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The Thermoeconomic Environment Cost Indicator ($i_{ex\text{-}TEE}$) as a One-Dimensional Measure of Resource Sustainability

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Abstract: This paper presents a conceptual development of sustainability evaluation, through an exergy-based indicator, by using the new concept of the Thermoeconomic Environment (TEE). The exergy-based accounting methods here considered as a background are Extended Exergy Accounting (EEA), which can be used to quantify the exergy cost of externalities like labor, monetary inputs, and pollutants, and Cumulative Exergy Consumption (CExC), which can be used to quantify the consumption of primary resources embodied in a final product or service. The new concept of bioresource stock replacement cost is presented, highlighting how the framework of the TEE offers an option for evaluating the exergy cost of products of biological systems. This sustainability indicator is defined based on the exergy cost of all resources directly and indirectly consumed by the system, the equivalent exergy cost of all externalities implied in the production process and the exergy cost of the final product.

Keywords: resource sustainability; exergy; exergy cost accounting; exergy cost of biological resources

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1. Introduction

It can be noted that an effort is under development in the literature to define resource sustainability indicators based on thermodynamic quantities, in particular on exergy. Exergy is widely recognized as a proper tool for evaluating the resources required by energy systems [1–5] or by technological production systems in general [6–11]. In addition to the basic exergy analysis, an exergy cost accounting must be implemented [12–15]. When dealing with complex, multi-component, energy systems with both direct and indirect exergy consumption, exergy cost accounting is required for obtaining a certain product flow. Furthermore, when the goal is to assess the impact or the sustainability of the production system, the actual primary exergy resources directly and indirectly available for the production system itself must be considered. The expectation is that an exergy-based sustainability indicator could encompass, in a one-dimensional figure, various aspects of sustainability, or even all of them.

This paper first summarizes different exergy-based cost accounting approaches presented in the literature, highlighting the effort to include in the analysis a progressively more complete picture of the indirect effects and externalities of the production process, which may affect the sustainability of the process itself. Then, an extension of the previous cost accounting method is presented, based on the concept of TEE. This is a consistent ultimate boundary of exergy cost accounting, where various exergy reservoirs of limited content are immersed in the zero-exergy matrix, as shown in Figure 1, but they remain separated from it because of some confinement constraints. Starting from this very simple but meaningful framework, the concept of bioresource stock replacement (BSR) cost is precisely defined, allowing the exergy cost evaluation of all biological resources used as production process inputs. Introducing the concept of the BSR cost does not need any arbitrary hypothesis, or cost allocation rules not consistent with the input/output framework [16] that is a characteristic of the great majority of the cost accounting approaches presented in the literature. Moreover, it is consistent with the replacement cost of mineral resources presented recently by Valero and Valero [17], as an extension of the thermoecological cost introduced by Szargut [15,18]. Finally, the Thermoeconomic Environment Cost (TEEC) is presented, and, on this basis, a new exergy sustainability indicator is easily defined, and its potential as a one-dimension measure of resource sustainability is discussed.

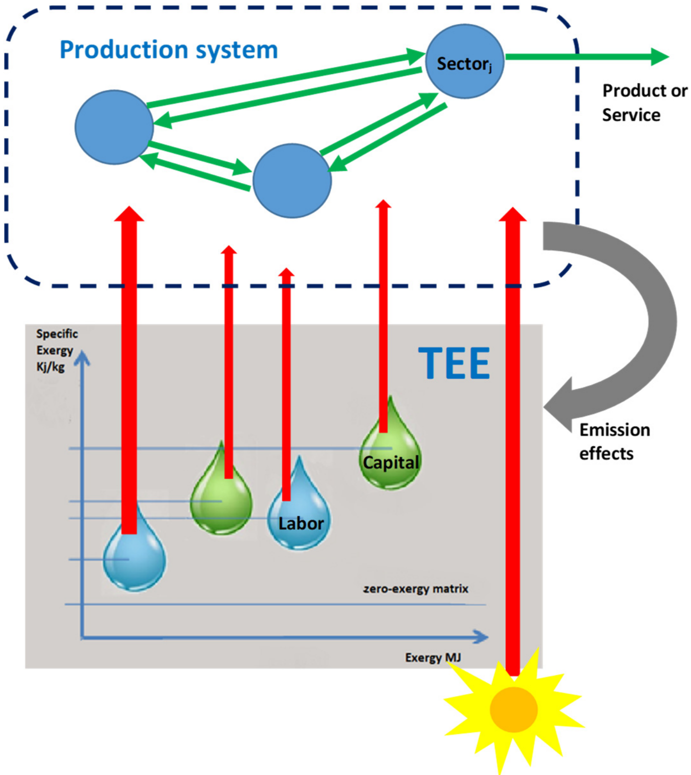

Figure 1. A qualitative representation of the flows involved in the TEEC evaluation.

An Outlook to Some Sustainability Indices in the Literature

A critical summary of the previous effort for identifying exergy-based sustainability indicators can be found in Kharrazi et al. [19], where the authors highlight the limitations of two approaches based on thermodynamics in defining a proper sustainability index: Emergy Synthesis and Exergy Analysis. In particular, agreeing with Kharrazi et al., the sustainability index proposed by Emergy Synthesis [20,21] allows us to highlight important measurements of sustainability, but it does not consider any limit to the minimization of input emergy consumption, implicitly assuming that a reduction is always possible and desirable, as is a wider usage of renewable resources. In addition, the emergy sustainability index is defined as a ratio [21] where the product of the yield and the input renewable resources is the numerator, whilst the sum of the capital invested plus the input non-renewable resources, both multiplied by the capital invested, is the denominator. The reasons for such a definition are not immediately evident. Moreover, its physical meaning is not clear, beyond the idea that a higher product yield and a higher renewable input at constant non-renewable and capital resource consumption is a more sustainable condition for a certain system.

