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Article

A Thermodynamically Correct Treatment of Externalities with an Exergy-Based Numeraire

Enrico Sciubba

Department of Mechanical & Aerospace Engineering, University of Rome 1 La Sapienza, Rome, Italy; E-Mail: enrico.sciubba@uniroma1.it; Tel.: +39-06-44585244; Fax: +39-06-44585249

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Abstract: The concept of "sustainable development" implies that the environmental externalities unavoidably generated by human activities be reduced to a minimum: In fact, the very definition of "sustainability" leads—as it will be briefly discussed in the paper—to a physically measurable upper limit for untreated discharges. Since the current state of affairs on Earth is far from being sustainable, any proposal for a future scenario that is not substantiated by an accurate assessment of the effects of the environmental externalities is devoid of real sense and ought not to be pursued. The present paper illustrates the application of Extended Exergy Accounting (EEA) to the quantification of such externalities. The exergy flow diagrams of EEA include non-material and non-energetic production factors like labor, and capital and environmental remediation costs, providing a quantitative measure of the amount of primary resources that are cumulatively used in the production of a good or service, and it is shown to provide a wealth of quantitative information to energy managers and planners.

Keywords: sustainable development; exergy; extended exergy; environmental externalities

Nomenclature:

c	Molar concentration	P	Power, W
En	Energy, J	Q	Heat flux, W
e, E	Exergy, J/kg or J	T	Temperature, K
g_a	Gravitational constant, m/s^2	t	Time, s
g,G	Gibbs free energy, J/kg; J	V	Velocity, m/s
h	Enthalpy, J/kg	W	Work, J
m	Mass flow rate, kg/s	z	Elevation, m
p	Pressure, Pa		

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1. Introduction

"Sustainable Development" is often referred to as "the goal" which the human race ought to aim to if it wants to survive on Earth. Unfortunately, while both words "sustainable" and "development", taken individually, have a precise meaning (though the concept of "sustainability" is in strong need of redefinition, see [1–10]), their combination does not. This depends on the meaning that we usually attribute to the word "development", which is regarded—especially in the West, but in recent times unfortunately even in the Far East—as if it implied "throughput growth" and "increase in number of individuals". As Daly [11] warned almost two decades ago, and Costanza [12] quantified some years later, increasing throughput in a finite world is definitely not our best option as a species. The fundamental reason is that, since the global scale of the human "economic" system at large has reached a dimension comparable with that of the entire biosphere, our activities inevitably produce a modification of the environment that, if in excess of the Earth's capability of "buffering" these effects by using the external low-entropy input provided by solar radiation, leads to a degradation of the available resources and in the end to a scarce supply of the most vital of them (drinkable water and breathable air). In fact, Georgescu-Roegen [13] had warned the economic and engineering community that an inevitable effect of the Second Law of Thermodynamics is that of "diluting" resources, equalizing concentrations, and smoothing out some of the gradients (in the context of this paper, temperature and concentration of resources and nutrients) on which life thrives: But his lesson went mostly unnoticed until much later.

The goal of this paper is to present and discuss a thermodynamically sound method for the quantification of the environmental externalities, which is clearly a necessary (but often unfortunately neglected!) step in the definition of any future "less unsustainable" scenario.

The analysis presented here was prompted by the consideration that any production process at large, including the "natural" ones (photosynthesis, chemical buffering in the atmosphere and in the oceans, thermal evaporation and convection in the atmosphere and in the water reservoirs), can initiate and progress only if it can avail itself of a sufficient amount of primary resources.

The approach discussed here is a development of the fundamental work initiated and perfected in the last two decades by several scientists. Mention must be made of Costanza [12] who stressed the importance of what he called "natural capital" in all human activities: In his view, all technological processes make use of "monetary" capital and of an often neglected amount of resources extracted from the biosphere. These resources can be material and irreplaceable (mined ores, fossil fuels), material and renewable (water, wind, solar irradiation), immaterial and replaceable (know-how and genetic information), immaterial and irreplaceable (biodiversity, species distribution on Earth). All of them can be regarded as either directly depending on the sole final source of exergy influx onto Earth (solar and cosmic radiation), or to indirectly represent "accumulated" forms of the same. In this view, it seems natural to seek for a measure of their "value" based on a physical rather than on a monetary basis (see also the recent work by Valero and coworkers [14–16]. Costanza stopped short of this last step, and took a different route instead: He calculated the monetary equivalent of such a natural capital, and proposed to include the corresponding amount in the calculation of production cost. Such an approach is very close to Daly's ideas, in that it quantifies the consumption of irreplaceable resources in industrial processes, and it is at the basis of Industrial Ecology. Other scientists [17–21] proposed instead to introduce in the economic calculations an energy-based production factor that represents the equivalent total amount of primary energy embodied in a commodity: Their methods differ to a non-minor extent from each other, but the underlying idea is the same. Even economists came to consider the need of introducing an explicit measure for energy dissipation in the calculation of the production cost [13,22,23]: The underlying rationale of all of these efforts was the understanding that the current methods of cost calculation are rooted in an obsolete theory of economic value that can be easily shown to be biased towards "throughput increase" and does not properly reward primary resource-to-end-use efficiency. From the early 1960s to the mid 1970s, use of the thermodynamic function exergy was mainly advocated [24–26] to eliminate the bias implicitly contained in all engineering calculations of the production cost of a commodity for which the technological production chain received energy inputs of different quality (e.g., heat, electricity and chemical energy): Later, this approach led to the formalization of Thermo-Economics [27–31], an engineering costing procedure in which the "unit cost" is referred not to the physical unit of product (mass, piece, kWh) but to its specific exergy. Thermo-Economics has been extensively applied to the analysis and optimization of industrial processes ever since, and led to the identification of different process optima in all processes with at least two outputs (final products) of different quality (e.g., cogeneration plants, space conditioning units) and in all technological chains whose energy inputs were of different quality. Much earlier, Szargut [32] had independently developed an entirely physical exergy accounting method for technological chains in which an accurate record was kept of all the exergy input and output flows: As a result, the "cost" of a commodity is expressed in Joules of exergy cumulatively used in the production line, whence the name of Cumulative Exergy Content (CEC). The CEC is a quantitative measure of the exergy "embodied" in a commodity, and as such it represents a purely physical (and Second Law proper) cost indicator. Neither Valero's version of Thermo-Economics ([33,34] later renamed "Exergy Cost Theory", ECT, [35]) nor CEC made account in their first formulations for environmental damage and/or remediation costs, and this originated some attempts (most notably by Frangopoulos & von Spakovsky [36], Szargut [37] and Valero [38]) to introduce an indirect calculation of the "environmental externalities" into ECT/CEC. In retrospective, it must be remarked that this is a difficult task, for quite opposite reasons:

a) Most TE practitioners use a monetary quantifier, and therefore the environmental externality is computed in terms of some additional monetary cost to be included in the traditional production cost; but since most of the pollution is non-local, a monetary measure—no matter how detailed—ends up to be based on health and risk assessment estimates that are both fundamentally unfair and inaccurate [39]. Most recently, Tsatsaronis' "Berlin school" [40] proposed to estimate the monetary cost of the unit exergy discharge on the basis of an analogy with the LCA indicator for the same discharge: The convenience of such an approach is though doubtful, because it introduces an additional arbitrary assumption in the TE cost allocation procedures.
b) Since CEC ("Gliwice's school") and ECT ("Zaragoza's school"), on the opposite, adopt a purely exergetic basis and completely neglect monetary costs, the need arises to introduce a functional link between the exergy of the discharges and the ensuing pollution, which can be easily proven to be impossible to find [41–43], because the exergy content of a stream is not related to its toxicity. Both schools resorted to including the "avoidance exergy cost" of pollution by including in the exergy flow diagrams a term representing the amount of exergy required to treat the effluents.

