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Exergy-based ecological indicators: From Thermo-Economics to cumulative exergy consumption to Thermo-Ecological Cost and Extended Exergy Accounting

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No theory is originated in an isolated scientific environment: EEA could not have been conceived were it not for the previous work by Professor Jan Tadeusz Szargut. This work is my humble tribute to him.

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ABSTRACT

This paper presents a summary of the conceptual development and the practical applications of exergy-based Environmental Indicators. After a brief historical introduction, the two most popular methods are presented and discussed: the Exergo-Environmental Analysis (here TEA, as a *memento* of Jan Szargut's original denomination "Thermo-Ecological Analysis", currently adopted also by Valero's school) and the Extended Exergy Accounting (EEA). Both emerged from Szargut's idea of the existence of a consumption index, the Cumulative Exergy Consumption (CExC), which can be used to quantify the consumption of primary resources "embodied" in a final product or service. The extension introduced by both methods with respect to CExC consists in the explicit inclusion in the exergy budget of one or more of the Externalities, lumped in the original CExC formulation into the exergetic material contents of the single commodities. The differences between the three formulations are obviously reflected in the numerical values of the resulting indicators. The Thermo-Ecological Cost (TEC) and the CExC differ because of the inclusion in the former of the exergetic resources that reflect the "penalty" in the use of primary non-renewable consumption caused by the anthropic intervention. The CExC index and the Extended Exergy Cost EEC differ because the latter explicitly includes in the calculation a "Labour and Capital equivalent exergy consumption" that allows for the survival of the individuals in a given region according to the respective life standards (variable in space and time). Another difference is the way the Environmental Externality is computed: while TEA takes an *ex-post* assessment, EEA introduces a calculation of the -ideal or real-remediation costs.

1. Introduction

Environmental considerations are an essential part of the correct assessment of any energy conversion system: the concept of "anthropogenic environmental impact" substantially evolved in the last decade, from a pure "assessment of ecological damage" (pollution) to a more complex, more comprehensive and more detailed examination of the local and global implications of the interactions of anthropic processes with the biosphere (both locally and at large). Several sets of quantitative measures of such interactions, known as Environmental Indicators (EI in the following), have been proposed and applied, with the intent of providing a sufficiently accurate and reliable decision support basis for process engineers, energy managers, planners and decision makers. This approach is not devoid of problems: to begin with, generality conflicts with specificity, and it is often difficult to connect a local EI with a more global measure of environmental impact; moreover, several of the proposed indicators are neither consistent nor sufficiently predictive because they are not rooted on rigorous thermodynamic principles. This paper provides a preliminary analysis of this problem, from a specific perspective*: how can thermodynamically correct Environmental Indicators be constructed that properly address the problem of* "*sustainability*"? It is rather clear, to begin with, that a thermodynamic interpretation of the concept of sustainability is in order: in fact, strictly speaking, the Second Law negates the possibility for any open and evolving system to maintain itself in a "sustainable" state without availing itself of a continuous exergy supply (and destruction). A second important

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Nomenclature

B	System immediate surroundings
$\dot{E}$	[W] Exergy Flow
E [J]	Exergy
EI	Environmental Indicator
EPA	Environmental Protection Agency
H	Human society
O	Environment
t [s]	Time
η	Efficiency
k	Dimensionless coefficient

Suffixes

0	Initial Conditions
acc	accumulated
b	consumed by **B**
in	input
out	output
w	waste
δ	exergy destruction

issue is the need to separate “local” from “global” indicators: this topic is worthy of a separate treatment and is not addressed here.[1] A third issue is that of reconciling with Thermodynamics some of the local indicators adopted by biologists, sociologists and ethnologists, EIs that are usually based on a “numerosity” index of a certain population and on its time evolution in the environmental niche of observation. All three issues are treated in the following sections. The approach taken in this paper is “honestly biased”, in the sense that, following a large number of previous studies in the field of Applied Thermodynamics, a resource-based exergy metrics is strongly favoured, and as a consequence all of the non-thermodynamic attributes of a “sustainable system” are intentionally neglected. This is not to be perceived as a limitation of scope: our argument is, on the contrary, that the widespread perception of the inherently fuzziness of the current concept of “sustainability” is due to the neglect of the fundamental separation between its two essential constituents: the thermodynamic basis, addressed in this paper, and the socio-economical one, which falls under the domain of different branches of science, but ought to consider the thermodynamic part as a necessary foundation to build upon.

1.1. Outline of the paper

The first part of this paper is dedicated to a brief critical analysis of the concept of “Environmental Indicator” and to a summary recapitulation of the reasons that led to the extended use of this type of numeraires in the assessment of the interconnections between the “state of development” of a society and its impact on its surroundings. The conclusions of this analysis support the conclusion that the current conception of “sustainability” and “sustainable development” are flawed on two counts: first, both are clearly anthropocentric, because they imply that what ought to be “sustained” is the survival of the human race; second, they are too vague, because they do not make sufficiently clear what should be the measure of the “degree of (un-)sustainability of present social organizations. It is then proposed to adopt a thermodynamic criterion to measure how “sustainable” a system is, by accounting for the actual primary resources used up (embodied) in the production of material or immaterial commodities. In the second part of the paper, after providing a brief description of Thermo-Economics, three exergy-based methods are examined: Szargut's Cumulative Exergy Consumption (CExC) and Thermo-Ecological Analysis (TEA) and the Extended Exergy Accounting. It is concluded that all three lead to the definition of proper, congruent EIs that are rationally and rigorously rooted in Second Law, and that their numerical values are not only different, but also incommensurable: there is no “formula” to convert from one to the other.

2. Do environmental indicators “represent reality”?

“Indicators” are used at different aggregation levels in industrial, economic, social and environmental studies as a synthetic and significant way of “representing reality”: they are intended to facilitate a concise and correct information exchange between specialists (scientists of specific branches) and non-specialists (herein collectively denominated “decision makers”, including in this term the public opinion). Semantically, the problem resides in the proper definition of these quantifiers [36], and this requires a more detailed analysis of the link between the definition of each indicator and the phenomenological model it subsumes. Care ought to be exercised to circumscribe the domain of application of each one of such EIs, and the first problem that is encountered when approaching this issue is the undeniable fuzziness of the concept of “sustainability”, which has its origins in social sciences and cannot be applied to thermodynamic analyses without a redefinition of its scope, meaning and boundary conditions. An example is useful to clarify the problem: in the last decade, extensive field campaigns were conducted in the island of Soqotra (Yemen) to study the population of an endemic tree, the Dracaena Cinnabari [1,60]. The researchers studied the distribution, health, growth rate and life spans of about 4000 individual trees, and elaborated a sort of “guidelines” for the protection of the species. The “sustainability” of the Dracaena population was found to depend on climatic and socio-economic factors (e.g., free grazing by the imported goat population which feeds on the youngest shrubs). Suitable “ecological indicators” were developed for this case, but none of them can be reformulated in terms of the availability and allocation of resources. The same applies to studies on local populations of ants [32], of sea cucumbers [68], of mammals [50], etc. The challenge here is clearly one of integrating the large amount of data experimentally collected, concoct a general thermodynamically based resource model and derive proper EIs.

3. A brief historical perspective into environmentalism

According to generally accepted estimates [39] 10000 years ago human population totalled about 10 million individuals. As the number of humans grew, in the sense that their density became locally higher, their hunting and gathering caused a decrease of the on-site availability of wild (=raw) resources, mainly wood, berries and small prey. Some of our ancestors reacted by intensifying their migratory lifestyle, initiating a well-documented series of

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[1] It is not implied here that “local” EIs ought to be *a priori* discounted: they relate to specific features of the environmental niche they refer to. Examples are the time histories of the numerosity of a certain species in a given area; or its diffusion to- or from different areas (migration); or the assessment of the “health” of an isolated population and the normalized measure of its net growth rate (birth-minus death rate); or the evolution of the taxonomy of certain species under given environmental stresses: many other similar examples can be found in the archival literature. None of such EIs involves thermodynamic considerations: nevertheless, they maintain their significance outside of the realm of Thermodynamics, and may be very useful descriptors of experimentally measured “evolution histories” of the niche they apply to. Similar remarks apply to all purely social indicators like “life standards”, “degree of alphabetization” or “infant mortality”.

migrations from their sites of origin into the northern- and eastern parts of the world; others began domesticating animals and cultivating, selected plants and became settlers. Mixed types of behaviour is also documented: over the centuries, nomads at times found it convenient to reconvert to settlers, and wars, periodic droughts, floods or meteorological events forced settlers to resume nomadism. As a result of this change in human behaviour, history from 8000 B.C. to the present witnessed the development of more advanced agricultural techniques, an increasingly complex social structure based on a division of tasks (farmers, labourers, warriors, aristocracy) and means of exploitation, and an ingenuous creation of tools to exploit the Earth and its products. This development also caused the partial depletion of what is currently referred to as “natural capital”, which brings us directly to the scope of this paper.

Evermore intensive agriculture resulted in a continued -albeit slow for modern standards-population growth, which over centuries led to a numerosity of about 800 million in 1750 [39]. Locally, the resulting higher population density created new scarcities of fertile land and energy resources, which prompted, in the more densely populated and energy-intensive northern Europe, what is today known as “the industrial revolution”. This began in England and at its inception consisted simply in the substitution of the then locally abundant coal for the dwindling natural wood resource. The use of coal raised immediate and practical problems (mining, transportation, water pumping, controlled combustion), and required both greater concentrations of labour around the mines and mills (thus spatially skewing the population distribution), and use of larger amounts of energy (exergy in the context of this paper). The extensive industrial use of coal led to steam engines, and machines gradually displaced land as the central means of production. The success of extensive industrialization brought about, in a way surprisingly similar to the one caused by the ancient hunting-gathering and agricultural transformations, new ecological scarcities: this time global rather than local, and not only due to the finite available supply of natural resources, but also to the overloading of the buffering capacity of local natural sinks.