Kharrazi et al. [19] also recognize that recent methods based on exergy cost accounting (like the EEA [22–25]) attempt to unify capital investment, human labor, and environmental resources into a common exergetic description. Nevertheless, they note that, in the exergy literature, no sustainability index similar to the one defined by the Emergy Synthesis model have been presented. In fact, the latter not only considers the strict (and arbitrary) control volume of the analyzed system but also attempts to consider the direct and indirect effects of system activities. On the other hand, emergy cannot be obtained from a straightforward input-output approach. Instead, a peculiar algebra must be used, which implies a non-conservative nature of the emergy itself.

Various exergy indexes claim to express sustainability [26], but they mainly relay the exergy efficiency concept without prescribing a specific control volume or a pre-defined origin of the supply chains that feed the considered production process or component. This is the case, for instance, of the Depletion number (D_P) and the sustainability index (SI) shown by Rosen [27]. D_P is the complement to one part of the exergy efficiency model, and SI is the inverse, i.e., they convey the same information as the exergy efficiency model itself.

A different definition of the exergy sustainability index is used in [28], as the ratio of the exergy of the products and the exergy content of waste flows. Another index was defined by Dewulf et al. [29] as the fraction of renewable energy in the total input (named the exergy renewability indicator) and the ratio of the input exergy and the sum of the same input exergy plus the expected exergy consumption for a complete abatement of harmful wastes from the process (named the environmental compatibility).

All these indices do make sense, but the direct and indirect effects of system activities, outside the control volume of the system itself are not systematically investigated, they are simply supposed to be proportional to the exergy of some input or output flow.

In the following, the most relevant properties expected in a sustainability index are presented by critically combining and integrating the requirements highlighted in [30–32]:

a. It must be expressed by a—possibly simple—numeric expression and produce results that can be unambiguously ranked within two opposite limits.
b. It must be calculated based on intrinsic properties of both the process (the system that it refers to) and of the (local or global) environment.
c. It must be normalized in some sense, so that it may be used to compare different systems, different environmental conditions, different scenarios and/or different time series for the same community.
d. It must be calculated based on an unambiguous, reproducible method under a well-defined set of fundamental assumptions.
e. It must comply with the accepted laws of physics.

2. Exergy Cost Accounting for Assessing Sustainability

Generally speaking, when dealing with complex, multi-component, energy systems with both direct and indirect consumptions for obtaining a certain product, an exergy cost accounting must be implemented besides the basic exergy analysis. Exergy cost accounting definition requires:

a. cost allocation rules input/output algebra by Leontief [16] are widely accepted, but other cost allocation rules may be found in the literature [13,33,34].
b. clear limits for the control volume, where the start of the exergy supply chains of the system is located, and where the unit exergy costs of all inputs crossing the limits must be known [35].

Some other additional conditions must be considered to use exergy cost as a sustainability indicator. The actual primary exergy resources must be identified, and the exergy cost of polluting emissions must be evaluated. There is wide agreement about cost allocation rules and in practice, all exergy-based costs must be allocated to the product. There is still some investigation to avoid what is called double accounting when a multi-products system must be analyzed or some other constraints occur. The conservative nature of the cost flow through the energy conversion system is important if the aim is to quantitatively evaluate the impact on the primary resources of goods or services, and not to obtain only meaningful indicators. Moreover, to assess sustainability, it is important to indicate the impact affecting the resources available at the present moment, not in the distant past time, so the time scale must be defined properly. Even if the cost allocation rules are defined and consistent with conservative cost balances of all control volumes, the ultimate boundaries play an important role in exergy cost accounting and must be consistent with assessments of the impact in primary exergy resources of a product and service. The reference environment used in the basic exergy analysis cannot be identified with these ultimate boundaries of the exergy cost accounting analysis [36]. Because it is perfectly homogenous, its temperature and pressure cannot be modified, and it cannot be affected in any way by its interaction with the production system being considered.

If the goal is to assess sustainability, and not merely to obtain a rational comparison among products or technologies, the additional conditions may be summarized as:

a. The actual primary exergy resources must be identified, considering both renewable and non-renewable resources.
b. The impact affecting the resources available at the present moment, not that in a distant past time, must be assessed.
c. All exergy costs related to polluting emissions must be evaluated, besides the exergy costs of the inputs.

It must be recognized that the EEA defined by Sciubba [22–24,37] has achieved an important advance in this direction. It measures the amount of primary exergy absorbed by a system throughout its life cycle, without any special attention to biological resources, which are accounted-for in their exergy content. In addition to material and energy flows received directly and indirectly from nature (where all the supply chains start), EEA includes externalities for capital investments, human labor and polluting emissions, the latter being calculated on a remediation basis, similarly to Dewulf et al. [29]. The exergy cost of the products, as well as the exergy efficiency of a process or a region [38,39] calculated through the EEA approach, are certainly not limited to the only strict (and arbitrary) control volume of the analyzed system.