In 1998, this author introduced the Extended Exergy Accounting method [43], later developed and perfected in other related publications [7,8,39,44–60]. The Extended Exergy (discussed in detail in Section 3 here below) borrows some concepts from Odum's Emergy Analysis [21], some from an original and little-known proposal by Tribus & McIrvine [61], and some from ECT/CEC, and results in a cost quantifier that is purely physical (expressed in J/unit of product) and is equal to the (properly weighted) sum of the exergy of the input materials, of the energy inputs, of the labor, of the capital and of the environmental remediation expenses, each measured by its respective equivalent amount of primary resource. The EE of a product is thus a physical cost (like in CEC/ECT and in Emergy Analysis) that includes the Labor and Capital production factors (like in TE) and properly allocates the exergetic remediation costs for each pollutant to the individual products. It can therefore be considered a viable Ecological Indicator, and a comparison between EE and several other EI's is presented in [56]. While referring interested readers to that paper, it can be mentioned here that EE is the only existing indicator that can account for all five production factors (Material, Energy, Labor, Capital and Environmental Cost) in a homogeneous way and in full agreement with the Second Law.

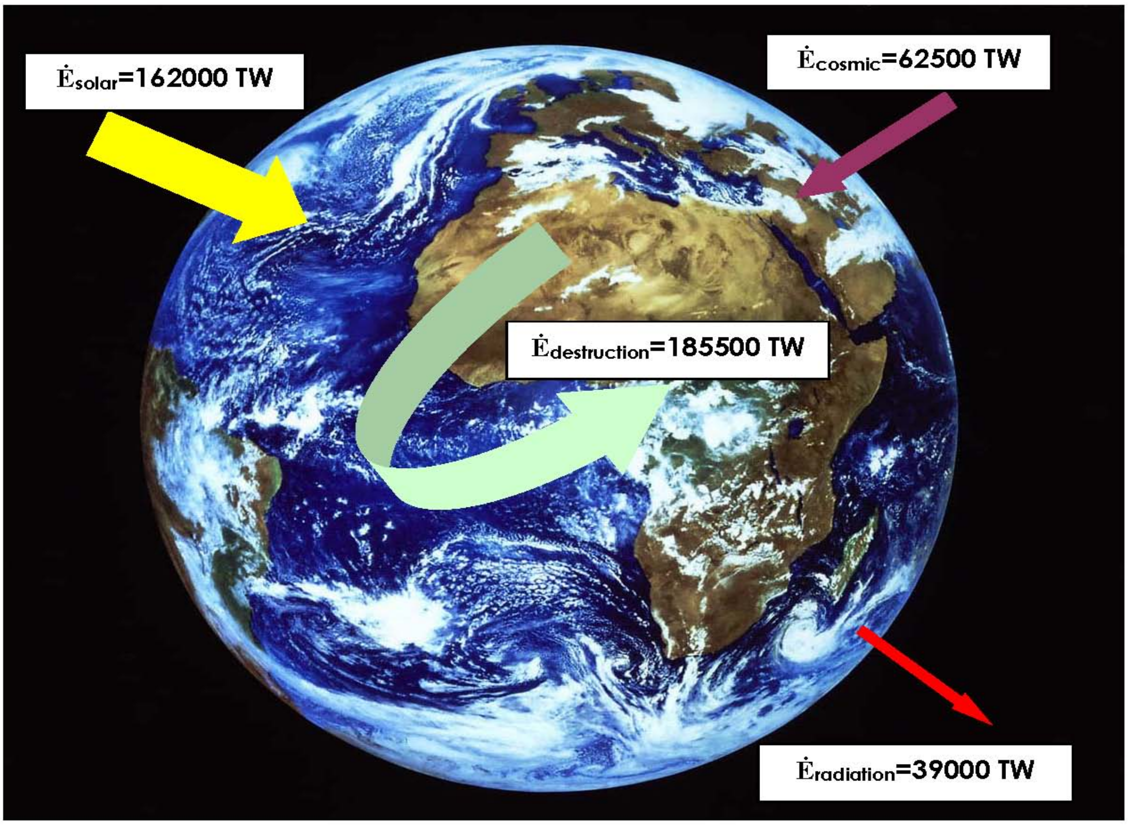
2. Spaceship Earth and the Environmental Externalities

In 1966, Kenneth Boulding, an economist, coined the expression "Spaceship Earth" [62]. It is instructive to quote here some of the main statements of that really seminal lecture: "*In regard to the energy system there is, unfortunately, no escape from the grim Second Law of Thermodynamics; and if there were no energy inputs into the earth, any evolutionary or developmental process would be impossible. The large energy inputs which we have obtained from fossil fuels are strictly temporary…* (omissis)*… For the sake of picturesqueness, I am tempted to call the open economy the "cowboy" economy, the cowboy being symbolic of the illimitable plains and also associated with reckless, exploitative, romantic, and violent behavior, which is characteristic of open societies. The closed economy of the future might similarly be called the "spaceman" economy, in which the earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy.*"

Boulding was evidently proposing an economy based entirely on renewable resources, with the explicit constraint of "total stock maintenance", *i.e.*, of the complete conservation of natural capital. Though often quoted, relatively little recognition has been given to his visionary insight into many of today's concerns about "conservation" and "sustainable development". Bouldings' ideas can be rephrased in the context of the present paper as follows: Let us consider that Earth is an open system maintained at an (almost) stationary non-equilibrium state by an (almost) constant supply of exergy (solar and cosmic radiation) originated outside of its boundaries and virtually independent on its global thermodynamic state. From the material point of view, though, the mature Earth of today is well approximated by a closed system, because to all practical measures both the mass gain from space (meteorites) and the loss to it (cosmic dust and light atoms from the upper atmosphere) are negligible. Ignoring for the moment the material balance within system Earth, let us consider its exergy "balance" (it is well known [63–65] that exergy does not obey a balance equation, and therefore is not a conserved quantity. For this reason, the expression "exergy balance" in this paper is always used between quotation marks, to signal the non-rigorous use of the word "balance"). The Earth's exergy flow diagram, including the allocation of different exergy flows among different terrestrial phenomena, has been calculated in detail by different authors [37,66,67]: We are interested here only in the difference between the low-entropy input flow of radiation from outer space and the low-T, high-entropy output into it. With reference to Figure 1, we can identify three major terms [67]:

1) An exergy inflow, $\dot{E}_{in}$, approximately equal to 225,000 TW (7.1 × 10^{24} J/yr = 7.1 YJ/yr) [23], consisting mainly of solar radiation (no accurate calculation is available for the cosmic radiation, which is generally assumed to amount to 0.25–0.3 of the total inflow);
2) An exergy outflow, $\dot{E}_{out}$ approximately equal to 39,000 TW (1.23 × 10^{24} J/yr = 1.23 YJ/yr), consisting of low temperature back-radiation from the outer boundary of the system (a virtual sphere embedding the upper atmosphere) towards the 3 °K background;
3) According to the exergy flow diagram, the difference $\dot{E}_d = \dot{E}_{in} - \dot{E}_{out}$ = 5.87 10^{24} J/yr is cumulatively destroyed (annihilated) by the large and small-scale processes on the planet. For comparison, the total energy use by humans on Earth (including foodstuff) amounts to approximately 0.02 YJ/yr.

Figure 1. The overall yearly exergy budget of planet Earth (adapted from [67]).



Though the suffix "d" stands for "destruction", we see that it is on $\acute{E}_d$ that the system Earth thrives: This "virtual flow", introduced in the exergy "balance" only to avoid the inequality sign, represents the cumulative effects of the irreversibility generated by an innumerable series of processes that absorb low-entropy energy, use a portion of it to complete their internal processes (possibly accumulating some of it in a suitable material or immaterial form), and discharge the difference between the input and the accumulation in the form of high-entropy energy. The system, and life indeed, survives on this exergy destruction! Less vividly, but more precisely, the system maintains itself in a globally quasi-stationary non-equilibrium state by exploiting (and destroying) the difference between the exergy input and output. Or, in more explicit terms, by capturing the exergy input, using (and possibly accumulating) whatever it can in its internal processes, and discharging the rest.