The mainstream of the contemporary environmental debate links environmental concern to the problem of industrial pollution and considers it to be a feature of the industrial and post-industrial society. Historically, however, pollution, deforestation, land degradation, and chemical food adulteration effects have afflicted humanity, to a greater or lesser extent and to a more “local” scale, for most of its existence [79]. For instance, heavy metal pollution (lead), is considered as one of the factors that contributed to the fall of the Western Roman empire [46]. And there is a growing consensus among environmental archaeologists that most of the ancient densely populated societies, including the Babylonian empire, the Maya kingdoms, the Ethiopian empire, the ancient Chinese reigns etc., may have collapsed because of the environmental degradation of their respective immediate surroundings caused by an over-exploitation of land resources. The growth of population, the degradation and depletion of resources with the resulting necessary restructuring of societies, and the development of new technologies have usually been so slow to be barely perceptible during an individual lifespan [40]. However, over the past two centuries, and especially during the last six decades, the global economy has become, so to say, of the same scale as the global biosphere, transforming, for the better or for the worse,[2] the character of the planet and -as a result-of human life: the natural environment has reached a state where it appears to give short-term “negative feedbacks” [39]. These are the conditions in which contemporary environmentalism began to emerge [40]. The topic is interesting both from a sociological and from an engineering viewpoint, because there is sufficient historical evidence that the “environmental problem” was long known and consciously dealt with at institutional level, but a more detailed historical review is outside of the scope of this paper and is thus left for future investigations.

3.1. *The emergence of the concept of sustainability*

The modern concept of environmental sustainability dates back to the early 60'es, when the then dominating view of technology-driven economic growth came under the fire of a generic criticism based on the perception that the quality of the environment is closely linked to economic development. While in those years academic support for the “steady state” economy (i.e., no-growth in mass throughput) was less than lukewarm, public opinion became strongly involved through the environmental movements, until public Agencies and Governments decided to tackle the issue: in 1968, a group of European economists and scientists founded the Club of Rome, under whose collective denomination they published in 1972 *Limits to Growth* [9]. This was in fact the first official report in which the hitherto vague “concern for the environment” attained scientific roots: the argument of the book was that humans are a) depleting their fossil resources and b) using up the Earth's renewable resources at a rate faster than their natural replenishment rate. The Club of Rome advocated the abandonment of economic development based on “material growth” as the cure for both problems. In retrospective, this accent on the criticism of “material growth”, and an undeniable flavour of Malthusianism, makes it clear why most economists of the time voiced a strong and acrimonious criticism towards such stance. Nevertheless, on the wake of *Limits to Growth* a worldwide movement was born that, both in public forums and in scientific circles, argued that human society was growing “too quickly” and using up its resources “too fast”. A Worldwatch Institute was established in 1975 as a result of the first type of these concerns. In the same years, yet other groups focussed their efforts on the establishment and legal enforcement of environmental standards [72].

In 1987, on the basis of suggestions formulated in the previous decade by Daly and Costanza [11,14] (later revised and recalculated in 1997, [47]), the term *sustainable development* was officially coined by the United Nations Commission (usually referred to as the “Brundtland Commission” from the name of its president, Gro Harlem Brundtland). Their 1987 report [72], *Our Common Future*, contains the (too) often cited definition of “*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*”.

In 1992, the concept was further developed, and its applications defined, at the United Nations Conference on Environment and Development in Rio de Janeiro; and then again re-elaborated in the *United Nations Millennium Declaration*, signed in September 2000, and in the World Summit on Sustainable Development (WSSD), held in Johannesburg in 2002, which resulted in a poignant and well-known political declaration (the “*Johannesburg Plan of Implementation*”).

In retrospective, it is clear that the link between environmental and developmental issues did not emerge suddenly in the ‘60es and 70'es, in spite of some visionary writings indicating that the form of economic development would have to be altered [8,14]. But in those decades the seed grew at an accelerating pace: in the

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[2] The fact that, according to [https://www.worldbank.org/en/topic/poverty/overview], 736 million people lived on less than $1.90 a day in 2015, signals that “the better” has not yet come for 10% of the human population. Though the number of humans living in extreme poverty is steadily decreasing, the spread between the *pro-capite* primary resource use of industrialized societies and that of under-developed Countries is increasing, indicating that the benefits of modern technologies are not as widespread as commonly purported.

following years, new terms were coined like “environment and development”, “development without destruction” and “environmentally sound development.” The term “eco-development” appeared in the UN Environment Program review in 1978, which explicitly stated that environmental and developmental ideas must be considered concurrently. The paradigmatic definition of the Brundtland Commission, though too vague for the thermodynamic approach proposed here, contains two key concepts:

a) The concept of “needs,” in particular the essential needs of the individual, to which overriding priority should be given; and
b) The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet the present and future needs of the human race.

Not surprisingly, it is exactly its vagueness that made such a definition palatable to decision makers worldwide: “sustainable development” is something everyone can agree to, but merely positing it does not provide exact guidelines on how to achieve its goal. In his usual blunt style, Herman Daly pointed out that “*although there is an emerging political consensus on the desirability of something called sustainable development, this term -touted by many and even institutionalized in some places-is still dangerously vague*” to be used as a guide for making the desired changes. But he also noted that “*having a consensus on a vague concept, rather than disagreement over a sharply defined one, was a good political strategy*” [15].

Today, any “environmental policy declaration” makes explicit or implicit reference to the need for a *measure* of environmental effects, both at local and global scales.

The above cited Rio declaration states “*Indicators of sustainable development need to provide solid bases for decision making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems*” [74]. Such a definition may of course have important political consequences, but it is far too vague for the purpose of the present study and logically circular (i.e., self-referential).

A more operative definition of an EI is provided by EPA [19]: “*An environmental indicator is a numerical value that helps provide insight into the state of the environment or human health. (*underlining by this Author*). Indicators are developed based on quantitative measurements or statistics of environmental condition that are tracked over time. Environmental indicators can be developed and used at a wide variety of geographic scales, from local to regional to national levels. By monitoring the environment using indicators* … (it is possible to) … *share meaningful environmental information with the public, and ensure that high-quality environmental decisions are made*”. In a related document [33], EPA also provides guidelines that further circumscribe the structural formulation of EIs, their conceptual relevance, and their functionality both to the type of the sought after assessment and to their ecological function. In the last decade, several reports were issued by international Agencies to define the scope, attributes and use of EIs [43,45,71,73].

3.2. “Anthropocentric” versus “environmental” sustainability

It is important to discuss in some detail the apparently anachronistic disjunction “state of the environment or human health” contained in the first definition of an EI reported above. The use of the “or” in lieu of an “and” is not a refuse, but rather the surfacing of a hidden contradiction that must be clearly and unambiguously addressed and resolved in a theory of thermodynamic sustainability: in spite of the repeated and strongly worded “concern for the state of the environment”, what we (humans) are really interested in, and what all current indicators really address is the welfare and secure survival of the human species. Even the “biological diversity conservation” issue is merely seen in an anthropic perspective (“if a species becomes extinct and its ecological niche is ‘damaged’ by such an event, what are the consequences for humans?”).

Returning for a moment to the currently accepted (non-thermodynamic) definition of sustainability, we note that the above quoted EPA guidelines [33] contain additional statements defining the essence and the structure of acceptable EIs and their functionality both to the type of the sought after assessment and to their ecological function: what emerges from that document is that indicators must subsume a model of both the “state” and of the “evolution” of the environment. In addition, they must implicitly contain a value judgement (let me pose in this regard some rhetorical questions: is “a growing number of whales” a positive or a negative attribute for the state of the environment? And, what about “a growing number of mosquitos” or “a growing number of red algae”?). The problem is, such value judgements are invariably linked to anthropocentric considerations, and this is a forceful reason to propose analyses are based on thermodynamically based EIs. In a 1980 public report [31] “*sustainable development*” is specified to consist in the “*integration of conservation and development*”, and further described as the “*management of human use of the biosphere so that it may yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations*”. The anthropocentrism here is even clearer.[3] Even a more recent definition of sustainable development issued by EPA reads “… to *create and maintain conditions under which humans and nature can exist in productive harmony and that permit fulfilling social, economic, and other requirements of present and future generations*”.

This is a relevant point, because a thermodynamic analysis, being purely system-oriented, remains absolutely neutral with respect to the survival of this or that species, human or not. As a corollary, we must observe that when addressing such issues, care must be placed in avoiding a “cultural” form of anthropocentrism, because some value choices, even if generally agreed upon, are not amenable to a scientific treatment.[4] Another major point about sustainability was brought up by one of the Reviewers: “*The future of Sustainability or lack thereof cannot be predicted from assessments made at 'this' particular time (any particular 'present time'), because future developments in science, in technology, and of resources (including new resources) cannot be exactly foretold … If the present and history can tell us anything it is this: past pessimistic assessments of sustainability have failed dismally as a consequences of such developments”.*

The remark is of course correct: future events cannot be predicted, be they quantum technological jumps or sudden catastrophic volcanic eruptions. Nevertheless, exergy-based assessments, at 'this' time *are* worthwhile, inasmuch they help identify critical features of the societal structure and direct our

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[3] This “anthropocentrism” is intrinsic in the Bruntland definition, which in essence states that the Earth is “sustainable” if and only if it allows for the perpetuation of our species. We shall not delve further in this issue here, except for pointing out that the planet was in a “sustainable state” well before the Mesozoic dinosaurs' extinction, and will be in a (certainly different) “sustainable state” even after a possible extinction of the human race [30,79,80].