2.1. Definition of the Thermoeconomic Environment (TEE)

The TEE was introduced as a consistent ultimate boundary for the exergy cost accounting, with the following objects [40]:

- Overcoming the drawbacks of the reference environment used in basic exergy analysis. Some of these drawbacks are that the reference environment has no resources of energy or raw materials that are required to be consumed to obtain a specific process or product. The reference temperature cannot be modified, which means that some phenomena, like global warming [41], cannot be accounted-for. In addition, the reference environment is not affected by any polluting emissions from the production system.
- Defining a framework consistent with the formulations of CExC [42] and EEA.
- CExC and EEA are milestones of the effort of including in the exergy accounting analysis a progressively more complete picture of the indirect effects and externalities of the production process. Some of the ideas developed in those approaches will be used in the following to define the proposed sustainability indicator.
- Suggesting new options for a consistent exergy cost definition of all resources. As will be evident in the following, the framework of the TEE may help the definition of a proper exergy cost for the effect of polluting emissions from the production process, or for the indirect destruction of resources, including living biomass.

The TEE is defined as a set of reservoirs, where different kinds of natural resources are confined. All of them are surrounded by the zero-exergy matrix (the dead state). Each available resource has a specific exergy content greater than zero, as shown in Figure 2.

From the previous definition, it can be easily inferred that the TEE is not too big to be modified by the interactions with the production processes because the amount of exergy in each reservoir is limited and because the confined conditions of the reservoirs can be compromised. In addition, to consider some real-world phenomena like the periodic oscillations of the availability of solar energy or global warming, which is increasing as a consequence of GHG emissions, it must be recognized that even the zero-exergy matrix may change its temperature T° and composition.

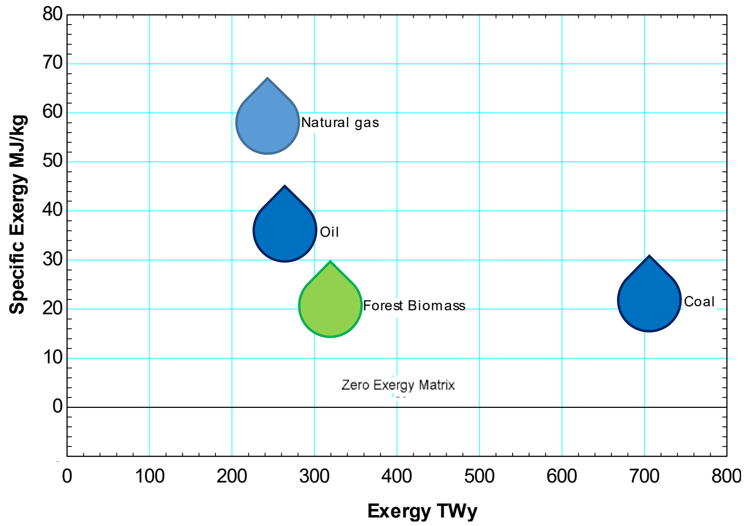

Figure 2. A partial semi-qualitative representation of the TEE.

2.2. *Chemical Exergy Calculation*

The zero-exergy matrix can be defined as the reference state model introduced by Szargut [43,44]. It is based on the identification of a set of reference substances whose specific chemical exergies can be determined as concentration exergy with respect to an ideal mixture of gas at T°, P°. The chemical exergies of all other substances in the TEE can be calculated by considering reversible chemical reactions. In this way, crude fossil fuels and other mineral resources are not obtained as confined inside reservoirs, but they may be better regarded as obtained all together, i.e., mixed in a condition that may be identified as the Thanatia planet introduced by Valero and Valero [17]. Notice also that additional exergy must be consumed to obtain the resources in a confined way, as they are found in real-world mines or as they are regarded as being inside the TEE.

The specific exergy costs of each available resource inside the TEE are the basis of the accounting: the specific exergy costs of each reservoir may be considered equal to 1, consistent with the hypotheses of the EEA and CExC models. This expresses the idea that a certain exergy stock of non-renewable resources is available in the TEE at the present moment, together with a set of exergy flows of renewable resources (including the renewable parts of all partially renewable reservoirs).

2.3. *The Exergy Cost of Mineral Resources*

If the dynamic process allowing exergy accumulation inside the reservoirs can be neglected, the assumption of the specific exergy costs of each reservoir being equal to 1 may be correct even if a larger amount of exergy was required in the distant past. For instance, this may have been the case when the accumulation process was very slow compared with the duration of the considered production process, such as in the case of natural fossil fuel, or other mineral reservoirs.

On the other hand, if a non-negligible dynamic exists inside the TEE, exergy extraction from a certain reservoir may produce additional exergy destruction in other reservoirs. In this second case, two options can be identified:

- To extend the supply chain describing the indirect consumption of resources.
- To define a set of unit exergy costs, not equal to one, which is regarded as equivalent to the mechanism of additional exergy resource destruction.

In 2011, [45,46] Valero introduced the exergy replacement costs (ERC) and the model of Thanatia to assess the concentration exergy of mineral resources based on their scarcity in nature [17].

In the TEE language, the proposals by Valero and Valero may be re-formulated by stating that, in the Thanatia planet, the confining constraints of all reservoirs were destroyed, all minerals are mixed, and they have all reacted with the zero-exergy matrix. Then, the ECR is the exergy required to produce a reservoir of a certain mineral resource, from the conditions defined for the Thanatia planet, by using real-world, irreversible technologies, as shown in Figure 3. This methodology was introduced to assess the concentration exergy of mineral resources based on their scarcity in nature. The combination of the ERC concept with the Thermo-Ecological Cost method (TEC) originally proposed by Szargut, allows us to assess products considering the exergy associated with the consumption of non-renewable resources extracted directly from nature, taking their scarcity into account.