Therefore, on a galactic perspective and timescale, the Earth system and all of its subsystems (inorganic, organic, inert and living) can maintain themselves in the proximity of the current stationary non-equilibrium state only if:

a) They continue to allocate the exergy surplus available to them (which seems to be a more proper name for $\acute{E}_d$ in this context!) in such a way to induce no major changes in the type of processes taking place in the ecosphere, in their spatial distribution and relative timescales;
b) They react to the unavoidable fluctuations caused either by small variations of the solar input or by "internal readjustments" among some of the subsystems (evolutionary processes, local climate variations, accidental epidemics or/and extinctions, local catastrophes like droughts, floods, fires, volcanic activity, *etc.*) in such a way that the global amount of exergy they "destroy" (*i.e.*, use!) remains approximately constant.

Both of the above behaviors are typical of complex systems subject to <u>small</u> disturbances and endowed with sufficient dissipative damping: Given the scales of the exergy inflow, it seems that the possible fluctuations are indeed so small that the system can perpetuate itself "forever". If this picture were correct, true sustainability would have been already attained, to our (and Earth's, presumably!) satisfaction.

The problem here lies in the fact that the above picture applies to a sparsely inhabited planet in which few humans share their resources with other species, or prey on them on a modest scale, and the "size" of the human society and of its economy is "small" in comparison with the scale of the biosphere. Currently, though, this is no longer true, not even in an average sense: As remarked by Daly [23], Ayres [41] and others, the scale of our society is the same as that of the biosphere, and the material throughput we demand (mass of material—including food—extracted from the biosphere per unit time) is no longer negligible with respect to the global mass of each material present on Earth; similar remarks apply to our rate of material extraction and discharge. Put another way, the time it takes for the biosphere to regenerate one unit of any material in the reservoir from which we "fish" is longer than the time it takes us to "fish" it: This is clearly an unsustainable situation, and is also a very simple but accurate description of the current state of affairs on Earth.

While we cannot substantially decrease the size of the human race, there is another road to a less unsustainable future, and it is indicated by the Spaceship analogy: We should exploit some of the currently untapped exergy flows to implement <u>total material recycling,</u> which is the most effective action to decrease our material throughput [56]. In reality, "total" recycling is negated by the Second law, but "almost total" would suffice: And our technological level is sufficient to attain this goal. Other alternatives, like a substantial reduction of the numerosity of our species, or a drastic abatement of our *pro-capite* consumption, are completely unrealistic under the present state of affairs.

It is clear that planning (and even devising) a "spaceship-like" scenario is a formidable task that calls for major changes in our societal organization. For the purpose of this paper, it is important to observe that one of the major challenges along the road is that of attributing a correct "cost" to environmental emissions, to prune (*i.e.*, gradually dismiss) technological chains and processes that—in physical terms—place a higher burden on the biosphere. Notice that in such a perspective monetary costs are not as relevant as their physical counterparts, because it is the natural capital we are trying to conserve: Therefore, we need a quantifier of environmental pollution that is based on a physical rather than on a monetary paradigm. In the next sections we shall argue that Extended Exergy is indeed a suitable quantifier.

3. Exergy and Extended Exergy

3.1. The Concept of Exergy

Energy is an *a priori* concept in Thermodynamics, defined as "an extensive property of a system such that its change in value between two states is equal to the adiabatic work between these states" [68]. It is a conserved quantity in an isolated system, and manifests itself in several forms, each endowed with a different *quality*. The concept of quality can be fully explained only recurring to the Second Law, but in a practical albeit not very rigorous way we can say that the higher the quality of an energy flow, the "more change" (*i.e.*, the more adiabatic work) it can produce with the same energy intensity (1 kWh, for example). Referring interested readers to the earlier books by Ahern [63] and Moran [65], or to the more recent ones by Kotas [64] and by Bejan, Tsatsaronis and Moran [69], we can identify "ordered" or "high-quality" energy forms (potential, kinetic, mechanical, electrical) that can be ideally converted into each other with 100% efficiency, so that even after a number of transformations, the outflow of useful energy is quantitatively equal to the inflow of used energy. There are other forms though (internal energy, chemical energy, thermal radiation, turbulent kinetic energy) that cannot be converted into high quality energy without an intrinsic transformation loss, so that the useful output is always lower than the used input. Since energy is conserved at the macroscopic level, the difference is accounted for as being terminally "dissipated" into a low-temperature flux absorbed or provided by the environment. The "environment", here and in the following, is a system endowed with such a large impedance that its average properties (pressure, temperature, chemical composition, kinetic or potential energy *etc.*) are not affected by the interaction with the system under consideration.

The concept of exergy provides a congruent and coherent quantification to the quality of an energy flux [25]. Let us consider a system S identified by a certain set of thermodynamic properties (V, z_B, p, T, c, m, μ…), suddenly placed at a certain time t_o in contact with the environment O. Assume that S may exchange mass and energy only with O (Figure 2: The entropy/energy plane used here is an adaptation of a more rigorous concept developed in [68]): A large number of experimental results confirm what our intuition can foretell, *i.e.*, that after a period of time t_{relax} which depends on the extension of S and on the difference between its initial properties and those of O, S will come to (a possibly dynamic) equilibrium with O, *i.e.*, even dynamic interactions will occur at a macroscopically stationary state, and will result in no net change in the mass and energy contents of either system [70]. *Exergy is defined as the maximum work developed in this ideal process*. Since the interaction is between O and S only, and we assume that all processes can be described by a succession of quasi-equilibrium states (so that the time interval t_{relax} drops out from the problem formulation), exergy is a function only of the initial and the final state of S (the final being equal to that of the environment), and thus it is an attribute of the pair (S, O), and not of S alone. S and O may exchange energy fluxes under different forms: Kinetic (all parts of S in relative motion with respect to E come to rest), potential (the barycentric position of S reaches a fixed elevation in the gravity field of O), thermal (heat flows from S to O or vice versa depending on the initial temperature difference $T_S–T_O$), work interaction (O performs or receives work from its boundary interactions with S), mass exchange (mass fluxes from S to O and vice versa carry different energies). If the flows of energy and matter from S to O are continuous and (on the average) steady in time, the energy and entropy balances to the complex system composed of S and O provide [71]:

$$E_Q + W + \sum_{i=1}^{K} m_{in}\, e_{in} - \sum_{i=1}^{H} m_{out}\, e_{out} + E_d = 0 \quad \text{[W]} \qquad (1)$$

where the first term represents the thermal exergy flow, the second is external work, the third and fourth the exergy in- and outflows due to material exchanges, and E_d is the exergetic destruction. Notice that this "exergy destruction" is NOT a physical flux, but rather a mathematically convenient concoction whose only goal is to avoid writing the right-hand side of equation (1) as ">0". The specific exergy terms in (1) are calculated on the basis of the thermodynamic properties of S and O [63–65]:

$$e = h - h_O - T_O(s–s_O) + S_k[\Delta g_k + RT_O * ln(c_k/c_{k,O})] + 0.5V^2 + gz \text{ [J/unit]} \qquad (2)$$

From equations (1) and (2) we can draw the following conclusions:

1) The initial kinetic and potential energy of S are completely "recovered" into useful work. In fact, all work exchanges between S and O are entirely (and quantitatively) equivalent to exergy flows, but this property is not symmetrical, since not all energy flows can be recovered into adiabatic work. Defining a *quality* or *exergetic factor* as the ratio between the exergy and the energy content of an energy flux, all of the "high quality" forms (mechanical and electrical work, kinetic and potential energy) have an exergetic factor equal to one. Each form has its own factor: For example, thermal energy has an exergetic factor equal to its associated Carnot efficiency, reflecting the fact that, under the present stipulations, the maximum work that can be extracted from a quantity of heat Q available at a certain temperature T is equal to $W_Q = (1 – T_O/T) Q$;
2) If S is initially at a lower temperature than O, thermal energy will flow from O to S, with a corresponding exergy flow equal to $E_Q = (1 – T_S/T_O) Q$. This amount is always positive [64];
3) The exergy of a simple substance whose states are defined by temperature and pressure (like all gases for most practical engineering purposes) is always positive. However, any substance in equilibrium with the reference environment has zero exergy [63,65,72];
4) The chemical potential of the elements in S cannot be entirely converted to work: When S comes to equilibrium with O, the most we can "recover" for the generic *k-th* component is the difference between the values of its Gibbs function in S and in O, each weighted by the respective concentration. In other words, we can ideally transform only a portion of the initial ΔG_S into useful work, because the products of reaction must be at their respective standard environmental concentrations and chemical potentials at T_O and p_O;