[4] For example, the vegetarian diet imposed by some forms of religious cult and by lay “lifestyle philosophies” may result in a “more sustainable lifestyle”, but is devoid of any scientific (in Popper's sense, i.e., falsifiable) form. Another fitting example are the “taboos” most present day western and eastern cultures place on killing and eating some specific species (pork, cow, rat, bat, dog, cat, snake, most insects). Such otherwise perhaps culturally valuable dietary prescriptions are completely unrelated to scientifically valid sustainability issues.

attention to possible remedies that may require new developments. Identifying a low exergy efficiency in a system or subsystem immediately stimulates reflections on how to ameliorate it, and generates challenges and opportunities that are not ruled solely by a monetary "return of the investment".

4. Thermodynamics and resource exploitment

The second EPA statement cited in Section 3.2 is important because, if sustainability is the issue, it clearly indicates that an EI must be aimed at facilitating the decision-making process but also at making it more understandable to the public. The problem is that, if "sustainable development" is defined [72] as a process that "*meets the needs of the present without compromising the ability of future generations to meet their own needs*", conciseness and clarity conflict with physical correctness. To make this point physically explicit, let us examine the relationship between any "living society" (***H***) and "the environment" (***O***) using thermodynamic tools. Since diverse forms of energy flows are involved, and since it is rather obvious that "thermodynamic sustainability" is inextricably linked to the Second Law, we shall use without further justification exergy as the measuring stick for our considerations.

4.1. Methodological remarks

In strong contrast with Classical Thermodynamics, in which the concept of "time" has no meaning and all processes are analysed assuming they may be described by a succession of (quasi-) equilibrium states, when we deal with natural systems time becomes an essential parameter, because "thermodynamic evolution" -in the sense of "time history of the systems object of the study"- is really what we are after. Therefore, the "balances" described in this context must be intended as integral values over the entire duration of the time window of interest. In the model we are proposing, this time dependence is enforced in two ways:

a) The "internal dynamics" of each system are allowed to vary in a prescribed fashion: for instance, with reference to Fig. 5, the growth rate of H, measured by $\dot{E}_{acc}$ can be specified as a *f(t)*, so that the history of system evolution becomes a function of this quantity and of the boundary conditions;
b) The boundary conditions ($\dot{E}_{in}$, $\dot{E}_{out}$, $\dot{E}_b$) may display in turn a time dependence (daily, seasonal, or otherwise): this dependence is not considered as an internal variable of the system and it is imposed *a priori* for each scenario of interest.

Starting from an initial time t_0, the evolution of a system on a realistically extended time scale can be described by an initial transient, possibly followed by a more or less steady condition of a variable duration and by a final "approach of the limit" for very long times. For the sake of simplicity, since our goal here is to describe a possible model, we shall assume in the following that for all systems under examination a steady state portion of the evolution exists and has been reached, and shall refer only to it in the ensuing analysis. This is not, however, a limitation of the model, which is perfectly suitable for reproducing all types of time histories.

4.2. Intermission: what is the correct choice of the "Reference Environment"?

The use of exergy flow diagrams[5] in the definition of an EI implies the definition of a proper "Reference Environment" (RE). Incidentally, it must be remarked that, even if overlooked in most energy analyses, a reference state is necessary for, and in fact implicitly subsumed by, any "mass" or "energy" balance method: no correct material balance can be performed if the global and local composition of a "reference crust", "reference atmosphere" and "reference hydrosphere" is disregarded, and obviously no correct environmental analysis can therefore be completed if "reference compositions" of the Environment are not exactly defined, etc.

With reference to Fig. 1, exergy flows can be used to assess thermodynamic sustainability at both a local or a *global scale* because, since they intrinsically quantify a System/Environment interaction, the balances for **O**, **H** are inevitably *global* [see equation (1) below].

A third element could be introduced into the scheme of Fig. 1 as a RE (for instance, the *outer space*) but, in this case (Fig. 3), the subsystem **B** would have, in addition to the input flows $\dot{E}_{w,H}$, $\dot{E}_b$ and the exergy destruction $\dot{E}_{\delta,H}$, an output flow with a non-zero exergy value. But a logical and more convenient expectation is that the products of the *neutralization* of waste flow $\dot{E}_{w,H}$ were in chemical, mechanical and thermal equilibrium with **O** and with a null exergy content [as it is implicitly assumed in the exergy balance for **B** in equation (1)]. This is possible only if **O** is actually regarded as the RE for exergy evaluation.

Taking into account that **O** may be taken to coincide with the *global biosphere*, a RE of the kind "equilibrium model" cannot be used; in fact **O** can evolve in stationary conditions, but not in internal equilibrium, because it is continuously receiving the flow $\dot{E}_{in}$ and re-emitting the flow $\dot{E}_{out}$ [40]. Therefore, to simulate realistic subsystems of the natural environment, it is necessary to define a RE of the kind "Natural-Environment-Subsystem Model" (NESM), like the one proposed by Gaggioli [26–28]: it consists of saturated moist air and liquid water in phase equilibrium, and of the following condensed phases at 25 °C and 1 atm: water, gypsum, and limestone. Additional condensed phases could be added if necessary for the exergy evaluation of particular compound. But the RE model by far most popular is Szargut's model [66], in which the non-equilibrium system **O** is "photographed" at an arbitrary instant of its evolution (the current geological period) and the exergies of its constituents are calculated as being proportional to their mass fraction. Such a choice has been criticized as being arbitrary (a fact well-known to Szargut), but since no process in the Universe is really stationary, ANY instant of time chosen to take the picture would display a different RE composition, and thus ANY choice would be arbitrary: this applies also to the recently formulated Thanatia concept [76,78]. An additional consideration is of importance here: since we are far from a completely renewable resource use and complete recycling, if we wish to properly define acceptable EIs (in the sense explained in detail in Ref. [56]), natural non-renewable energy and material resources must be explicitly considered as well. This suggests the possibility of introducing in the definition of **O** a set of (optional) *reservoirs*, representing for instance raw ores mines and fossil fuels fields [30,80]. These *reservoirs* must not necessarily be in equilibrium with the matrix they are surrounded by, so that: i) they do not necessarily interact with any generic system, or flow, during the exergy evaluation of the latter, ii) they may possess exergy, and they generally do. The idea of a RE made by a NESM that embeds a set of *reservoirs* can be also useful for other purposes than the representation of natural not-renewable energy and material resources. For instance, the concept may be used to define an *internal dynamics* of the natural environment, or for representing the sequestration of a specific type of waste from **H** (like the recently proposed CO_2 sequestration

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[5] for a definition of exergy, see for example [18,20,41,65,66].

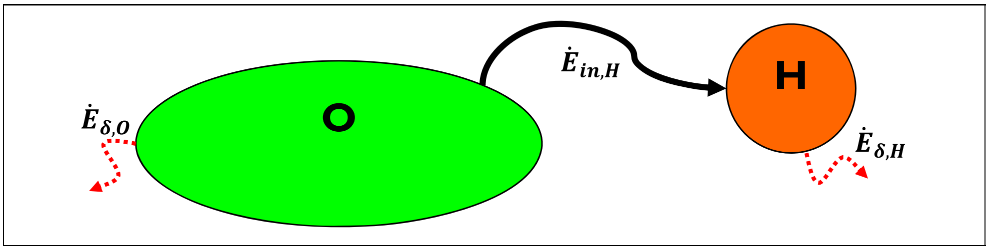

Fig. 1. The closed-system model of the Society-biosphere interaction.

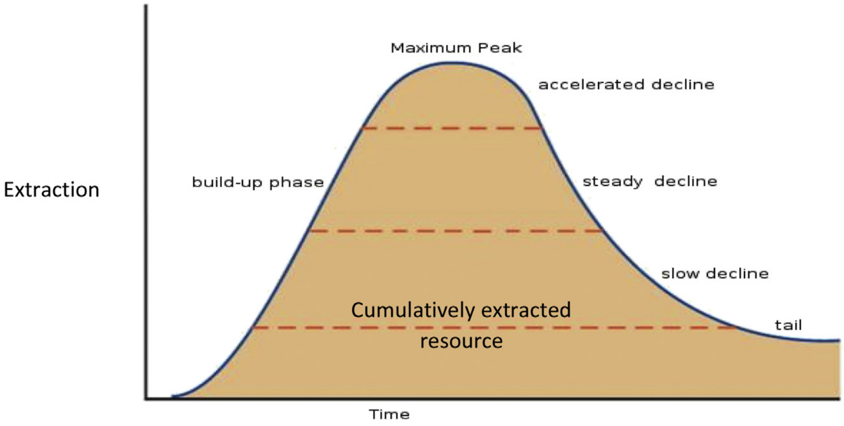

Fig. 2. The closed-system time evolution (qualitative).

in underground cavities or in deep ocean canyons), or finally for introducing into the analysis some kind of *special* product of **H**, that must be employed in a particular site, or a specific time, very far from the place or the instant in which it has been generated, so that natural capital may be treated by methods similar to those adopted for its monetary counterpart. However, this problem can be addressed without problems by using Szargut's RE or one of its updated versions [2], which we favour for its simplicity, completeness and reproducibility.

