Advances in exergy analysis: a novel assessment of the Extended Exergy Accounting method

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Nomenclature

En	energy, J
$\mathbf{E}$	exergy, J
en	specific energy, kJ/kg
$\mathbf{e}$	specific exergy, J/kg
$\mathbf{EE}$	extended exergy, J
$\mathbf{eec}$	extended exergy cost, J/kg, J/J, J/unit
EMPL	workload factor, h/year
f	consumption amplification factor
F	cost function
g	gravity acceleration, 9.81 m/s^2
$\dot{m}$	mass flow rate, kg/s
M	monetary circulation, €/year
$M2$	monetary aggregate, €/year
MM	molar mass, g/mol
n	number of unit products
N	population/workers numerosity
p	pressure, bar
Pf	plant factor
Q	heat, J
S	entropy, J/K
$\mathbf{S}$	gross yearly cumulative wages, €/year
s	specific entropy, J/(kg K)
$\mathbf{s}$	specific yearly wage per capita, €/(worker year)
T	temperature, K
t	time, s
u	velocity, m/s
V	volume, m^3
W	work, J
Wh	average annual working hours of one worker, h/(year worker)
x	mass fraction
z	height, m
α	first econometric coefficient
β	second econometric coefficient
η	efficiency
ν	employment rate

Subscripts

0	environmental state
00	dead state
1	generic state
ch	chemical
D	destruction
des	destruction
en	energy
ex	exergy
F	"fuel" of the system
fp	finished product
h	population
I	first law
i	ith stream
in	inlet
j	jth inlet mass stream
K	capital
k	kth outlet mass stream
kn	kinetic
L	labour
L	losses
l	lth heat flow
m	mass flow rate
M	materials
mix	mixture
Nu	nuclear
O	environmental costs
out	outlet
P	"product" of the system
Ph	physical
pt	potential
Q	heat
R	radiation
$surv$	survival
W	work
W	workers

Acronyms used in the text

CExC	Cumulative Exergy Content
ECS	energy conversion system
EE	extended exergy
EEA	extended exergy accounting
eec	extended exergy cost
ELCA	Exergy Life Cycle Assessment
GDP	Gross Domestic Product
HDI	Human Development Index
LC	life cycle
LCA	Life Cycle Assessment
OECD	organization for economic co-operation and development
TE	Thermoeconomics
TEC	Thermo-Ecological Cost
TPES	Total Primary Energy Supply

1. Introduction

1.1. Natural resources: concept and evaluation

Advances in energy systems are, with very few and specific exceptions (e.g.: space applications or installations in extreme environments), driven by the search for the attainment of the maximum useful effect with the minimum resource consumption. Until recently, the classical view of a resource was "all material and energy flows absorbed by the system under consideration during its operating life". Today, the very concept of "resources consumption" is undergoing a radical re-evaluation, in response to the acknowledged interdependency of the energy sector with both the environment and the society at large. Following an approach that combines the pioneering ideas of Daly [1], Costanza [2] and Ayres [3] with the genuinely Second Law approach of Gaggioli [4], Szargut [5,6], Tsatsaronis [7] and Valero [8], the following definitions are adopted in this paper:

(a) An "energy conversion system", ECS in the following, is any system, natural or artificial, that converts any form of energy (material or immaterial) into any other form (material or immaterial).
(b) "Product" of an ECS is every material or immaterial stream whose generation is one of the design goals of the system.
(c) "Fuel" of an ECS is every material or immaterial stream whose exploitation is one of the design inputs.
(d) "Resource" of an ECS is any material or immaterial stream entering the system boundary.
(e) "Effluent" of an ECS is any material or immaterial output stream which is not a product.

Obviously, no ECS operates in isolation: in the real world, it is surrounded by other systems with which it interacts and this requires its abidance by technological, economic, environmental and social constraints: unfortunately but necessarily, accounting for such an interaction complicates the process assessment procedure.

The impact of an ECS must be evaluated over time (life-cycle approach) and must include the effects at the local and global scales- on the surrounding environment and on the society in which the system is called to operate. It is along these lines that the concept of "Sustainable Development" came to light in the late eighties [9], originating an international debate about its meaning and its implications.