5) Equation 1 can be rewritten in such a way that the different “components “of exergy are explicitly represented:

$$e_S = e_{ph} + e_{ch} + e_k + e_p + ej \text{ [J/unit]} \quad (3)$$

where the suffixes indicate the usual denomination of the various terms: Physical, chemical, kinetic, potential exergy [73]. If other forms of energy fluxes are involved (magnetic, nuclear, *etc*.), one needs only to explicit the suffix “*j*” and apply the corresponding definition. Use of (3) is very convenient in the evaluation of a technological chain;

6) Exergy enjoys both the extensive and the additive property ($E_{(S1+S2)} = m_{S1}e_{S1} + m_{S2}e_{S2}$);
7) The maximum work obtainable from the exclusive interaction of two systems S_a and S_b is $|E_a - E_b|$;
8) If a stream *a* undergoes a series of transformations *i*, *j*, *k* ... *z* in which it receives (+) or delivers (−) the exergy rates E_i ...E_Z, its final exergy content is the sum of $E_a + E_i - E_j + E_k - ...E_Z$. Thus, the net cumulative amount of exergy used in a process can be added to the pristine exergy of the input materials to obtain the global exergy embodied in the (material or immaterial) product [31,72]. This is the theoretical foundation of Szargut’s CEC and Valero’s ECT;
9) Neither in (2) or (3) is an implicit or explicit link detectable between exergy of a stream or substance and its toxicity.

The exergy concept has important engineering applications (for a historical account see [57]): It can be shown that a “second-law efficiency” defined on the basis of exergy fluxes provides more information than the “first law efficiency” based on energy fluxes [25,64].

Figure 2a. For the model of the dynamics of the System-Environment interaction (notice that the model stipulates both $m_1 \ll M$ and $(m_2-m_1) \ll M$).

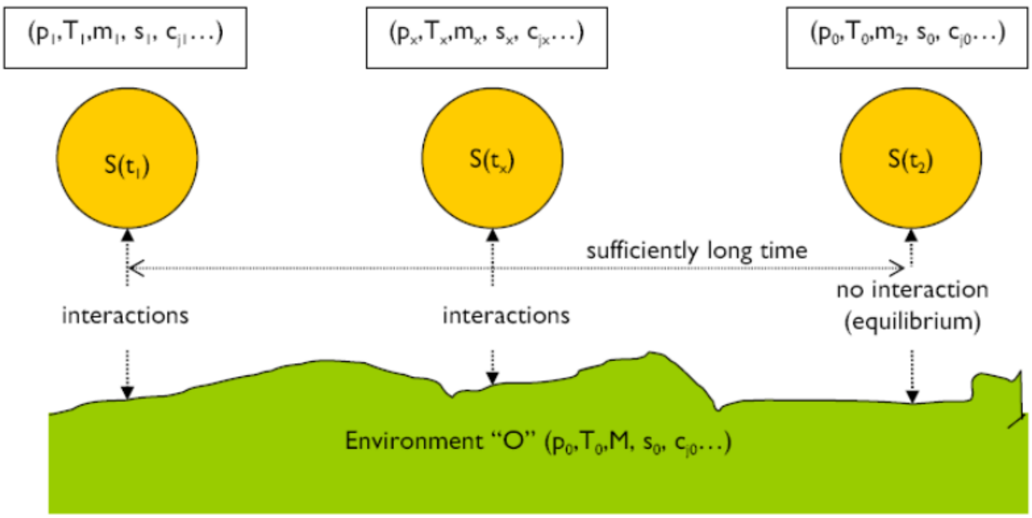
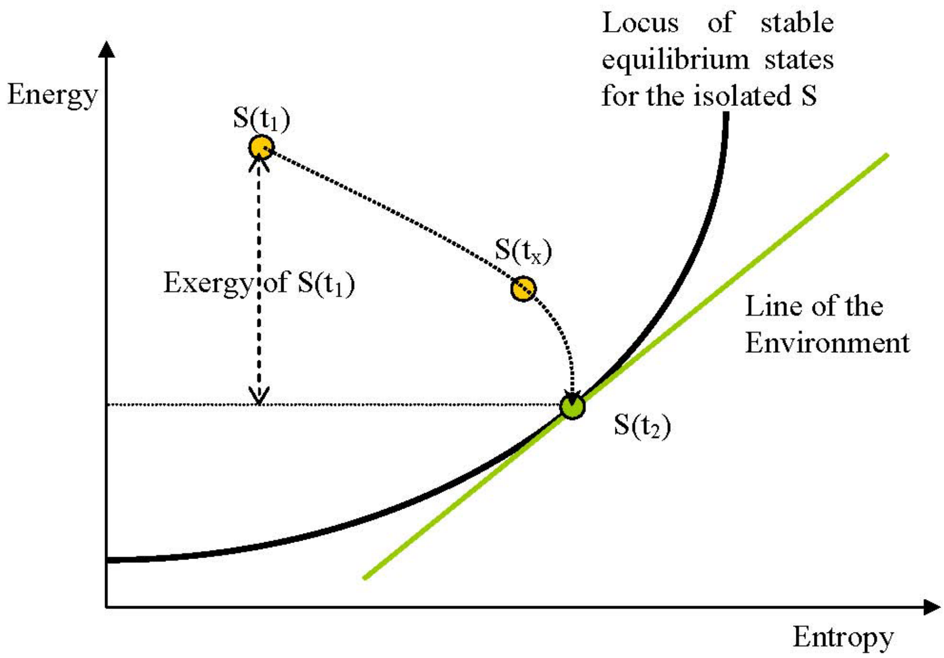


Figure 2b. The evolution of S towards S_0 (adapted from [68]).



3.2. Exergy and the Non-Energetic Production Factors

Toxicity (point 9 in the previous section) is not the only factor that is not amenable to an exergy measure. A requisite of any method for the assessment of environmental "damage" is that of including toxicity and the other "environmental expenses" that must be charged to a certain commodity. As recalled in the Introduction, modern economic theory tells us that the "cost" of a product is given by an expression called the Production Function, generally represented in its implicit form:

$$c_{Pj} = f(K, L, E, M, O) \quad (4)$$

Where c_{Pj} 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 labor (work hours), 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). The five terms within brackets in equation (8) are called the Production Factors. For convenience of calculation, the production function is usually assumed to be of the form:

$$c_{Pj} = a_K \cdot K^{b_K} + a_L L^{b_L} \cdot + a_E \cdot E^{b_E} + a_M \cdot M^{b_M} + a_O \cdot O^{b_O} \quad (5)$$

Where a_K... a_O are dimensional coefficients (because each term of the sum (5) must have the dimensions of €/unit) and the exponents "b" depend on the process under consideration.

Our goal here is to express both c_j and the Production Factors homogeneously and in terms of exergy. We know already how to assign an exergy value to a flow of energy or matter (equations (2) and (3) above): To use exergy as the common quantifier for the remaining, non-energetic production factors K, L and O, we need to devise a general method to link both the work hour and the monetary unit to some reference exergy flows that can be regarded as their respective "equivalents".