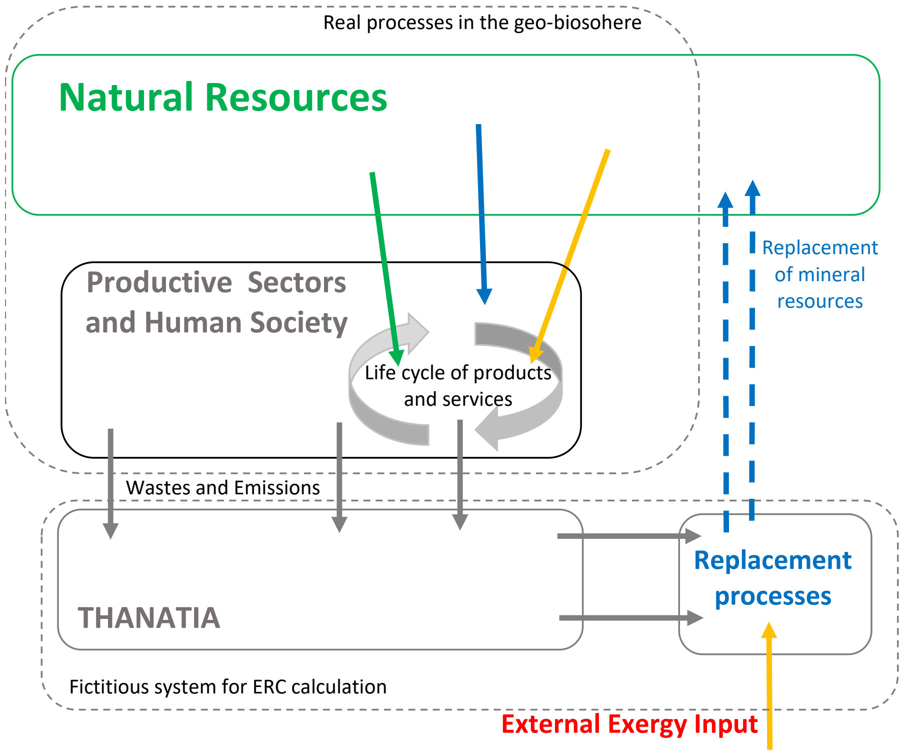

Figure 3. Cradle-to-grave-to-cradle process for calculating the exergy replacement cost (ERC).

The only exergy input external to the geo-biosphere is solar energy (and possibly tidal and geothermal energy). Therefore, the ERC can be properly understood as the cost that should be paid to consider a non-renewable resource as if it were completely renewed using solar energy, i.e., as if it were renewable on a human time scale, like solar energy itself. It is worth noting that this interpretation makes the ERC of mineral resources and renewable energy in the input of a generic production process homogeneous, so that they may be added together without inconsistency.

2.4. *The Exergy Equivalent of Capital and Human Work*

In the EEA, externalities can be assigned "equivalent exergy values", under a set of assumptions [25,47]. The more recent proposal by Rocco and Colombo [48] may be regarded as an attractive alternative, since it was directly derived from the input/output algebra by Leontief [8]. In this approach, the interactions among the sectors of the whole production system are described by the monetary magnitudes usually adopted in the economic analysis. Then, the exergy evaluation of each flow in the model is obtained by considering the exergy of all the inputs coming from the environment and feeding the sectors (the nodes) of the production network. In this way, the exergy equivalent of capital has not been evaluated explicitly and, if it is evaluated a posteriori, the result may be different for the different production sectors considered.

As far as the exergy evaluation of human work is concerned, the approach suggested by Rocco and Colombo [48] is a direct extension of their exergy input/output analysis. The human labor production sector is embodied as an additional sector, without the need for any arbitrary assumptions, as schematized in Figure 4. This sector supplies the required human labor to all the others (only two big sectors, final goods production, and intermediate goods production are shown in the Figure) and receives from the final goods production sector all the necessary inputs for human labor production. Obviously, additional information, such as the quantitative evaluation of the inputs required by the human labor activities from each one of the other sectors and, the human working hours required by each of them, is required.