4.3. Closed systems

Consider first (Fig. 1) a "closed system model": let us identify the "environment" with "planet Earth", modelled as a closed system in this case, and consider a hypothetical time evolution scenario in which ***H*** grows in time by mining some materials from ***O*** while also tapping some energy out of ***O***'s reservoirs: it is convenient to combine both fluxes into a single exergy flux $\dot{E}_{in,H}$. Under the additional (albeit irrelevant for our present purposes) assumption of a Hubbertian extraction rate, the scenario of the two systems will evolve as shown in Fig. 2, i.e., clearly in a non-sustainable way: the resources are gradually exhausted, and when the $\int \dot{E}_{in,H} dt = E_{0,O}$, $E_{0,O}$ being the exergy content of **O** at the initial time, their extraction necessarily ceases.[6] Notice in passing that if we identify **H** with the whole of the human species and wish to account for -say- space exploration, the consideration that humanity may be able to mine resources from an additional series of reservoirs $\mathbf{O_1}$, $\mathbf{O_2}$,… located in other celestial bodies, the above conclusions would still stand, except for the need to extend the original control volume to include the additional "sources" (Fig. 3). The timescale of the scenario may change, but the long-term outlook remains the same: any model based on a "closed system" approach negates the possibility of a "thermodynamic sustainable state" for the composite system.

4.4. Open systems

Things change though if we adopt an open system model (Fig. 4): if ***O*** receives a steady influx of (material or immaterial) exergy from outer space, it can feed **H** indefinitely, provided the global exergy destruction is compensated for by a sufficient net exergy inflow:

$$\begin{array}{ll}\text{(balance for O)} & \dot{E}_{in} - \dot{E}_{out} = \dot{E}_b + \dot{E}_{in,H} + \dot{E}_{\delta,O} \\ \text{(balance for B)} & \dot{E}_b + \dot{E}_{w,H} = \dot{E}_{\delta,B} \\ \text{(balance for H)} & \dot{E}_{in,H} - \dot{E}_{w,H} = \dot{E}_{\delta,H} \\ \text{(global system balance)} & \dot{E}_{in} - \dot{E}_{out} = \dot{E}_{\delta,O} + \dot{E}_{\delta,H} + \dot{E}_{\delta,B}\end{array} \quad (1)$$

The first equation in system (1) represents the exergy budget of the "environment" **O**, which "invests" the flux $\dot{E}_b$ to biodegrade (by buffering, dilution, diffusion …) the effluents of **H** that cumulatively carry an exergy $\dot{E}_{w,H}$; the second is the budget of the portion of **O** that directly participates to the biodegradation, which we shall call "immediate surroundings" [42] and denote by **B** in the following; the third expresses the "steadiness" condition requiring that the difference between the exergy flow rates absorbed, discharged and destroyed by **H** be equal to zero at all times; the fourth is the global balance for the combined system ($\boldsymbol{O} \cup \boldsymbol{H}$). Notice that subsystem **B** has been introduced here for computational convenience only: "immediate surroundings" is an intentionally vague denomination for that part of the biosphere providing the exergy flux for bio-

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[6] This is the well-known "Hubbert scenario". It clearly represents an over-simplification of the actual resource exploitation curve, because it neglects for instance changes in the extraction/refining technology and in the final demand, but it suffices here for our general treatment of a "fossils only" society.

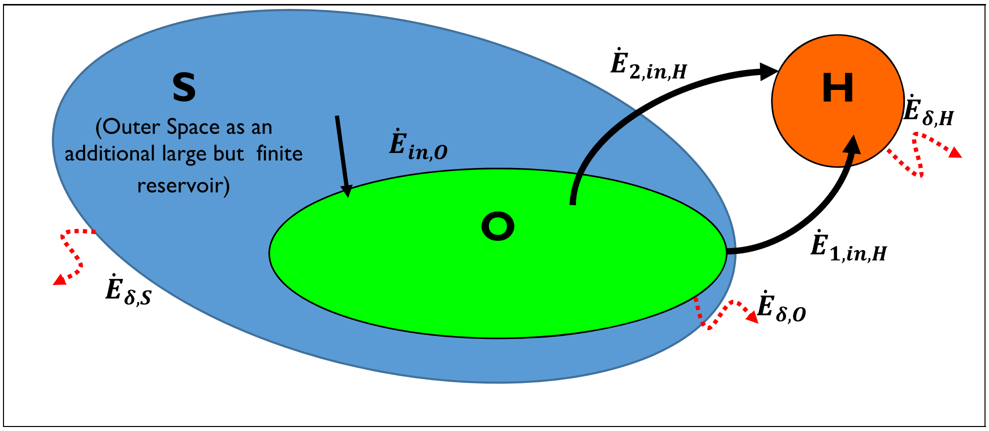

Fig. 3. The closed-system model extended to out-of-Earth reservoirs.

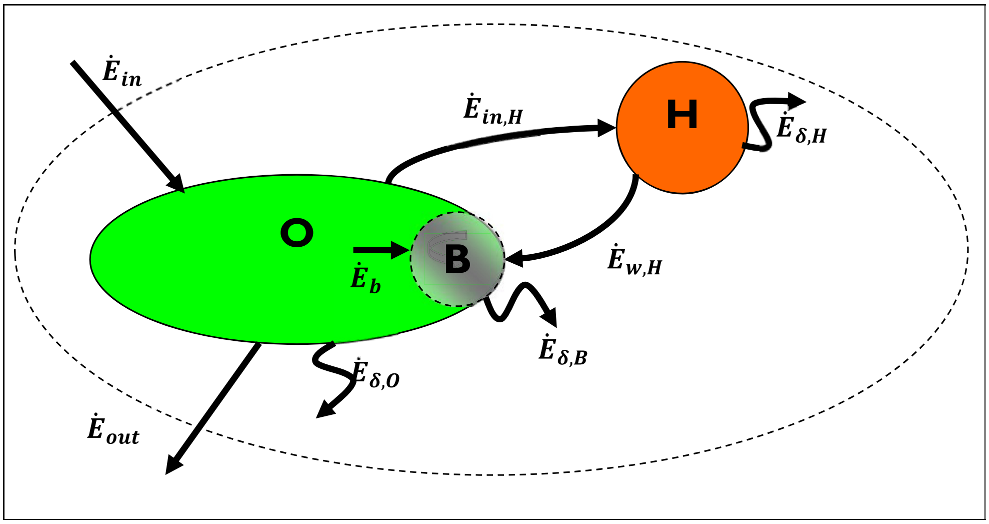

Fig. 4. The open-system model of the Society-biosphere-outer space interaction.

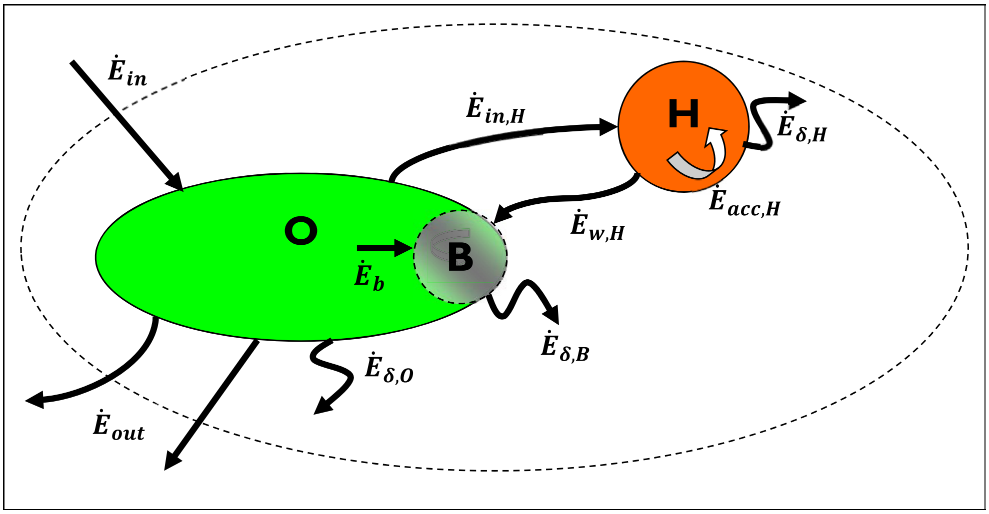

Fig. 5. The open-system model with accumulation in H (growth).

recovery through a complex cascade of processes fed by a portion of the instantaneous difference $\dot{E}_{in}-\dot{E}_{out}$. Our model views $\dot{E}_b$ as a "service" provided by **O** to **H** (through **B**) to compensate for the changes that would otherwise be induced by the wastes $\dot{E}_{w,H}$ on the steady-state of **O**: biodegradation is an "output" from **O** and takes up (uses and consumes) some of the external input $\dot{E}_{in}$. In spite of the oversimplification embedded in such a model (in which for instance accumulation effects are neglected), the meaning of equation (1) is clear: a steady state is indeed possible for **H,** as long as a sufficient external exergy flow rate is available to the system. This confirms remarks previously made by several Authors [7,8,38,51] about life being "*maintained by the planet exergy destruction rate*".[7] Readers are warned that the above example is intended only to demonstrate the different meaning of "thermodynamic sustainability" with respect to the current layman definition, and is far too simplified to account for even the most basic phenomenological evolutionary scenarios (accumulation of exergy in the form of fossil fuels and ores, different timescales for the biodegradation action of the biosphere, etc.), a discussion of which is outside of the limits of this paper.