3.3. Extended Exergy Accounting

Let us define a new function, the *specific extended exergy*, *ee*, as the sum of the physical exergy defined by (2) and of the—yet to be functionally defined—equivalent exergy of capital (ee_K), labor (ee_L) and environmental remediation activities (ee_O). 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 work hour (ee_L) and to annihilate a certain amount of pollution (ee_O):

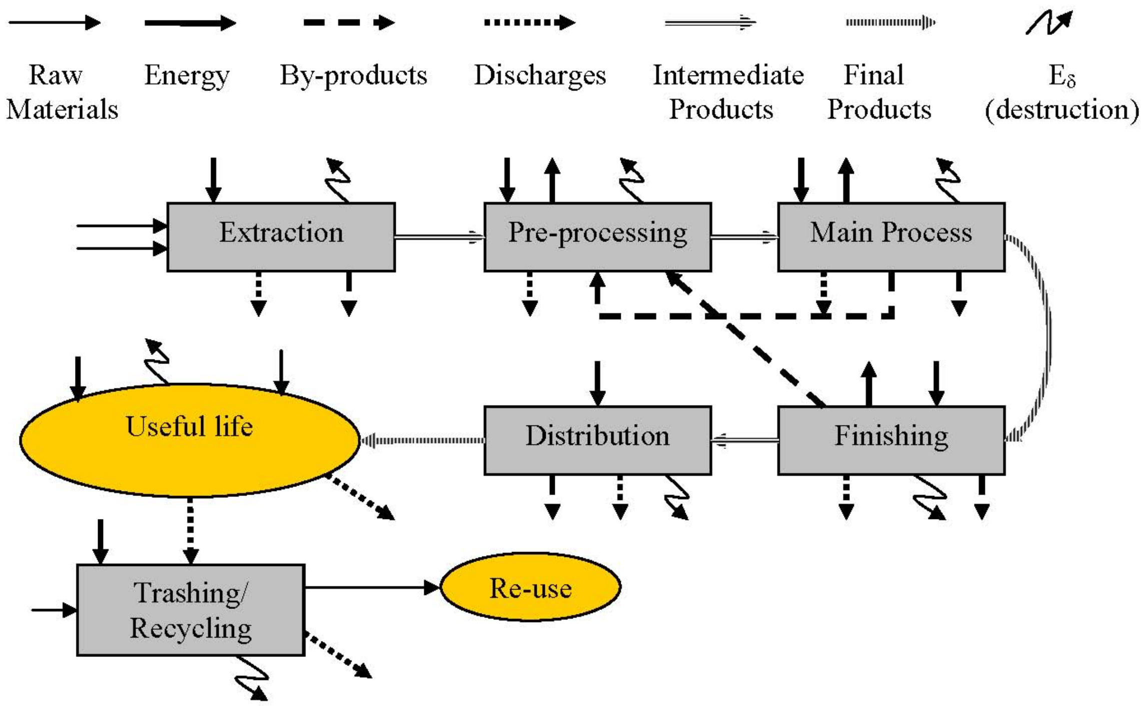
$$ee_{commodity} = e_{ph} + e_{ch} + e_k + e_p + ee_K + ee_L + ee_O \text{ [J/kg, J/J or /unit]} \quad (6)$$

Extended Exergy is additive: a commodity of mass m has a total EE equal to $m \times ee_{commodity}$; an immaterial commodity of energy content y has a total EE equal to y × $ee_{commodity}$; N equal commodities, an EE equal to $N \times y \times ee_{commodity}$, and so on: EE a physical quantity measured in kJ, with its flux measured in kW.

To calculate the equivalent exergy of a work hour (ee_L) or of a monetary unit (ee_K), we must explain in some detail the fundamental premises of the theory [20]. In the EEA framework, social (economic) systems belong to the sub-processes discussed in Section 2: They come to existence and evolve only because of the exergy fluxes that sustain human activities, and continue to operate as long as these fluxes are maintained. All agricultural, industrial, infrastructural and economic activities can only exist as long as they exploit ("use") biophysical resources taken from a reservoir of non-infinite mass capacity but of practically infinite exergy capacity (the physically "available" portion of the 225,000 TW mentioned in section 2, the attribute "available" being used here in its etymologic meaning "what the system can avail itself of"): From this point of view, it is clear that <u>exergetic content, and neither capital nor labor is the correct measure for the value of a commodity or a service</u> [53]. It is worth mentioning here that the cancellation of monetary prices is <u>not</u> the objective of EEA: Rather, this theory demonstrates that every commodity carries an alternative "price tag" that reflects its extended exergetic content (*i.e.*, its total embodiment, in a life-cycle sense, of primary exergy). As mentioned in the Introduction, this line of reasoning is not new: Herendeen [20], Odum [21] and of course Boulding [62] had already formulated similarly worded statements, expressing it though in terms of (solar) energy. From a slightly different point of view, Daly [23] had also reached similar conclusions. Wall [74] was though the first to pose this statement in terms of exergy.

EEA adopts the standard ECT/CEC exergy accounting method to embody into a product all of the exergetic expenditures incurred during its production. Extraction, refining, transportation, pre-processing, final processing, distribution and disposal activities are computed in terms of exergy "consumption" (recall that at each step of the production line a portion of the incoming exergy is irrevocably destroyed by irreversible entropy generation, Figure 3). The ECT/CEC accounting is subsequently "extended" by including in it the equivalent exergy fluxes for the three "non-energetic" externalities (labor, capital and Environmental remediation costs), as discussed in the next Sections.

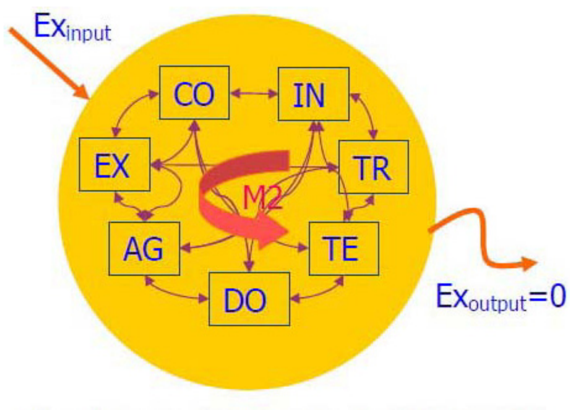
Figure 3. Exergy flows in a production process.



3.3.1. The Equivalent Exergy of Labor

The numerical correlation between the equivalent extended exergy of the unit of labor can be established by the following reasoning: The total net exergy primary influx $\dot{E}_{in}$ (J/yr) that flows from the environment into a society S in the form of energy and material fluxes can be regarded as the "thermodynamic fuel" of the large number of very complex processes that result in the operation of the society. The "products" of S are all generated, used and disposed of internally, and its only "outputs" are the waste materials and the waste energy that S discharges into the environment (Figure 4).

Figure 4. A society modeled as an extended thermodynamic system.



The four classical Production Factors" within S are Energy (exergy), Materials, Labor and Capital: The first two are already contained in E_{in}, while the last two are generated within S. The EEA theory assigns to labor—and in general to human services—an equivalent exergetic value equal to a portion of the total (yearly averaged) primary exergetic resource input E_{in} divided by the number of working hours "generated" in S:

$$EE_L = \alpha E_{in} \quad [W]$$
$$ee_L = \frac{EE_L}{N_{work\,hours}} = \frac{\alpha E_{in}}{N_{work\,hours}} \quad [J/work\ hour] \tag{7}$$

where α is an econometric coefficient to be derived from an analysis of the exergy flows in S and from socio-economic data: the matter is discussed in [55], and Table 1 displays the values of a for some selected Countries [75].

3.3.2. The Equivalent Exergy of Capital

To compute the exergy equivalent of capital, let us observe that, in general, the monetary circulation in a society S is proportional (in a very broad sense) to the labor generated in it, so that one can write:

$$EE_K = \beta EE_L = \frac{\alpha\beta E_{in}}{N_{work\,hours}} \quad [W]$$
$$ee_K = \frac{EE_K}{M2} = \frac{\alpha\beta E_{in}}{M2 \cdot N_{work\,hours}} \quad [J/€] \tag{8}$$

Here, M2 is an indicator of the "money and quasi money" circulation in a country: It comprises the sum of currency outside banks, demand deposits other than those of the central government, and the time, savings, and foreign currency deposits of resident sectors other than the central government. It corresponds to lines 34 and 35 in the International Monetary Fund's (IMF) International Financial Statistics (IFS), where the data are however provided in local currency: The values reported in Table 1 have been converted at the exchange rates in force on December 1, 2011 [76]. "β" is a Country-specific constant that represents the "capital intensification factor" of that Country (see below), is space and time dependent, and must be derived from econometric studies: Some calculated values are also shown in Table 1.

Table 1. Estimated values of α, β, ee_L and ee_K for selected countries.