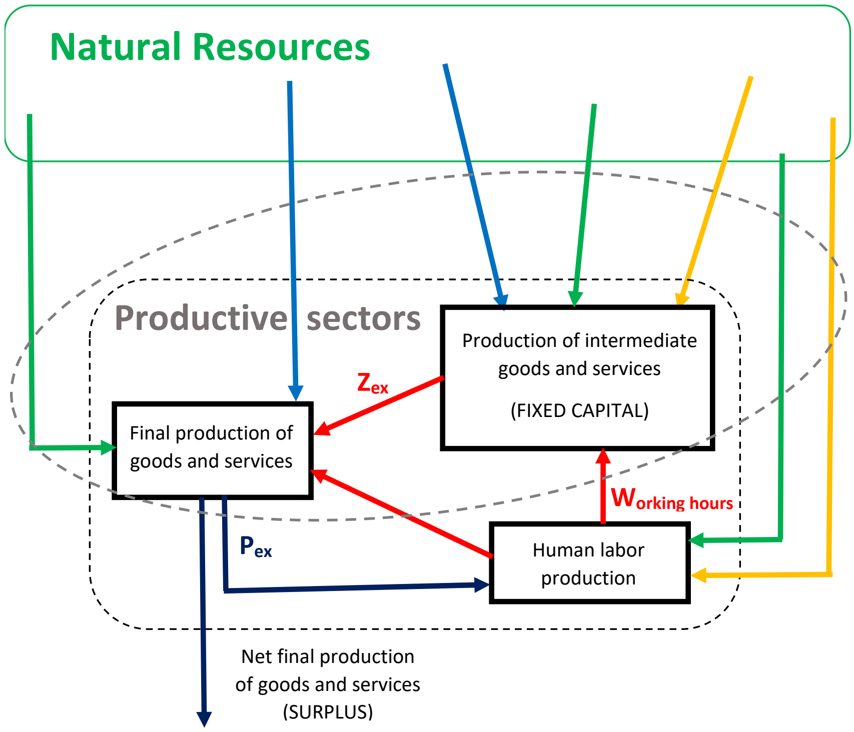

Figure 4. Schematic of the sub-system introduced by Rocco for the internalization of human labor in embodied energy analysis. Adapted from [41].

2.5. The Exergy Cost of Products of Biological Systems

The frame of the TEE offers an option for evaluating the exergy cost of products of biological systems. As shown in Figure 5, a fictitious extension of the system, with the function of replacing the stock of the bioresource reservoir, was considered analogously with the replacement processes considered in the definition of the ERC of mineral resources. The object is to stay as close as possible to the latter methodology. Unfortunately, the ultimate waste produced by the use of biological substances include carbon dioxide, water, and very few other elements, so the replacement processes of the original resources (forests, agriculture fields, ecosystems, etc.) cannot be defined based on actual technology. The methodology is then adapted as follows.

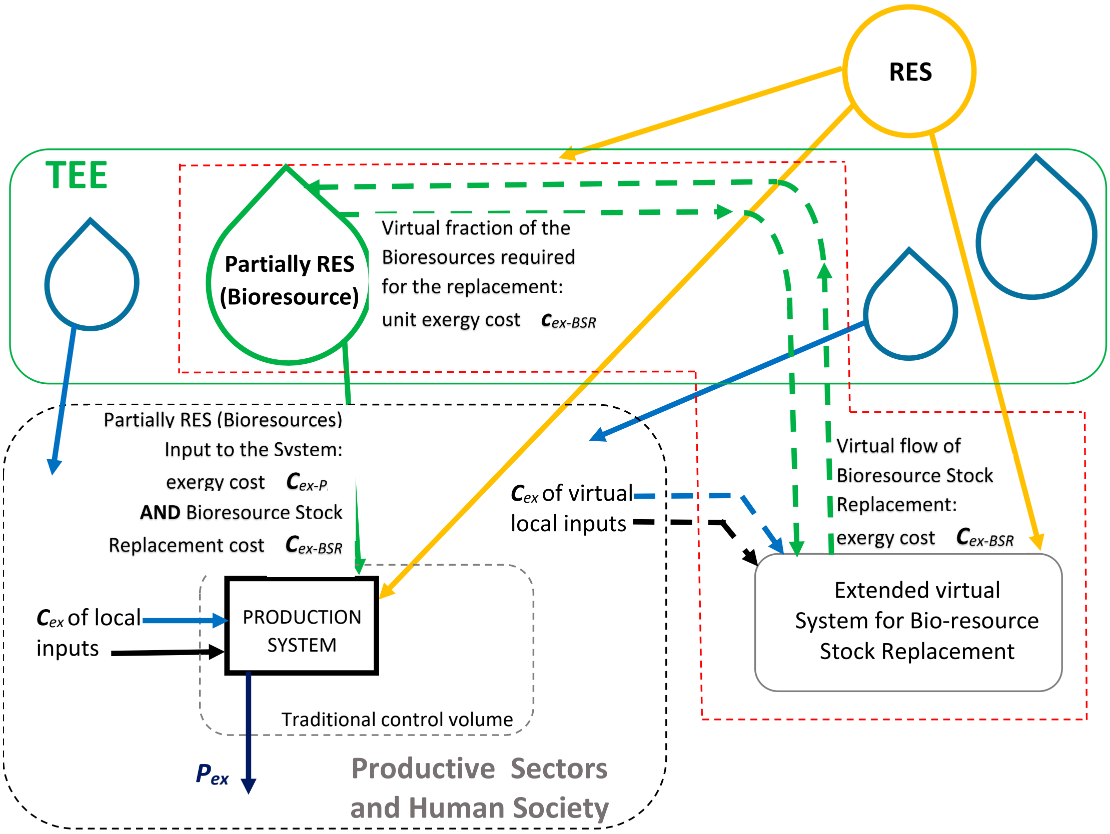

Figure 5. The concept of bioresource stock replacement cost.

If the bioresource is consumed (or indirectly destroyed) at an extraction rate (β) lower than its natural growth rate in the reservoir (α), the stock is not affected, and the input to the production system is regarded as completely renewable (specific exergy costs equal to 1). If instead the extraction rate is greater than the growth rate ($\beta > \alpha$), the fictitious extension of the system must cultivate the ecosystem to replace the original stock. The BSR cost (C_{ex-BSR}) can thus be calculated because all the input costs of the extension of the real system are known:

- Solar energy and other renewable resources have a unit exergy cost equal to one.
- All non-renewable resources can be evaluated at their exergy cost, including indirect consumption and the ERC of the mineral resources.
- The capital and human work can be evaluated at their exergy equivalent, via one of the methodologies previously outlined.