4.5. Growth and thermodynamic sustainability

Natural systems possess self-regulating mechanisms, consisting of a complex web of positive and negative feedback processes that operate within the context of the carrying, regeneration, and assimilation capacity of the respective systems. For example, mobility is a peculiar attribute of plants and animals that denotes the capability of the species to physically "explore", "conquer" and "exploit" new land: it is an essential element of self-regulation of the biotic system which has played a major role in the evolution of planet Earth. As an integral part of the vegetal and animal kingdoms, mobility governed by ecological factors has patterned the dominant lifestyle of humankind for millions of years [39]. But mobility implies "non-equilibrium"[8]: how can we adapt the model of Fig. 4 to account for situations in which, for instance, **H** "grows" in time and is non-homogeneous?

The solution is to introduce in equation (1) an additional term representing the "accumulation" (embodiment) of exergy into **H** (Fig. 5): such an embodiment can be material (mined ores are transformed into artifacts) and/or immaterial (exergy extracted from **O** is consumed in the production processes). In the additional assumption of a steady rate of accumulation, the third equation of (1) becomes:

$$\dot{E}_{in,H}-\dot{E}_{w,H}-\dot{E}_{acc,H}=\dot{E}_{\delta,H} \tag{2}$$

It is convenient to assume that the biodegradation effort be proportional to the exergy of the waste flows:

$$\dot{E}_b=\kappa\dot{E}_{w,H} \tag{3}$$

Where κ is a function of the respective thermodynamic states of **O** and **H** and of the intensity of the waste flux: $\kappa=\kappa(O,H,\dot{E}_{w,H})$. Equation (2) becomes:

$$\dot{E}_{acc,H}=\dot{E}_{in,H}-\frac{\dot{E}_b}{\kappa}-\dot{E}_{\delta,H} \tag{4}$$

Equation (4) can be used to assess the thermodynamic sustainability of the open system (**O**∪**H**). Some conclusions are:

1) A positive rate of accumulation in **H** is possible if there is a sufficient exergy input $\dot{E}_{in,H}$ from **O**;
2) If $\dot{E}_{in}-\dot{E}_{out}$ remains constant, the admissible rate of accumulation decreases if the biodegradation service requested of **B** increases (larger amount of wastes or higher κ, i.e., more polluting wastes);
3) A higher conversion efficiency on the part of **H** is reflected in a lower $\dot{E}_{\delta,H}$ and results in an increase of the admissible accumulation rate;
4) Combining eqtn. (4) and the first of (1), we obtain:

$$\dot{E}_{acc,H}=\dot{E}_{in}-\dot{E}_{out}-(1+\kappa)\dot{E}_{w,H}-\dot{E}_{\delta,O}-\dot{E}_{\delta,H} \tag{5}$$

Which sets a global upper limit to the accumulation rate $\dot{E}_{acc,H}$.

Eqnts. (1–5) constitute therefore a suitable, albeit still strongly lumped, model for assessing the thermodynamic sustainability of a human society interacting with an open environment. As a demonstration of the validity of such an approach, we shall now derive some global indicators on this basis.

Let us define first an "intrinsic efficiency" of **H** as the ratio of the *useful product* of all processes enacted within its boundaries ($\dot{E}_{acc,H}$) to the total incoming exergy flux $\dot{E}_{in,H}$:

$$\eta_H=\frac{\dot{E}_{acc,H}}{\dot{E}_{H,in}}=1-\frac{\dot{E}_{w,H}+\dot{E}_{\delta,H}}{\dot{E}_{H,in}} \tag{6}$$

And its reciprocal, c_H, an "exergy cost" that measures the exergy Watts needed to produce a unitary rate of accumulation:

$$c_H=\frac{\dot{E}_{H,in}}{\dot{E}_{acc,H}} \tag{7}$$

Both of these indicators are indeed *global*, because they do not explicitly relate to "local" conditions around or within **H**, and also *relevant*, because they provide a quantitative measure of how well **H** "exploits" the exergy flow it extracts from **O**. They also offer a glimpse on how **H** could increase its accumulation capability: by reducing $\dot{E}_{\delta,H}$ (i.e., streamlining its internal processes to reduce dissipation and therefore increase η_H and decreasing c_H) or/and $\dot{E}_{w,H}$ (i.e., reducing the unused portion of $\dot{E}_{in,H}$ released as waste into O, for instance by a more effective recycling).

If we expand our horizon and consider that the environment uses a portion of its exergy supply ($\dot{E}_b$) to buffer the waste it receives from **H**, another measure of the efficiency can be defined:

$$\eta_{H,extended}=\frac{\dot{E}_{acc,H}}{\dot{E}_{H,in}+\dot{E}_{b,O}}=\frac{\dot{E}_{acc,H}}{\dot{E}_{H,in}+\kappa\dot{E}_{w,H}} \tag{8}$$

This appears to be a better global efficiency indicator, because it accounts for the gross exergy input into **H** and includes the "hidden" load placed by **H** on the environment by forcing some biodegradation action. Its reciprocal, the cost $c_{H,ext}$, measures the exergy Watts needed to produce a unitary rate of accumulation including the environmental "service" provided by **B**:

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[7] Boltzmann ("*… The general struggle for existence of animal beings is therefore not a struggle for raw materials – these, for organisms, are air, water and soil, all abundantly available– nor for energy, which exists in plenty in any body in the form of heat, but a struggle for entropy*", [7]) and Schroedinger ("*What an organism feeds upon is negative entropy*", [51]) expressed the same principle in terms of entropy production, which is equivalent to exergy destruction. Lotka [38] used the expression "*consumption of available energy*".

[8] Non-equilibrium is of course not caused only by mobility: in fact, life itself is a continuous interaction among non-equilibrium sub-systems [17,23,24,34].

$$c_{H,ext} = \frac{\dot{E}_{H,in} + \kappa \dot{E}_{w,H}}{\dot{E}_{acc,H}} \quad (9)$$

From a "total system" point of view, though, the useful exergy flux available for the accumulation in **H** is $\dot{E}_{in} - \dot{E}_{out}$, so that a combined system efficiency can be defined:

$$\eta_{H \cup O} = \frac{\dot{E}_{acc,H}}{\dot{E}_{in} - \dot{E}_{out}} \quad (10)$$

Its reciprocal, the cost $c_{H \cup O}$, measures the net exergy Watts needed to produce a unitary rate of accumulation, i.e., a global "production cost":

$$c_{H,ext} = \frac{\dot{E}_{in} - \dot{E}_{out}}{\dot{E}_{acc,H}} \quad (11)$$

The latter indicators provide a global measure of the ability of **H** to interact with **O** so as to exploit a given portion of the overall available "fuel", defined as the difference between the incoming (low entropy) exergy flux and the (high entropy) portion re-radiated by **O**.

The method can be extended to more than one system interacting with **O** and can easily be manipulated to include interactions between several systems $\mathbf{H_1}$, $\mathbf{H_2}$ …: notice that the EIs defined in this way are completely devoid of anthropocentrism and -being time dependent-can be used to assess the evolution of the interplay between systems and the environment and of the state of the combined system $\mathbf{O} + \mathbf{H_1} + \mathbf{H_2}$ etc.

Notice also that a continuously decreasing value of either one of the above efficiency indicators in time (or, which is equivalent, an increase in the costs) signals a situation in which **H** (or indeed the combined system $\mathbf{O} + \mathbf{H}$) may approach a condition of thermodynamic unsustainability: in fact, $\dot{E}_{acc,H} = 0$ is the limit case of "steadiness" (survival with no growth) and $\dot{E}_{acc,H} < 0$ indicates negative growth, an obviously unsustainable condition. Thus, if we could maintain $\dot{E}_{acc,H} \geq 0$ "forever", this would be a sustainable growth. Equation (5) shows that this is not an unattainable limit:

a) $\dot{E}_{in}$ can be increased by, for instance, exploiting deep crust heat sources or installing solar energy converters in the stratosphere (technological challenge), or by importing materials from extra-terrestrial sources (technological quantum jump needed);
b) $(1+\kappa)\dot{E}_{w,H}$ can be decreased either by reducing the amount of waste (recycling) or by recovering its exergy (incineration or chemical treatment: technological challenges);
c) $\dot{E}_{\delta,H}$ can be decreased by improving the system configuration (social & technological challenge) and/or improving the efficiency of the conversion and production processes (technological challenge).

5. EXERGY-BASED indicators

Under this denomination we group all methods based on a model in which resources are quantified by their exergy content. While such a description is perfectly suitable for all primary resources (solar irradiation, water, air and material taken directly from some natural *reservoir* in the environment surrounding the system), exergy *per se* is not a proper quantifier for secondary resources, i.e., resources on which some "work" or "action" has been performed by a system to bring them to the state at which they cross the control surface. Without further justification, and referring the reader to [16,52,53,55,63], we shall assume that the correct measure of the "exergy cost" (i.e., of their total cost of natural resources expended in their transformation from the "state 0" to the state in which they cross the boundary of the system, measured in units of exergy) of such pre-treated resources is their *embodied exergy content*, calculated as the sum of all primary exergy resources that have been consumed (directly and *indirectly*) for obtaining an exergy unit of each secondary resource entering **H.** Quite clearly, the identification of the production chains (the direct one and all of the indirect processes that generated the individual externally manufactured inputs) and the definition of the limits for the *indirect* exergy supply (i.e., the proper identification of the relevant control volume) are crucial issues for this approach. Let us remark in passing that an important merit of exergy methods is that the exergy consumption allocation across bifurcations is assumed to be proportional to the exergy content of each bifurcating flow, which is both thermodynamically correct and convenient in an engineering perspective.[9]

The embodied exergy content of a product or service can be obtained following, for instance, the Cumulative Exergy Content [66], the Thermo-Ecological (or Exergo-Ecological) Cost [65,67,69] or the Extended Exergy [10,53] methods. All three methods maintain that any kind of external intervention that adds or subtracts exergy from a stream before it crosses the control surface can be perfectly and completely accounted for in terms of expended exergy. Since the terms in the balance equation (1) through (5) are completely quantified (and perfectly homogeneous), the expenditures incurred in by performing these external interventions can be algebraically added. Before we examine these methods, mention must be made of a mixed monetary/exergetic analysis procedure, Thermo-Economics (also known as Exergo-Economics), TE in the following.

