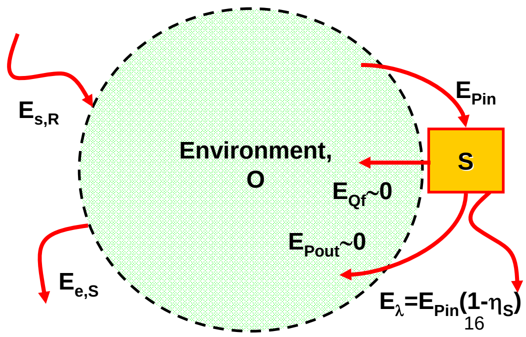
4.2 – Mechanical dissipation

The power P_{in} enters the system (e.g., hydraulic or wind power), and the power P_{out} leaves the system (the difference is accumulated within S). The system's internal conversion efficiency is equal to η_S. The frictional heat Q_f (proportional to 1- η_S) is dissipated into the environment at a temperature so close to T_O to be indistinguishable from it.

$$e_\lambda = e_{Pin} - e_{Pout} - e_{Qf} = P_{in}(1-\eta_S)$$

With η_S =0.7, the above equation tells us that, for every kW of mechanical input, 0.3 kW (30%) are destroyed in this mechanical transformation chain.

El is a correct indicator of the adverse ecological impact of mechanical dissipation.

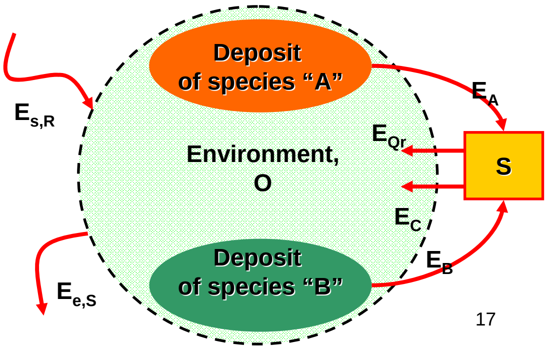


4.3 - Chemical "dissipation" (lost work)

S exchanges only chemical species with the environment O. The two pure substances A and B enter the system (e.g., carbon C and oxygen O_2), and the single product C leaves the system (CO_2 in this case). The reaction A+B ⇒ C is exothermic and the heat flux Q_r is at a temperature $T_r >> T_O$.

$$e_\lambda = (g_C - g_A - g_B)\left(\frac{T_O}{T_r}\right) - R\ln\left(\frac{c_{A,O}c_{B,O}}{c_{C,O}}\right)$$

The above equation tells us that, with T_O=293°K, T_r=1000°K and $(c_A*c_B)/c_C$=1, for every kW of chemical input, 0.293 kW (or 29.3%) are destroyed in this chemical reaction.



The e_λ equation, however, does not convey any information on another important property of the product C of reaction: whether C is toxic or not, and if it is, does not provide a measure of its toxicity level either.

We are faced here with an extremely clear and profound limitation of our so-called "environmental approach": from all point of views, ***except from the anthropocentric one***, E_λ is a perfectly acceptable ecological indicator, because it correctly quantifies the effective "impact" on the environment of any natural or man-made process. Since though our real interest is of a more species-egoistic type, we cannot accept "impacts" like sweetwater eutrophication or global warming, to which the biosphere would perfectly adjust (possibly without us!), because these phenomena are certain to have a negative impact on the survival of our species.

The choice is one of value, of course, and therefore cannot be judged on a thermodynamic basis: but the fact that a thermodynamic indicator like E_λ that correctly measures irreversibility is not suitable as an EI because of our own anthropocentric attitude is perhaps worth some reflection.

However, in line with the presently dominating perception of "environmental impact", we must conclude that E_λ is only an *incomplete indicator* of the adverse ecological impact of chemical reactions.

- Toxicity is not the only factor that is not measurable with a purely thermodynamic analysis. We must therefore extend our method to include all the "environmental expenses" that must be charged to a certain commodity.

- In Economics, the "cost" of a product is given by an expression called the Production Function, that takes the general form:

$$c_j = f(K,L,E,M,O)$$

Where c_j is the "cost" of a unit of the (material or immaterial) commodity, ***K*** is the amount of monetary capital (€) required by its production, ***L*** the amount of labour (workhours), ***E*** the exergy (J), ***M*** the necessary materials (kg), and ***O*** the environmental remediation cost (monetary cost of the remedial action necessary to annihilate or reduce the effects of product *j* on the environment). These five terms are called the Production Factors.

- We are looking for a method in which both c_j and the Production Factors can be homogeneously expressed in terms of a thermodynamic function.

- Exergy accounts "automatically" for ***E*** and ***M***: since the exergy destruction appears to be the most complete indicator we have analyzed so far, it seems proper to use exergy as the common quantifier for the remaining, non-energetic Production Factors.