Notice that even a fraction (ρ) of the bioresources considered must be virtually extracted to be used as an input to the extended system for bioresource replacement. This is because the living substance cannot be obtained from the products of the economic sectors with actual technologies without using some living input. The unit exergy cost of this flow must be regarded as the same as the BSR, without introducing any problem in the calculation of the latter, based on the usual rules of exergy cost accounting. This assumption is equivalent to considering a bifurcation of the virtual flow of BSR into two parts, one for the actual replacement and one for recirculating the input required by the virtual system. This cost allocation rule in bifurcating flows must be regarded as a well-consolidated result in the field of Thermoeconomics [49]. Moreover, it can be easily noted from Figure 5 that the BSR cost can be inferred from the cost balance of the sub-system inside the dotted red line, without the need to explicitly know the cost of the bioresource recirculated as an input to the virtual system. In fact, the unit cost of the bioresource consumed by the production system, disregarding the stock replacement, is known to be is equal to its chemical exergy (consistently with EEA).

It is worth noting that, if the extended system for BSR is considered, the differential equation governing the bioresource stock decline (Equation (1)) is replaced by differential Equation (2):

$$\frac{dM}{dt} = (\alpha - \beta)M_0 \quad (1)$$

$$\frac{dM}{dt} = [\alpha(1-\rho) - \beta - \rho]M_0 + \frac{dR}{dt} = 0 \quad (2)$$

where dR/dt is the flow of bioresource replacement allowing a constant value M_0 of the bioresource inside the reservoir to be maintained. Therefore, it can be easily obtained that:

$$\frac{dR}{dt} = M_0[\beta - \alpha + \rho(1+\alpha)] \quad (3)$$

$$\rho = \frac{(\beta - \alpha)}{(k - \alpha)} \quad (4)$$

where ρ, in the last equation, can be more properly understood as the fraction of the whole M, where a growth rate ($k > \beta > \alpha$) must be obtained thanks to the additional local inputs coming from the productive sectors and additional renewable energy resources. The last two terms, evaluated at their proper exergy cost, constitute the BSR cost of the partially renewable input consumed by the production system.

2.6. The Exergy Evaluation of Polluting Emissions

To assess polluting emissions, the exergy remediation cost has been suggested in the literature for both the CExC and the EEA models. In the EEA model, the direct and indirect exergy consumption during the overall system operation and to support system decommissioning are considered, consistent with the LCA approach [23]. The ecological cost of the polluting emissions is calculated on a remediation basis by introducing a fictitious extension of the system, where the waste treatment process has been completed, as shown in Figure 6.

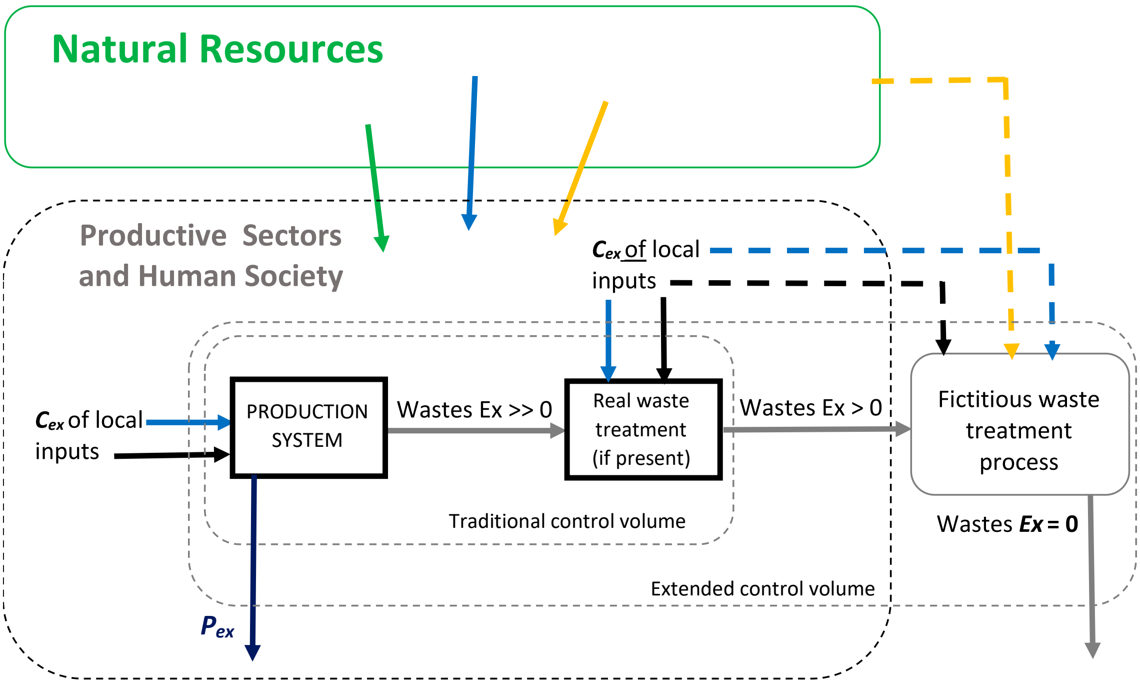

Figure 6. The extended control volume for exergy cost evaluation, following the EEA.

It is worth noting that the remediation cost for neutralizing the chemical and physical exergy of waste (the cost actually incurred plus the virtual cost) may be the same whether or not waste treatment strategies are applied. Treatments are required to convert all wastes into a flow with temperature and composition similar to those of the zero-exergy matrix of the TEE, but the non-incurred part of the cost is calculated, inside the extension of the system. The cost for the actual treatment is generally even higher because real processes are less efficient than virtual ones. The result is that a highly polluting plant may appear to be less resource-consuming (more sustainable) than a plant that obtains the same product cleanly.