Country	$\dot{E}_{in}$ J/yr	N_W workforce	M2 €/yr	α	β	ee_L MJ/work hour	ee_K MJ/€	Source
Cameroun	$2.62\ 10^{21}$	$7.83\ 10^{6}$	$1.31\ 10^{9}$	0.00014	1.23	28.67	612.46	[37]
China	$56.70\ 10^{21}$	$815.00\ 10^{6}$	$3.52\ 10^{12}$	0.00113	9.28	49.11	187.16	[60,31]
Italy	$1.07\ 10^{21}$	$24.7\ 10^{6}$	$2.10\ 10^{12}$	0.00746	2.54	201.40	13.43	[6,37]
Spain	$2.32\ 10^{21}$	$22.2\ 10^{6}$	$2.22\ 10^{12}$	0.00270	3.17	176.44	11.76	[61,37]
Turkey	$3.09\ 10^{21}$	$25.60\ 10^{6}$	$2.30\ 10^{11}$	0.00111	0.40	83.56	20.90	[71,37]
USA	$64.60\ 10^{21}$	$154.00\ 10^{6}$	$8.18\ 10^{12}$	0.00159	0.33	415.74	16.64	[83,60]
Yemen	$3.82\ 10^{21}$	$6.83\ 10^{6}$	$4.00\ 10^{9}$	0.00008	10.71	26.96	863.09	[31,33]

Note to Table 1: The values reported here are purely indicative. No exergy balances have been published for Cameroun, Spain, and Yemen: The corresponding data have been extrapolated from [77–79]. The exergy flow diagrams for Italy [80] and for the U.S. [81] date back to 2000 and 1975 respectively, and the data have been conventionally actualized to 2010. Extended exergy analyses for China and Turkey have just been published ([46,58]), and, as it will be explained in section 4, both contain minor but not negligible methodological discrepancies with the "standard" EEA theory outlined above.

Notice that the very same definition of the exergy-equivalent implies that different Countries may have different ee_K, due to their different productive and economic structures and lifestyles, and that for a Country both ee_K and ee_L may vary over time, due to an evolving social structure [54]. Differences among Countries are apparent in Table 1, and in general it can be said that a lower α is a symptom of lower life standards: As a matter of fact, in [55,60] a significant correlation was shown to exist between α and the Human Development Index, HDI [82]. The interpretation of the β factor is not so univocal: If we denote by $\mathbb{S}$ the cumulative amount of wages [€/yr], while it is true that low values of this coefficient [($M2 - \mathbb{S}$) small w.r.t. $\mathbb{S}$] in general indicate an intense monetary circulation, and *vice versa* high values are typical of societies with a strong accumulation of capital (old-fashioned capitalism), it is also true that poor and not well structured economies, like for instance Cameroun in Table 2, also display low values of β.

Table 2. Specific chemical *vs.* extended exergy for the three selected pollutants [4].

Pollutant	e_{ch} (kJ/kg)	ee_{env} (kJ/kg)
CO	9825	11800
NO_x	2963	3610
SO_2	4892	5890

More insight is offered by the equivalent exergy factors, ee_L and ee_K: A high ee_L corresponds to a high exergetic expense to "sustain" a worker, and implies therefore higher life standards (in fact, it correlates well with the HDI). A high ee_K signals that high amounts of input exergy are needed to generate one monetary unit (more precisely, of monetary circulation), and indicates an ill-structured economy.

The capability of attaching to the labor input (taken here to include all service-related, blue and white collar human activities) a properly computed exergetic value is perhaps the most relevant novelty of EEA. Currently, in all practical applications of Engineering Cost Accounting, including Thermo-Economics, labor is either completely neglected or it is accounted for on a purely monetary basis: This is though unsatisfactory, because it assigns a higher weight to market conditions and financial considerations than to social, technical and environmental issues that if properly valued may displace the "optimal scenario" in the solution space [54].

3.3.3. The Equivalent Exergy of the Environmental Impact

All current methods for assigning a monetary cost to environmental damage in essence suggest that, once a substance is acknowledged to be (in some sense) harmful, it becomes "regulated", *i.e.*, legal upper limits are set to its free release into the environment, and the excess is subjected to a (usually monetary) penalty. This is equivalent to setting, for a given technology, an *upper limit to the acceptable clean-up costs for that particular effluent*. For many pollutants, though, the present environmental situation demands that even a small amount of each one of these pollutants be, strictly speaking, intolerable. To circumvent this incompatibility, *i.e.*, to make a non-zero limit "acceptable", the risks to humans are assessed in terms of monetary health- and life-expectancy parameters, and an upper bound is set to the expenditures in such a way to remain below a certain statistical probability of incurring that risk. It is easy to see that this method actually promotes an *unfair transfer not only of the pollution, but also of the health risks from a region to another*. As a partial remedy to this unfairness, it has recently been proposed to link the monetary structure of the environmental levies to energetic considerations: This is the rationale behind the "pollution commodity trading" and the "exergy tax", that tax directly or indirectly the "excess" amount of pollutants emissions above certain pre-set limits. Both are remedial measures though, aimed at a fairer redistribution of the "environmental pressure" on a local or global scale, and do not address the issue of how high the actual environmental "cost" is (all current methods take the currently regulated values as a basis for their calculations).

The EEA approach [43,52] is based instead on the calculation of the (real or virtual) exergetic clean-up (remediation) costs: Consider a process **P** (Figure 5a), and assume that its only effluent is a stream which contains hot chemicals, some of which are not at their standard environmental concentration. In a physical sense, to achieve a *zero* environmental impact these chemicals ought to be brought to both thermal and chemical equilibrium with the environment O: Thus, the real exergetic cost of the zero-impact is not proportional to the physical exergy of the effluent, but is rather equal to the extended exergy (sum of the net physical exergy spent in the clean-up process, plus the invested exergy—labor and capital—required by the installation and operation of the effluent clean-up devices) required to cool the effluent to T_O and break it up into its constituents such that each one of them is in equilibrium conditions with the surroundings. A representation of such an effluent treating process is shown in Figure 5b: The additional process $\mathbf{P_t}$ may generate some useful exergetic output, requires an energetic input, use of additional materials, labor and invested exergy, but its output will have a zero physical exergy. *The additional exergetic expenditures required by* $\mathbf{P_t}$ *must be charged to the effluent*, whose extended exergy (*i.e.*, its "cost" in terms of primary equivalent resources) will now be higher than the one assigned to it by a shear exergy "balance" (CEC). Because of the inclusion of the virtual remediation costs in the extended exergy balance, the overall conversion efficiency of the joint process ($\mathbf{P}+\mathbf{P_t}$) is decreased. In most cases, there are effluents for which some of the chemical decomposition reactions take place "spontaneously", in a short time and in the immediate surroundings of the emitting source ("buffering"): In such cases (Figure 5c) the reactions must draw on some exergy source within the environment (a certain particular chemical catalyst, oxygen, water, solar radiation, or even a biological system), and this exergy flow must be accounted for as well.

Figure 5a. Model of a process with an effluent not in equilibrium with the environment.

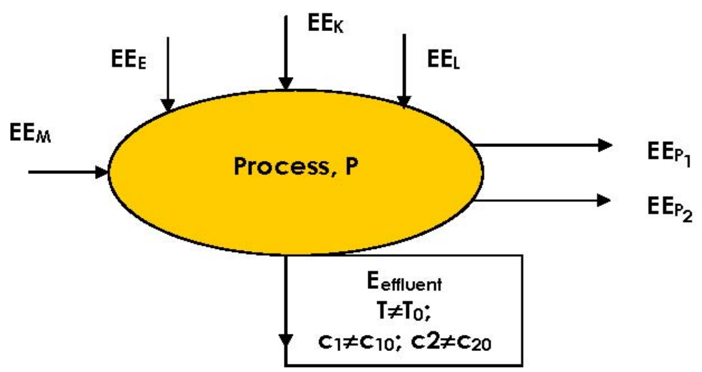


Figure 5b. Effluent treatment in EEA.