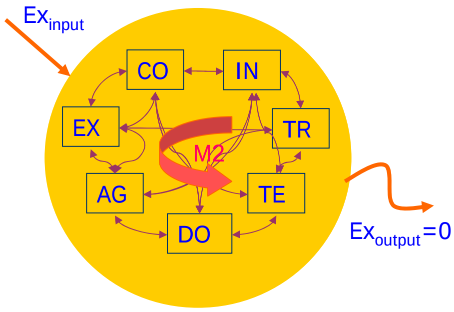
5) Extended Exergy as an ecological indicator

The *specific extended exergy*, *ee*, is defined as the sum of the physical exergy and of the equivalent exergy of Capital (ee_K), Labour (ee_L) and Environmental Remediation (ee_O) activities. These ***equivalent exergies*** are expressed in kJ (their fluxes in kW), and ***represent the amount of primary resources required to generate one monetary unit (ee_K), one workhour (ee_L) and to annihilate a certain pollution (ee_O)***:

$$ee_{commodity} = e_{ph} + e_{ch} + e_k + e_p + ee_K + ee_L + ee_O \qquad \text{[J/kg, J/J or /unit]}$$

The fundamental premise of Extended Exergy Accounting is that *economic systems are eco-systems that function only because of the energy and material fluxes that sustain human activities*. The correct measure for the cost of a commodity or a service is the extended exergetic content, and not capital or material flow or exergy or labour alone.

EEA adopts the standard exergy accounting method of Szargut to embody into a product all of the exergetic expenditures incurred in during its production. Extraction, refining, transportation, pre-processing, final processing, distribution and disposal activities are computed in terms of exergy "consumption".

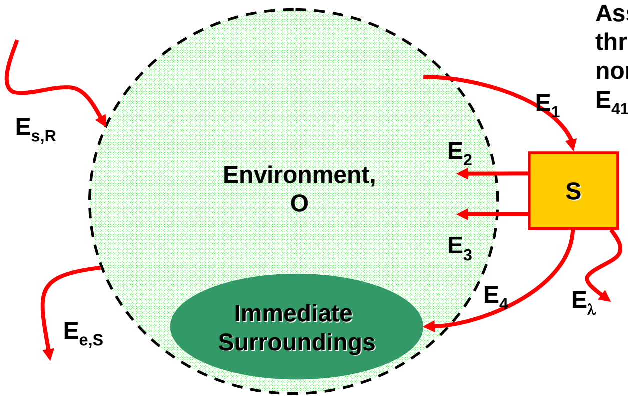


5.1 – Calculation of the ee of L and K

$$ee_{L,S} = \alpha \frac{E_{in,S}}{n_{workhours,S}} \qquad [J / workhour]$$

$$ee_{K,S} = (1-\alpha)\frac{E_{in,S}}{M2} \qquad [J/€]$$

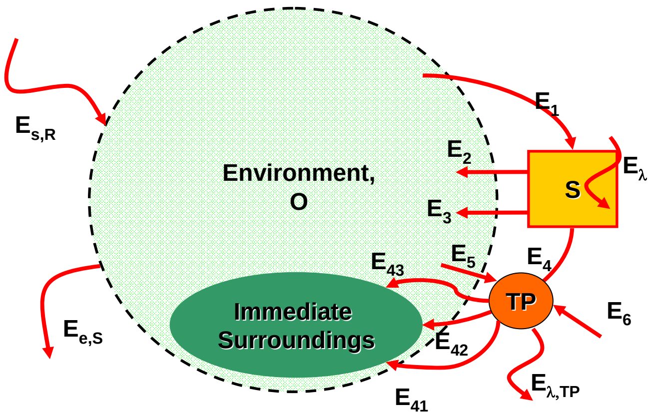
5.2 – Calculation of the ee of the Environmental Remediation costs



Assume E_4 consists of three substances, each at non-reference conditions: E_{41}, E_{42} E_{43} are all >0

To annihilate the environmental impact, we insert a "treatment process" TP

Now, E_{41}, E_{42} E_{43} are all =0, but we have "used" additional amounts of (extended) exergy to build & operate TP: the EE-cost of the products E_2 & E_3 is higher



Conclusions

1. Exergy destruction is a proper indicator of the global performance of an energy-conversion chain, including complex production structures;
2. As an Ecological Indicator, though, it fails to account for non-thermodynamic effects, like toxicity, cost and labour intensity;
3. Extended Exergy, or better yet the Equivalent (or Extended) Exergetic Content EE, enjoys the necessary attributes of an Ecological Indicator;
4. If we base our cost-accounting procedures on EEA, we can assess our natural and anthropogenic processes by means of performance indicators (EE and its inverse, the net extended exergetic efficiency) that correctly reflect the resource-to-final-use (including disposal, in a omni-comprehensive cradle-to-grave approach) of our exergy resources.

Final remark

1. Extended Exergy Accunting was first presented in 1998. Several applications have been published, but…
2. Antonio Valero says it has limited merits…
3. George Tsatsaronis does not like it…
4. Jan Szargut says it is affected by double-counting (L & K)…
5. Richard Gaggioli has reservations about it…
6. Elias Gyftopoulos does not even want to hear about it…

…therefore, it MUST be a good theory!