In an alternative approach, the actual exergy cost of polluting emissions can be defined, in the frame of the TEE, as the real exergy stock depletion produced by the polluting emissions, caused by:

- The destruction of the confine restrictions of reservoirs.
- The variation in the zero-exergy matrix temperature or composition.
- The dilution of substances inside the reservoirs, reducing their concentration.
- The indirect destruction of the (living) biomass stock inside the reservoirs.

In this way, virtuous plants, which effectively include emission neutralization systems, may have a specific exergy cost of their products lower than polluting plants, highlighting that the former requires less consumption of resources (i.e., they are more sustainable).

3. The Thermoeconomic Environment Cost and the Exergy Resource Sustainability

Combining all previous considerations, the TEEC can be calculated as follows:

$$C_{ex-P} = \sum C_{ex-RES} + \sum (C_{ex-PRS} + C_{ex-BSR}) + \sum (C_{ex-NRS} + C_{ex-Rep}) \tag{5}$$

where:

- C_{ex-P} is the TEEC of the product P.
- C_{ex-RES} is the exergy cost of the product P, taking into account only RES.
- C_{ex-PRS} and C_{ex-NRS} are the exergy costs of the product P, taking into account only partially RES, or non-RES, respectively,
- C_{ex-BSR} and C_{ex-Rep} are the exergy costs of the product P, taking into account only the exergy BSR cost of partially RES, or the ERC of mineral non-RES, respectively.

As shown in Figure 7, the flows extracted from the TEE must include both the direct inputs and all the other real exergy stock depletions in the whole TEE, because of the polluting emissions. In this context, an exergy-based sustainability indicator easily arises, named i_{ex-TEE}, as the ratio between the exergy cost (calculated ignoring the ERC of non-RES and the BSR cost) in the numerator and the total exergy TEEC (calculated taking all terms into account) in the denominator.

$$i_{ex-TEE} = \frac{\sum C_{ex-RES} + \sum C_{ex-PRS} + \sum C_{ex-NRS}}{C_{ex-P}} \tag{6}$$

The exergy resource sustainability index i_{ex-TEE} is equal to one in the ideal case, where all direct and indirect consumptions are in the form of RES, while it is internal to the 0–1 interval in all real cases, where both RES and non-RES are consumed.

The index i_{ex-TEE} may approach one only if resources with a very low ERC or BSR cost are consumed, i.e., if all non-RES or partially RES possibly consumed are non-rare. It is worth noting that the recycling of materials reduces the value of both the ERC of the mineral resources and the BSR cost in this model, increasing the value of the proposed exergy-based sustainability indicator.

The index i_{ex-TEE} may approach zero when the primary inputs extracted from the TEE have a very high ERC or BSR cost, i.e., when rare mineral resources rare biological species, or even whole ecosystems, are consumed or destroyed, even if their exergy contents were small.

Let us consider that EEA is the starting point for calculating the TEE cost and the related resource sustainability indicator. In this case, the exergy equivalent of capital and labor are taken into account through the procedure suggested by Sciubba. Otherwise, the approach suggested by Rocco and Colombo may be followed. In the latter case, the exergy equivalent of capital is implicitly taken into account and could be calculated a posteriori.

If solar energy, as well as other renewable and partially RES, were properly taken into account, the total cost obtained in this way should be the sum of $(C_{ex-RES} + C_{ex-PRS} + C_{ex-NRS})$ in Equation (5). The exergy cost of the BSR (C_{ex-BSR}) of the biological products used as input in the production process must be evaluated following the frame shown in Figure 5, by using some additional information from the fields of agriculture and forest cultivation.

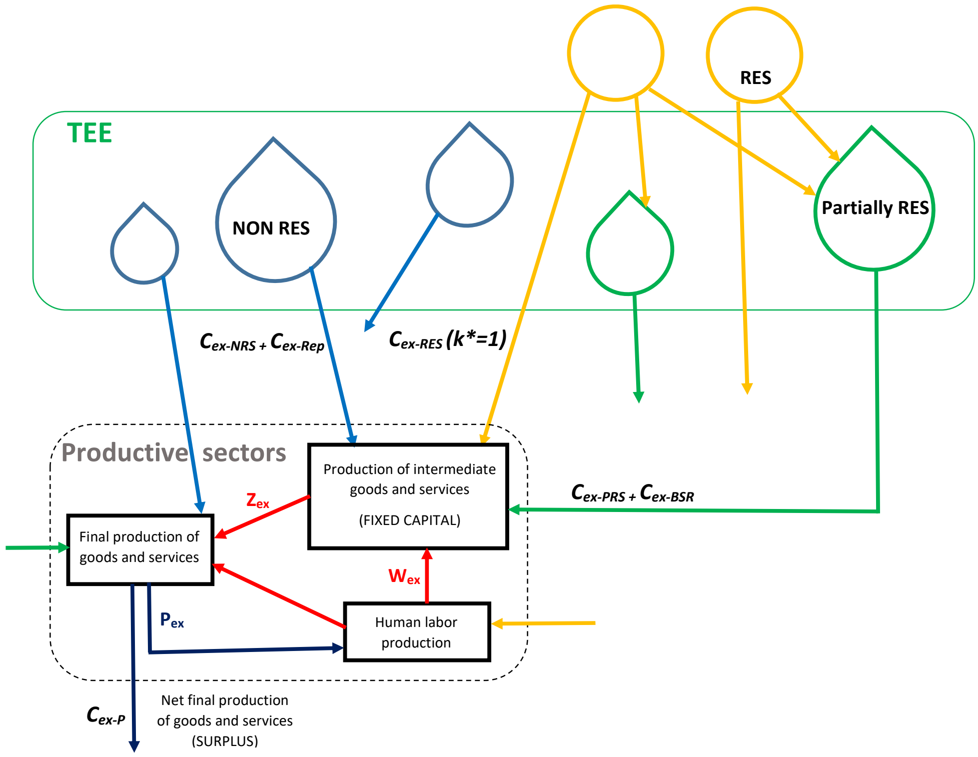

Figure 7. Illustrative sketch of the procedure for the calculation of the TEE cost and the sustainability index.