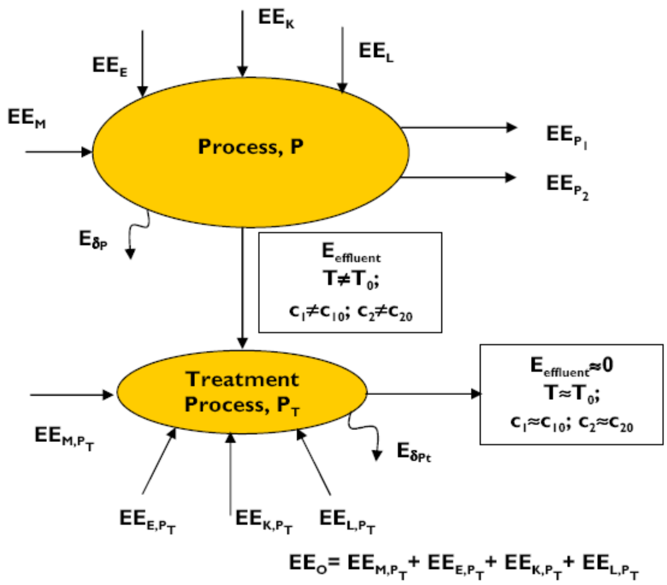
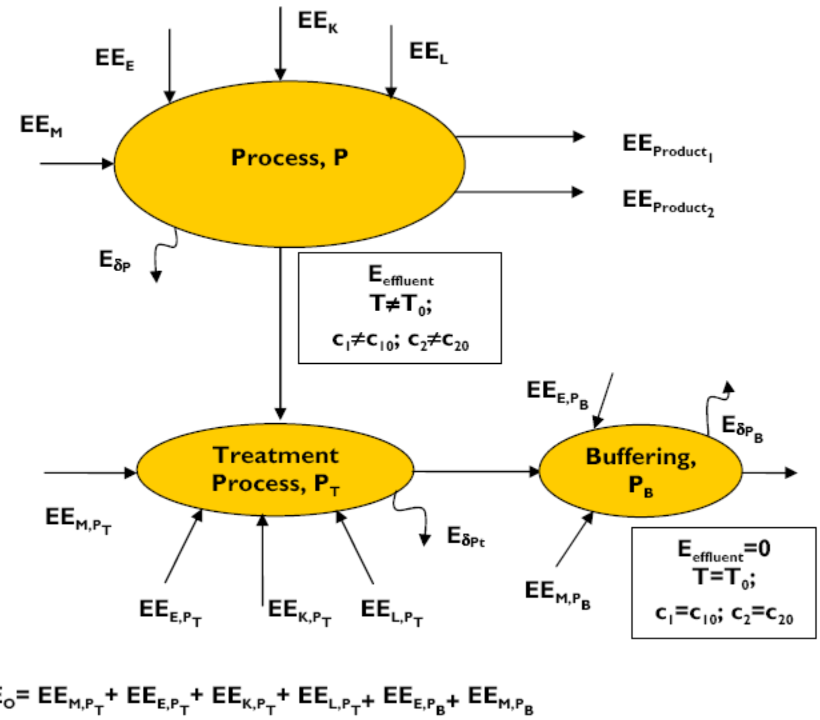


Figure 5c. Treatment of the environmental buffering in EEA.



EEA thus allows for a consistent incorporation of the effects of effluent treatment in the extended exergetic balance of a process, and provides an *absolute* order-of-magnitude estimate of the minimum exergy consumption necessary to achieve zero-impact. Notice that, if an acceptable level of pollutant is specified, then the minimum exergetic expenditure will be proportional to the difference between the values of the physical exergy of the effluent stream at the point of its release and the "regulated" state point. Thus, we recover one of the desirable features of present environmental cost estimates and at the same time avoid the considerable effort required to determine what the "tolerable environmental impact limit" for a certain pollutant would be.

Once the fluxes M, E, L, K, O (our individual "production factors) have been computed in terms of exergy-equivalents, EEA makes use of the detailed extended balances to compute the costs of the final products and to study their dependence on a variation of process parameters. All terms being now expressed in terms of a uniform quantifier, the procedure is somewhat simpler and-more important-independent of external factors as market fluctuations or time-varying currency exchange levels, provided a suitable scenario for the societal structure has been defined.

3.3.4. A Note on the Allocation Procedures of EEA

TE analysts often criticize the allocation procedures adopted in EEA as being obscure and incorrect. Allocating each one of the inputs to each one of the products is a fundamental problem with all cost theories. Except for the equi-allocation method, in which all products are assigned an equal portion of each input, it is quite obvious that if the cost of a "fuel" F_i is allocated among two products P_j and P_k with a weighted formula like $c_{Pk} = \gamma_k c_{Fi}$ and $c_{Pj} = \gamma_j c_{Fi}$, the final cost calculations will be dependent on the allocation coefficients γ_j and γ_k. In TE, and in ECT/CEC, a series of general rules have been formulated for a rational determination of the allocation coefficients [33,35,83]: They are generally adopted in the evaluation of technological energy conversion systems. Similar rules are possible also for biological systems, but since the distinction between "product" (the design purpose) and "byproduct" (a secondary output of the system) is not so crisp in this case, a general agreement on how to treat such cases has not yet been found [84]. In this regard, EEA enjoys the advantage of an easier and more accurate determination of the labor and capital allocation, because the usual industrial practices include a very detailed allocation of both the work hours and the monetary expenditures at component level. This additional information results in most cases in an uncontroversial determination of the γ_j and γ_k coefficients. Therefore, while it is true that the EE of an incoming flux ("fuel") is allocated by the usual rules of ECT, in all cases for which a more disaggregated database exists, its EE_L and EE_K components can be allocated exactly, without recurring to any allocation assumption. This is not a casual result, but rather the consequence on the one side of the additional "information" intrinsically contained in the EEA formulation, and on the other side of the dimensional homogeneity of the EE quantifier. As a side note, it must be remarked that attributing a "space-and-time integral" value to labor and capital represents a substantial improvement with respect to all previous methods: For instance, it allows to properly weight blue and white collar labor, avoiding market distortions and linking the "worth" of the work hour to the cumulative amount of primary resources embodied in it. A similar remark applies to capital: One of the Reviewers observed that M2 entails both "productive" and "speculative" capital, and that since the latter does not *per se* produce any goods, the conversion convention adopted in EEA to assign a primary resource equivalent to capital generates distorted results. This critique can be easily countered: If we think of capital as a "service", its equivalent primary exergy content must be calculated in the very same way it is calculated for all other services, by adding all of the exergy contributions that result (and allow for) its generation. These arguments have been presented in previous papers [45,53,56], but are repeated here for the sake of completeness.

In autonomous biological systems, *i.e.*, in systems in which there is no human intervention, the capital and labor contributions are of course both equal to zero, and the only significant contribution of EEA is its calculation of the environmental remediation cost. Non-autonomous biological systems (a case in point: Agriculture) must be treated as any other energy conversion process, because labor and capital contributions are in general not negligible factors in the assessment of their sustenance.

4. Two Examples of Application

Several examples of application of the EEA method have been published in the recent archival literature [45–49,51,52,58–60,85,86]. We are presenting here two of the most recent studies, related to the Transportation Sectors of China and Turkey, respectively. The studies were conducted with minor methodological differences, due in part to the different databases available for the two countries and in part to the personal preferences of the research teams, but their results provide additional insight into the possible remedial actions that must be planned to improve the clearly unsustainable situation: Since an analysis of the degree of sustainability of different scenarios is outside of the scope of the present paper, readers are referred to the original publications for a detailed discussion.