5.1. Combining natural and monetary capital: Thermo-Economics

In the field of exergy-based cost accounting, the first method proposed to combine the exergy analysis of the production chain of a commodity with the monetary cost balance of each component or process was Thermo-Economics (or Exergo-Economic in the German literature) [20,28]. This branch of Thermodynamics was originally not developed with the specific aim of defining an EI or a set thereof, but rather to support a rational cost allocation over the co-products of industrial plants, or for the engineering optimization of energy conversion systems. Credit for both the introduction of the name and for the theoretical formulation is usually given to Myron Tribus and coworkers, but a substantial amount of previous work on the same topic had been published in East Europe [3,6,21,25,62] and in the US [35]. A more modern formulation was presented by Tsatsaronis and Lin in 1984 [70], and Valero & coworkers finalized what was to become the Structural Cost Theory in their famous 1986 papers [61,75]. This is certainly the form that has enjoyed the widest general applicability, its most remarkable advantage being that of allowing for the inclusion in the proper exergy cost allocation of *Residues* and *By-products* [4,37,61,75] [10]. Thermo-Economics has been finally accepted as an important cost analysis tool, and its applications are published in virtually every issue of well-reputed energy Journals. Since TE arises from

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[9] In a cogeneration plant, for instance, the specific exergy cost of the electricity and of the heat are referred to a unit of exergy of the respective flows. Allocating over a unit of eNergy would underestimate the exergy cost of the heat.

[10] The Structural Exergy Cost theory [61,75] may be considered an extension of Thermo-Economics, because it does not need a monetary basis: its "cost" is a measure of the cumulative amount of primary resources expended in the fabrication of a material good. The similarity with Szargut's CExC is apparent. Notice though that neither method accounts for Labor or Capital.

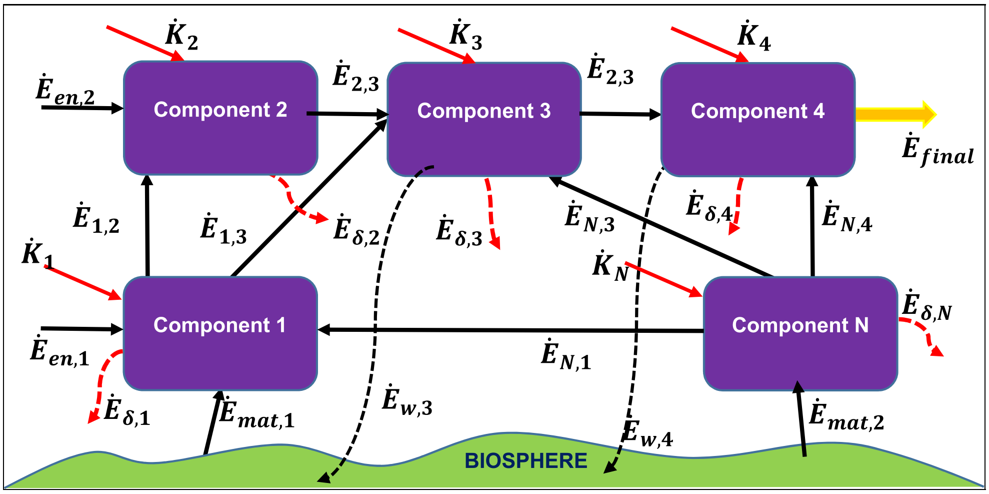

Fig. 6. The control volume for a Thermoeconomic (TE) analysis.

engineering practice, it takes into account capital and maintenance (and labour) costs by converting each exergy flow into its equivalent monetary cost. Thus, the cost per unit exergy of the final product can be obtained by summing the capital and maintenance costs (in form of monetary flows) into the economic balance of all the components involved in the production chain. Its control volume is shown in Fig. 6.

This kind of approach is clearly not-applicable to systems that consist, completely or in part, of biological eco-systems (what is the monetary cost of biomass growth originating from System **O**?): nevertheless, the environmental impact associated with a process can be quantified through a TE approach [78] as a cost function, which represents the required natural resources to obtain its final product, without considering capital and labour costs.[11]

All the above concepts are solidly rooted in the Second Law. Incidentally, the exergy replacement costs that can be computed with a Thermo-Economic analysis provide a measure for quantifying the mineral capital degradation, which is at present systematically ignored in conventional accounting systems.

5.2. EIs calculated via an exergy-based resource consumption analysis

The above sections have presented an overview of the development of exergy-based Ecological Indicators: here, a direct comparison of three well-published methods used to derive them, the CExC, the TEC and the EEC, is presented. The goal of this exercise is that of illustrating the difference between the three EIs, and to assess their commensurability (i.e., the existence of a procedure to convert one into the other).

Let us examine the three procedures separately, with reference to the respective "control volumes" depicted in Figs. 7 (CExC), 8 (TEA) and 9 (EEA) respectively.

6. Model comparison of CExC, TEA and EEA

In this section we examine the intrinsic characteristics of the three methods, with the goal of assessing whether they are in line of principle, commensurable, i.e., if it is possible to identify a paradigm to convert the CExC-based EI (the Cumulative Exergy Efficiency, CEE), for instance, into the EEA-based EI (the Extended Exergy Cost, EEC) and viceversa. For the sake of generality and concision, no specific application is discussed.

6.1. The cumulative exergy consumption analysis, CExC

This method, introduced by Szargut in 1967 [62] and perfected later [63,66,67,77], consists in the analysis of the complete line of production of a material good, from raw materials to the final product: the corresponding control volume is shown in Fig. 7. The rationale of CExC is simple: the exergy expenditure necessary to produce a material good (i.e., the exergy embodied in that good) is equal to the sum of all contributions along the production line, each one measured obviously in terms of exergy. The assumptions are as follows:

a) The raw materials entering the control volume directly from the Environment are attributed an exergy equal to their reference exergy [66];
b) Materials that enter the control volume after having undergone a pre-treatment of any kind are attributed an exergy content equal to their raw value plus all of the exergy expenditures necessary for the pretreatment (i.e., the CExC resulting from an analysis of the pre-treatment process);
c) At each production step, a portion of the incoming exergy flow is rejected to the environment in the form of "byproducts": these flows, be they simple discharges or scrap material (or rejected energy) that may be in principle recycled in different production lines, are collectively denominated $\dot{E}_{w,i}$
d) The incoming exergy flows include both renewable and non-renewable sources;
e) The exergy outflow from production step *i* to production step $i+1$ is considered a "product" of step *i* and a "fuel" for step $i+1$: $\dot{E}_{out,i} = \dot{E}_{in,i+1}$: since the sum of the inputs into component *i* ($\dot{E}_{in,i}$) is in turn the "fuel" for its "product" $\dot{E}_{out,i}$, and $\dot{E}_{out,i} = \dot{E}_{in,i} - \dot{E}_{w,i} - \dot{E}_{\delta,i}$, a "cumulative exergy cost" for the final (*N-th*) product of a technological production line can be defined as:

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[11] In fact, TE cannot be directly applied to ecosystems, for the "production process" of -for example-a cricket (its exergy budget) is not well known in detail. But, when dealing with industrial-societal issues, TE can account for Environmental Remediation costs by introducing an "extra" downstream effluent treatment devices and calculating their influence on the -monetary- production cost.

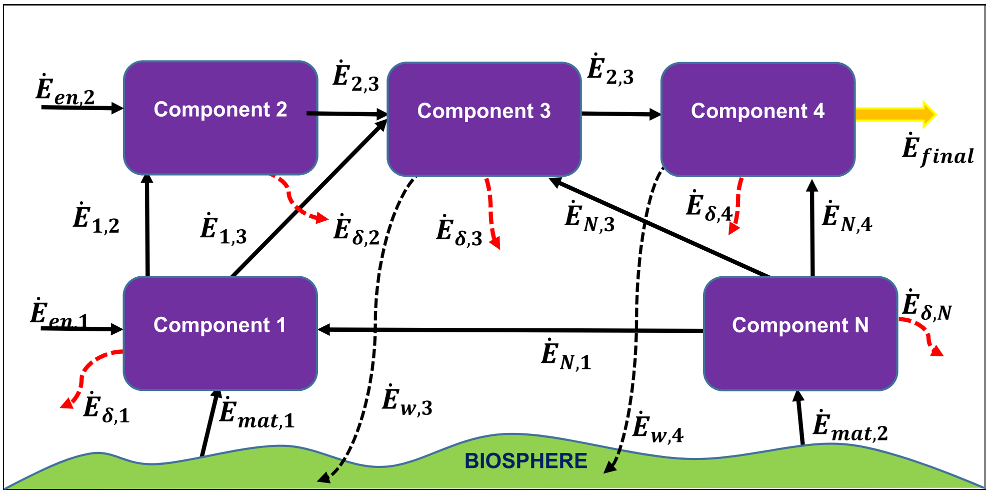

Fig. 7. The control volume for a Cumulative Exergy Consumption (CExC) analysis.

$$cexc_N = \frac{\dot{E}_{in,1}}{\dot{E}_N} = \frac{\dot{E}_{in,1}}{\left[\dot{E}_{in,1} - \sum_1^N \dot{E}_{w,i} - f\left(\sum_1^N \dot{E}_{\delta,i}\right)\right]} > 1 \quad [\mathrm{J/J}] \qquad (12)$$

Where the function $\left(\sum_1^N \dot{E}_{\delta,i}\right)$, a *process structure function*, is used instead of the simple $\sum_1^N \dot{E}_{\delta,i}$ to account for non-linear production chains. It is apparent from the definition that if the same product is generated starting from the very same raw materials via two different technological lines having different amounts of irreversible losses, its *cexc* assumes two different values. Thus, the *cexc* is a genuine measure of the environmental load posed on the primary exergy available in the environment, and therefore a proper EI, whose name reminds designers and energy planners to aim for the optimally feasible reduction of the technological irreversibility in each step of the process. If M kg/yr of a (material or immaterial) good X with a specific exergy e_X [J/kg] are generated each year, the total $CExC_X = cexc^*M^*ex_X$.[$\mathrm{J_{primary\ exergy\ resources}}$/yr]. In the case of multiple products, some proper allocation rules were suggested by Szargut [66].