The C_{ex-Rep} of all mineral resources consumed can be found in the papers by Valero [42,43].

EEA calculate the effect of polluting emissions based on the exergy cost of remediation (Figure 6). In this paper, it is suggested that the actual exergy depletion of the TEE should be calculated, because of its direct and indirect effects. To proceed in this way, the exergy cost of remediation should be eliminated from the total accounting of the exergy cost of the product if the remediation technologies are not actually put in operation. Then, an inventory should be compiled of the depletions in the TEE resulting from the polluting emissions of the production process at hand. The results of an LCA of a similar process taken from the literature may be used as a first attempt. Finally, the depletion of each reservoir should be estimated in terms of its exergy cost, including the exergy cost associated to temperature variations in the zero-exergy matrix. Notice that the depletion of mineral reservoirs must be accounted-for at the cost $C_{ex-NRS} + C_{ex-Rep}$, while the depletion of the reservoirs of biological products must be accounted-for at the cost $C_{ex-RES} + C_{ex-BSR}$. In this way, the effect of polluting emissions will affect all terms in Equations (5) and (6). At this point, an evaluation of each of the five terms on the right-hand side of Equation (5) would be obtained, and the indicator in Equation (6) could be calculated.

4. Conclusions

Exergy cost accounting introduces the sum of direct and indirect exergy consumption as a measure of the resources required to obtain a product. The necessary definition of a proper ultimate boundary of the exergy cost accounting may be carried out by introducing the TEE consistently to assess the sustainability of the production of goods and services. Then, the exergy replacement cost of mineral resources proposed by Valero and Valero, may be introduced as a meaningful improvement to actual exergy cost accounting methodologies, consistently with the frame of the TEE.

Likewise, the proposal by Rocco and Colombo for a definition of the exergy values of labour and capital (directly derived from the input/output algebra by Leontief) was shown to be also consistent with the framework of the TEE and can therefore be used to evaluate the exergy equivalent of capital and human work. In this way, production factors, such as capital investment, human labor and environmental resources, can be unified into a common exergetic description.

To properly take into account the interaction of the production system with biological processes, the bioresource stock replacement cost was here introduced, taking advantage of the idea of partially renewable resources (the living biomass) contained inside the TEE. If using exergy cost accounting to assess the sustainability of a specific product or service, it is important to notice that the TEE framework allows us to assess the impact of polluting emissions based on the actual exergy stock depletion throughout the TEE. Virtuous plants, which effectively include emission neutralization systems, may have a specific exergy cost lower than that of polluting plants, therefore justifying, from an exergy cost accounting point of view, the adoption of devices that strongly reduce polluting emissions.

In addition, an exergy-based sustainability indicator easily arises as the ratio of the exergy cost, calculated neglecting the exergy replacement cost of non-RES and the bioresource stock replacement cost, and the total bioresource stock replacement exergy Thermoeconomic Environment cost, calculated taking all terms into account. This new exergy-based sustainability indicator is expected to be well-suited to expressing the resource sustainability of goods and services. It is equal to one in the ideal case, where all direct and indirect consumption is of RES, giving a clear view of how far the process at hand is from the ideal case, and enabling the calculation of the margin available for possible improvements.

Finally, this method allows us to highlight the advantage of recycling and the usage of non-rare mineral resources, because they both reduce the exergy replacement cost of non-RES and the bioresource stock replacement cost of partial RES. In the same way, the disadvantage of consuming rare mineral or biological resources is properly drawn to our attention, even when their chemical exergy content is small.

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Nomenclature

α	natural growth rate of the bioresource in a reservoir
β	extraction rate of the bioresource from a reservoir

ρ	fraction of the bioresource required for the replacement (Figure 5)
k	growth rate in the extended system required for the replacement (Figure 5)
C_{ex-P}	TEEC of the product P
C_{ex-RES}	TEEC of the product P, taking into account only RES
C_{ex-PRS}	TEEC of the product P, taking into account only partially RES
C_{ex-NRS}	TEEC of the product P, taking into account only non-RES
C_{ex-BSR}	TEEC of the product P, taking into account only the exergy BSR cost of partially RES
C_{ex-Bep}	TEEC of the product P, taking into account only the ERC of mineral non-RES
k^*	unit exergy cost of a flow
i_{ex-TEE}	exergy-based resource sustainability indicator
M	amount of bioresource in a reservoir
M_0	bioresource stock at instant t = 0
P_{ex}	exergy of the product
dR/dt	flow of bioresource required for stock replacement
t	time
Z_{ex}	exergy of the fixed capital

Acronyms

BSR	bioresource stock replacement
CExC	cumulative exergy consumption
EEA	extended exergy accounting
ERC	exergy replacement cost
RES	renewable energy source
TEE	thermoeconomic environment
TEEC	thermoeconomic environment cost

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