4.1. Extended Exergy of the Environmental Remediation Cost for the Transportation Sector in China [48]

The rapid development of an industrial infrastructure in China has led to a remarkable increase of the material and energy throughput of the society, and one of the consequences is an unprecedented rate of growth of the transportation sector. Such an accelerated growth led to a somewhat uncontrolled increase of the number of vehicles, especially passenger cars and commercial trucks, resulting obviously in a corresponding increase in the traffic-related pollution. An EEA analysis of the Chinese transportation sector is presented in [48], using the data similar to those displayed in Table 2 and the following additional assumptions:

1) Under the current official accounting regulations, the M2 of China is difficult to calculate: Therefore, the GNP (gross national product) was used instead;
2) The yearly number of work hours in China is very low (average is about 240 work hours/yr) because the predominantly rural and scarcely industrialized population has a workload that depends on the harvesting seasons and agriculture is primitive and non-intensive. Furthermore, neither domestic work nor part-time work by minors and elderly is accounted for;
3) The average wage s = 280 €/yr, and is low for the same reasons as point 2 above;
4) The only pollutants taken under consideration in the analysis are CO, NO_x and SO_2, for which reliable data were available;
5) The effluent treatments were assumed to be post-combustion for CO ($CO + O_2 = CO_2$); catalytic reduction for NO_x ($2NO_x = xO_2 + N_2$) and calcination for SO_2 ($SO_2 + CaO + 0.5O_2 = CaSO_4$). Standard industrial processes were considered, but all reactions are assumed to be complete.
6) Material costs were taken from the Chinese market 2008.

The results are summarized in Tables 2 and 3.

Table 3. Absolute and relative values of the equivalent exergy of Labor, Capital and Environmental Remediation for the Chinese TR-sector in 2008 (adapted from [48]).

Transportation mode	Labor exergy, EE_L (J/yr)	$EE_L/\dot{E}_{in}$ (a)	Capital exergy, EE_K (J/yr)	$EE_K/\dot{E}_{in}$	Environmental Remediation exergy, EE_O (J/yr)	$EE_O/\dot{E}_{in}$
Highways	6.72×10^{18}	7.65%	8.06×10^{18}	9.17%	2.22×10^{18}	2.53%
Railways	4.71×10^{18}	5.36%	2.38×10^{18}	2.71%	3.21×10^{15}	0.004%
Waterways	1.18×10^{18}	1.34%	1.17×10^{18}	1.34%	1.31×10^{16}	0.015%
Civil aviation	6.87×10^{17}	0.78%	1.72×10^{19}	19.58%	1.88×10^{15}	0.002%
Total	1.33×10^{19}	15.14%	1.72×10^{19}	19.60%	2.24×10^{18}	2.5%

(a) The value for $\dot{E}_{in}$ is taken from [46], and is different from the one reported in Table 1 above.

Table 3 shows that (in 2008) in China the major consumer of primary exergy in the transportation sector was the capital investment, and that the environmental clean-up exergy played a relatively secondary role. Nevertheless, the amount of primary resources equivalent to the environmental remediation expense is very high in absolute terms, where 2.24 EJ/yr correspond to an installed power of 89 GW (China's cumulative installed power was approximately 800 GW in 2008). The EEA analysis therefore indicates that about 35% of the primary exergy input into the country is consumed in the transportation sector, and the environmental remediation cost alone absorbs (destroys) 2.5% of the country's primary resources. Consider that this grim picture is likely to have worsened since 2008, due to the high industrialization rate of the Chinese society.

4.2. Extended Exergy of the Environmental Remediation Cost for the Transportation Sector in Turkey [59]

The transportation sector represents an environmental problem in Turkey as well, but for reasons very different from those just described for China. The Turkish prevailing mode of transportation—both for goods and passengers—is by gasoline or diesel fuel based cars and trucks, railroad transportation playing a minor role and ship and air being secondary in the global picture. In addition, the railroad network is not entirely electrified, which adds to the pollution. Furthermore, urbanization has progressed so much that 70% of the Turkish population is concentrated in the eight major cities: This poses severe challenges both to the supply of goods to these cities and to the commodities transportation in general. Such a situation leads to an air quality that is substantially below standards in most large urban areas, and in general to a low sectoral efficiency. An EEA analysis of the Turkish transportation sector is presented in [59], using the data presented in Table 1 and the following additional assumptions:

1) The only pollutants taken under consideration in the analysis are CO_2, N_2O and CH_4: all other emissions were converted into their accepted CO_2 equivalents (Table 4);
2) The effluent treatments were assumed to be post-combustion for CH_4 ($CH_4 + 2O_2 = CO_2 + 2H_2O$); catalytic reduction for N_2O ($2N_2O = O_2 + 2N_2$) and calcination for CO_2 ($CO_2 + CaO = CaCO_3$). Standard industrial processes were considered, but all reactions are assumed to be complete.
3) Material costs were taken from the Turkish market 2006.

A critical comparison of Tables 3 and 5 leads to the conclusion that the incidence of Labor on the primary exergy consumption of the TR-sector in Turkey is much lower than its Chinese counterpart: This is due essentially to the better structured societal infrastructure. The incidence of Capital is about the same in the two countries, but in Turkey the environmental remediation expenditure represents, in terms of J/yr, a substantially higher percentage of the total exergy inflow.

Table 4. Specific and total environmental extended exergy for the three selected pollutants for the transportation sector in Turkey 2006 [59].

Pollutant	ee_O (kJ/kg)	EE_O (J/yr)
CO_2	57,600	2.52×10^{18}
N_2O	10,600	0.47×10^{15}
CH_4	322,400	0.55×10^{15}
	Total	25.22×10^{18}

Table 5. Absolute and relative values of the equivalent exergy of Labor, Capital and Environmental remediation for the Turkish TR-Sector in 2006 (adapted from [59]).

Labor exergy EE_L (J/yr)	$EE_L/\dot{E}_{in}$ [(a)]	Capital Exergy EE_K (J/yr)	$EE_K/\dot{E}_{in}$	Environmental Remediation Exergy EE_O (J/yr)	$EE_O/\dot{E}_{in}$
0.41×10^{18}	2%	3.85×10^{18}	20%	2.61×10^{18}	13%

[(a)] The value for $\dot{E}_{in}$ is taken from [58], and is different from the one reported in Table 1 above.

5. Conclusions

The purpose of this paper was to introduce a new candidate for a "Global Environmental Indicator", to discuss its properties, to define a procedure for its calculation and to argue for its merits. We have observed that exergy destruction is a proper measure of the global "force" that maintains Earth in its far-from-equilibrium state, and reflected on the fact that the global energy-conversion chain that includes complex production structures, both natural and anthropic, is "driven" by this force. Therefore, a measure of the amount of this exergy flow on which human societies thrive seems to be a legitimate —and surely a thermodynamically proper—measure of the possible stress placed by these societies on the environment. Extended Exergy Accounting is based on a purely exergetic paradigm and represents therefore the most general example of Exergo-Economics: It results in a quantitative "performance parameter", the Equivalent (or Extended) Exergetic Content EE, which enjoys the necessary attributes an environmental indicator ought to possess. It can be rightly said that the EE of a commodity measures its *Exergy Footprint*, and constitutes the basis for a cost-accounting procedure founded on Second Law concepts: It enables researchers and decision makers to assess our natural and anthropogenic processes by means of a performance indicator that correctly reflects the resource-to-final-use (including disposal, in a true life-cycle approach) of our exergy resources. Being expressed in terms of primary resource equivalents, EE is ideally suited for comparative purposes: Previous studies have demonstrated (see comments to Table 1 above) that ee_L and ee_K are significant indicators of the relative affluence and of the general state of the economy. A necessary caveat must be kept in mind to avoid arbitrary extensions and misuses of the concept: EE is fundamentally rooted in thermodynamics, and cannot be used to address issues about "economic value" (in the neo-classical sense), nor issues related to preference, ethical and political decisions, education, health care *etc*. outside of a resource-cost frame of reference. According to a discussion developed in [53], EE can however be used to quantify *use value*, which it measures by the amount of equivalent embodied primary exergy resources.

Conflict of Interest

The author declares no conflict of interest

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75. In response to a remark made by one of the Reviewers, it must be stressed here that the measure of Labor in EEA has nothing to do with the so-called “Labor=Added Information” assumption [4,22] nor with the purely metabolic exergy consumption.

76. One of the Reviewers suggested to use the PPI (purchasing parity index) instead of performing a purely monetary adjustment as proposed here. Use of the PPI may be advantageous for comparisons, but it would not distort the calculations, since it is perforce based on monetary equivalents itself.
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