The CExC does not contain any reference to the monetary circuit of the society in which the plant is located: it is a purely technological EI.

6.2. The Thermo-Ecological Cost analysis, TEA

To include in the CExC a measure of the additional load posed on the environment by the possibly damaging waste flows $\dot{E}_{w,i}$, Szargut introduced in Refs. [63,64] the concept of Thermo-Ecological Cost, TEC: the relevant control volume is shown in Fig. 8. The TEC (Szargut used the symbol ξ) is defined as the additional primary exergy consumption due to the emissions of the production line. For an arbitrary process ***S*** and for a certain pollutant *k*, the TEC is defined as:

$$TEC_{S,k} = \frac{B_S\sigma_k}{\left[DCP + \sum_1^K\left(\dot{P}_k\sigma_k\right)\right]} \quad [\mathrm{J/kg}] \qquad (13)$$

Where B_s is the yearly consumption of non-renewable exergy resources in the "immediate surroundings" of **S** [W]; *DCP* is the monetary value of all final products used in the Domestic Sector [€/s] (but NOT in the Production sector); P_k are the emissions of the *k-th* substance in the country [kg/s] and σ_k is the monetary index of harmfulness of the *k-th* pollutant [€/kg]. The TEC thus measures the average cost in terms of primary exergy caused by the pollution generated by **S** in the country where it is located. For example, if the only emission is CO_2, the total cost (CExC + TEC) for M kg/yr of a good X produced becomes

$$M\left(cexc^*ex_X + TEC_{S,CO2}\right) = \frac{\dot{E}_{in,1,S}}{\left[\dot{E}_{in,1,S} - \sum_1^N \dot{E}_{w,i,S} - f_S\left(\sum_1^N \dot{E}_{\delta,i}\right)\right]} + \frac{B_S\sigma_{CO2}}{\left[DCP + \dot{P}_{CO2}\sigma_{CO2}\right]} \qquad (14)$$

The calculation of the TEC is much more difficult than that of the CExC: additional, strongly disaggregated data are needed for the total consumption of the Domestic sector, for the total emission of each pollutant in the country, and for the monetary index of harmfulness σ of each pollutant. In his original formulation, Szargut adopted the legislative pollutant taxation values, but he also maintained that a more rational value for σ may be obtained by an iterative application of the TEA method.

6.3. The Extended Exergy Accounting method, EEA

The EEA method, first presented (in Gliwice [52]) and refined in subsequent papers [10,53,54], is based on the idea that the Externalities can be assigned "equivalent exergy values", under a set of assumptions derived from an exergy budget of the region in which the process is located. The assumptions are:

a) The exergy "inflow" consists of both renewable and non-renewable exergy inflows in the region, plus the "imported" exergy flows (fossil fuels and ores, material and immaterial goods), be they imported from other regions or from the Environment;
b) An "extended exergy" is defined as the equivalent exergy flow to each production factor: $EE_{energy} = Ex_{energy}$; $EE_{material} = E_{material}$;
c) A portion of this total exergy influx is "used" by the population (included conventionally in the Domestic sector) to survive and grow. This portion is called *extended exergy of*

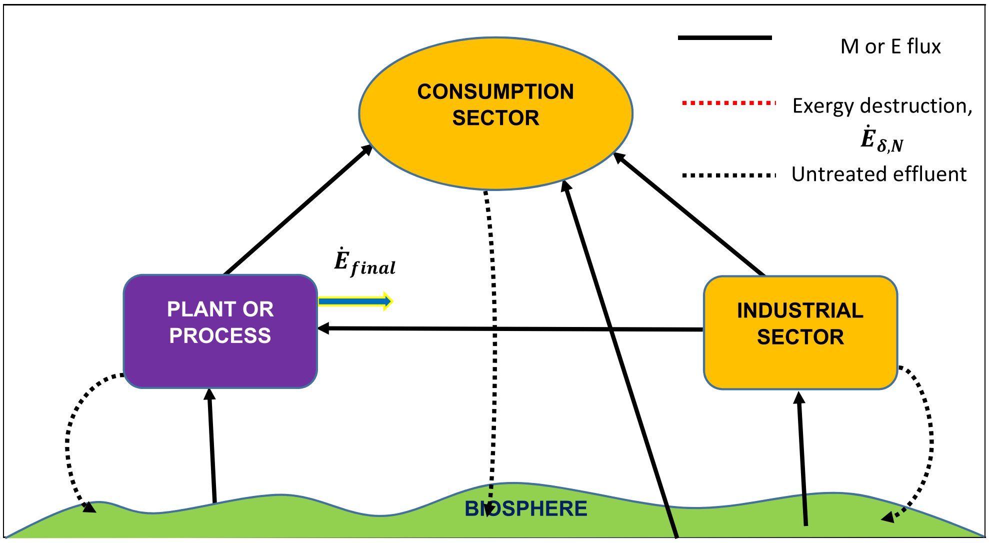

Fig. 8. The control volume for a Thermo-Ecological (TEA) analysis.

Labour, $\dot{EE}_L$ and is set equal to $\alpha\ \dot{E}_{in}$, $\alpha < 1$ being an econometric coefficient external to the theory that must be derived from the global exergy budget of the Country [52,53];

d) The monetary circulation in the Country, M€, is converted into another extended exergy flux, called the Extended Exergy of Capital, $\dot{EE}_K = \beta \dot{EE}_L = \alpha\beta\dot{E}_{in}$. The econometric coefficient β is also external to theory and its numerical value can be calculated on the basis of labour data relevant to the Country under examination [53,54] [12];

e) All EE forms are homogeneous and enjoy the additive property;

f) On the above basis, it is possible to calculate the specific extended exergy of Labour ee_L [J/workhour] and of Capital ee_K[J/€]. These quantities represent the amount of primary exergy resources needed to generate 1 workhour and 1 monetary unit respectively;

g) The Country (or region) in which the process is located is subdivided in 7 Sectors: Domestic (DO), Extractive (EX), Conversion (CO), Industrial (IN), Transportation (TR), Tertiary (TE) and Agricultural (AG). Most of these Sectors exchange fluxes of extended exergy, in its different forms, with other sectors, with the environment and/or with another conventional -fictitious- system called “Abroad” that accounts for the import/export;

h) When considering a single process **S**, its extended exergy influxes may come from any of the above sectors; in particular, $\dot{EE}_L$ is assumed to be originated only in DO, and $\dot{EE}_K$ in TE. The imported commodities are handled through TE.

Once the above quantities are known, the CExC procedure is applied, resulting in a specific extended exergy cost, ee_c [$J_{primary\ exergy}/kg_X$] that reflects the total amount of primary exergy resources consumed for the production of 1 unit of product X. The control volume for EEA is shown in Fig. 9.

To calculate the Environmental externality, EEA adopts a remediation approach (Fig. 10): to eliminate (or reduce below the regulated limits) the emission of m_k [kg/s] of pollutant k, a (fictitious or real) process is inserted downstream of **S** that uses additional primary exergy to reduce the concentration c_k to its limit value (c_{k0} or $c_{k,regulated}$) before discharging the exhaust into the environment. This additional consumption (per unit of product of ***S***) consists of materials ($\dot{EE}_M$), energy ($\dot{EE}_E$), labour ($\dot{EE}_L$) and capital ($\dot{EE}_K$): the normalized sum of these quantities, denominated ee_{ENV} is added to the ee_c.

The calculation of the ee_c requires a similar data mining effort as the TEC: disaggregated data are needed for each Sector, for the feasible technical treatment of each pollutant, and for the econometric coefficients α and β. Procedures to calculate the econometric coefficients in terms of monetary and statistical employment data are reported in Refs. [5,12,22,29,49,53,59].

For the sake of comparison, consider that for a process that produces M kg/yr of a good X and emits m kg of CO_2 per unit of product, the ee_c is:

$$ee_{c,X} = ee_M\dot{M}_X + ee_E\dot{E}_X + ee_L\dot{W}_X + ee_K\dot{K}_X + ee_{ENV}\dot{m}_{X,M,CO2} \tag{15}$$

In the case of multiple products, proper allocation rules are suggested in Refs. [53,56]: they are basically the same as those adopted in TEC, but the structure of eqtn. (15) allows for a more detailed (disaggregated) account for the individual contributions (Labour, Capital and environmental remediation cost), thus making the allocation easier. A perusal of eqtns. (11) and (12) makes it perfectly clear that the numerical values emerging from the calculation of the $cexc + tec$ and ee_c are incommensurable: in fact, they not only differ numerically, but cannot be consistently rescaled, because:

A – The RHS of eqtn. (15) contains terms ($\dot{EE}_{L,X}$ and $\dot{EE}_{K,X}$) that are not included in eqtn. (13);

B – The calculation of the environmental externality is performed according to two completely different criteria.

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[12] A critical remark often raised against EEA is that EE_L and EE_K “bring back”, so to say, social and economic issues into the model. They indeed do so, but in a rigorous thermodynamic way, because both quantities are calculated in primary exergy equivalent consumption by means of the two econometric coefficients α and β that are external to the theory and must be derived from statistical Labor and Monetary data of the Country in which the analysis is performed.

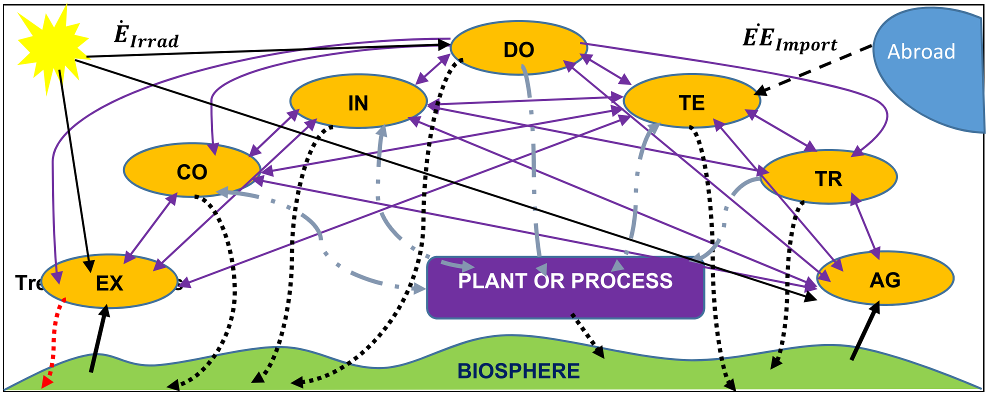

Fig. 9. The control volume for an Extended Exergy Accounting (EEA) analysis. Legenda: ——Primary exergy flux; ——Infra-sectorial flux; ------Imports; ⋯⋯⋯Exergy destruction; ⋯⋯⋯Treated effluents.

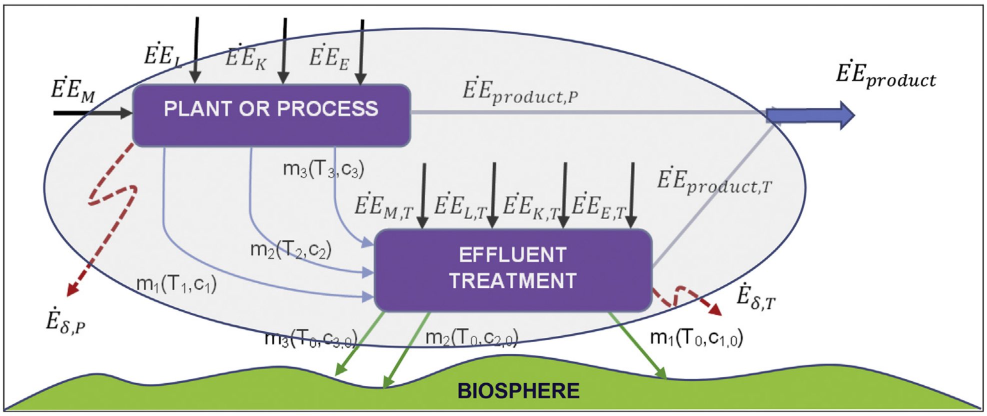

Fig. 10. Illustrative sketch of the procedure for the calculation of EE$_{env}$ in EEA. $\dot{EE}_{product} = \dot{EE}_{product,P} \pm \dot{EE}_{product,T} + \dot{EE}_{M,T} + \dot{EE}_{E,T} + \dot{EE}_{L,T} + \dot{EE}_{K,T}$

7. Are exergy-based indices proper environmental indicators?

The original question implicitly posed by this paper is whether the models used to derive exergy-based EIs can also be adapted to the assessment of the “degree of sustainability” of a resource-into-final goods conversion line (or society). The above discussion demonstrates that all three numeraires examined here are formulated in such a way as to express a measure of the “environmental load” placed on system ***O*** by activities originating in ***H***. They may obviously differ in the measuring stick they use to quantify this load.

By critically combining and integrating the lists of the most relevant properties of an EI compiled in Refs. [13,48,56], a list of necessary properties of an EI can be compiled:

a) The EI must be expressed by a -possibly simple-numeric or alphanumeric expression and produce results that can be unambiguously ranked within two opposite limits (“bad/good”, “high/low”, “desirable/damaging”, “standard/exceptional”, etc.);
b) The EI must be calculated on the basis of intrinsic properties of both the community (the system that it refers to) and of the (local or global) environment;
c) The EI must be normalized in some sense, so that it may be used to compare different communities or different environmental conditions, or else different scenarios and/or time series for the same community;
d) The EI must be calculated on the basis of an unambiguous, reproducible method under a well-defined set of fundamental assumptions;
e) The EI must comply with the accepted laws of physics.

Clearly, CExC, TEA and EEA satisfy the above requirements and can therefore be labelled as “Global EIs”. What are then their intrinsic differences? Consider the reasonably realistic “sustainable” scenario described by the following assumptions:

i) Each single component of the process (or society) is optimized so as to be affected by the minimum attainable degree of irreversibility: $(\sum_{1}^{N} \dot{E}_{\delta,i}) = min$; the sum of the exergy destructions extended to all components (or sectors) is the smallest one possible with the current technological level;
ii) The configuration (connectivity) of each conversion process is optimized so that the propagation of irreversibility from one component to the other is also minimized: $f_s(\sum_{1}^{N} \dot{E}_{\delta,i}) = min$;
iii) Each emissions k of each process (including all of the rejected flows $\dot{E}_{w,1,S}$) is conveyed to a treatment plant that reduces its temperature to $T_0 + \varepsilon$ and its concentration to $c_{0,k} + \Delta c_{kb}$, ε being a small quantity (e.g., 3–5 K), c_{0k} the standard concentration of k in the environment and Δc_{kb} the buffering capacity of the environment for k.

Under the above scenario, eqtn. (14) simplifies to:

$$M(cexc{*}ex_X + tec_{S,k}) = \frac{\dot{E}_{in,1,S}}{\left[\dot{E}_{in,1,S} - \sum_1^N \dot{E}_{w,i,S} - f_S\left(\sum_1^N \dot{E}_{\delta,i}\right)\right]} + \frac{B_S\sigma_k}{\left[DCP + \dot{P}_{CO2}\sigma_k\right]} \qquad (16)$$

Because the term I is completely offset by the environmental buffering (that requires only renewable resources), term II is minimal and term III is zero because no non-renewable resources are used to reduce the potential ecological damage. Thus, the cumulative exergy consumption attains its minimum value.

Eqtn. (15) becomes:

$$ee_{c,X} = ee_M\dot{M}_X + ee_E\dot{E}_X + ee_L\dot{W}_X + ee_K\dot{K}_X + ee_{ENV}\dot{m}_{X,M,k} \qquad (17)$$

Here, both IV and V reach their minima, the former because irreversibility is minimized within the system and the latter because the posited assumptions minimize ee_{ENV}. Of consequence, the extended exergy cost attains its minimum value.

Equations (16) and (17) demonstrate the merit of both approaches. Both TEC and EEA allow for the quantification of the primary exergy consumption in a given production line (or, cumulatively, in a given society), but they also result in EIs that have the proper limit behaviour, in the sense that display a minimum for a “totally renewable and recycling” society. Furthermore, neither minimum is zero, which is an unwelcome but rigorous consequence of Second Law.

The two minima are though expressed by different numerical values, and they cannot be transformed one into the other by a rational formula.

8. Conclusions

a) Exergy Analysis of complex systems can be formulated in such a way as to attribute a realistic and thermodynamically correct primary resource equivalent to any kind of flux, thus relating irreversibility to unsustainability;

b) Reversibility (i.e., absence of exergy destruction, an ideal case) is a sufficient but not necessary requirement for thermodynamic sustainability: in any real, “open” system it suffices for a conversion process to use renewable resources at a rate lower than their replenishment rate [57];

c) Both TEA and EEA make use of the concept of “embodied exergy”[13] to quantify the amount of primary resources consumed to produce a certain commodity. Their respective calculation methods for the Environmental externality are substantially different and cannot be reconciled;

d) EEA incorporates the Labour & Capital contribution to the “upgrading” of the exergetic fluxes in a production system, on the assumption that both contain a substantial amount of *embodied exergy*, which has been accumulated in the course of the process of formation and development of both people (education, sustainance, etc.) and society (government, structures and infrastructures, trading, life-supporting systems, etc.). TEA lumps the Labour contribution into the general Production/Consumption balance, and neglects the Capital production factor. These are additional reasons for their numerical values being incommensurable;

e) Both TEA and EEA are legitimate EIs, and both can be used to express the degree of sustainability of a process or society.

As a final remark, it must be added that recent attempts to link, in Lotka's line of reasoning, the dynamics and the statistically relevant behaviour of a population to thermodynamic principles [44,57,58] are still at a preliminary stage and need to demonstrate accurate and conclusive results to allow for their generalized application: they are therefore ignored in the discussion that is based solely on EIs of the global type.

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