While addressing this debate is outside the scope of this paper, we adopt here a pragmatic engineering perspective according to which sustainability is discussed only when technical feasibility is proven and the influence on economics, environmental and social constraints can be -directly or indirectly, but always quantitatively-measured.

From the analyst's perspective, three elements must therefore be taken into account:

1. **Use of natural resources**. The implicit goal is that of minimizing both the embodiment and the throughput of material and energy flows in the system per unit of "product", even if the problem of measuring such "consumption" is still open.
2. **Externalities**. The "cost" of the product cannot be measured only in terms of the gross amount of resources "consumed" within the production chain: labour, capital and environmental costs must be included in the "resource balance" of the system.
3. **Time- and space extension of the system**. The emphasis placed by the sustainability concept on the "effects on future generations' needs" implies that the system analysis must include the whole life cycle from construction to decommissioning, and thus requires a double integration over time and space.

It must be remarked that traditional engineering system analysis methods often do not properly account for the three elements above. A number of alternative approaches have been proposed in the last decades to overcome these limitations [10,11]. It suffices here to note that traditional material and energy based methods neglect the effects of Second Law or attempt to express them in terms of "energy dissipation", which is not a rigorous indicator of irreversibility. Only exergy-based methods are genuinely Second-Law based and will be addressed in this paper.

1.2. Application of exergy and exergy balances in system analysis

Exergy is a thermodynamic function that "contains" both First and Second Law: it provides a quantitative basis to measure the degradation of energy (i.e., the decrease of its capacity to generate useful work) in conversion processes.

The word *exergy* was conceived by the Slovenian Rant [12]: at a scientific meeting in 1953 he suggested that the term be used to denote "technical work capacity". But already in the works of Gibbs and Maxwell use was made of a function, called *available energy*, that expresses the capacity of a system to produce external work when proceeding from an arbitrary initial state to its stable equilibrium state through a series of reversible processes: a review of the connections between this function and exergy is provided in [13,14]. In the German literature, already in the '60s a function called *Arbeitsfaehigkeit*-completely equivalent to exergy- was being used in the evaluation of energy conversion processes: in the following two decades, the denomination of "exergy" slowly gained universal acceptance, though other terms such as available energy, availability, available work, potential work, useful energy, potential entropy and essergy are still occasionally found in the literature [15]. The method of exergy analysis has been developed both in its fundamentals and in several applications in the seventies through the works of Gaggioli, Moran, Fratzscher, Beyer, Szargut, Brodyanski and many others, both in the US and in Europe. Today, it is difficult to find archival publications on the analysis of energy conversion systems that do not make use of the concept of exergy. A comprehensive review of the concept of exergy and of its applications can be found in [15].

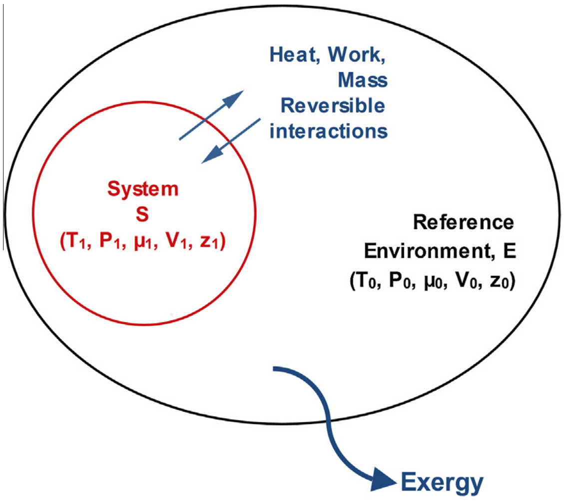

Fig. 1. For the definition of exergy.

With reference to Fig. 1 [16], exergy can be defined as *the amount of useful work extractable from a generic system S when it is brought to equilibrium with its reference environment E through a series of reversible processes in which the system can only interact with such environment* [16,17]. The general expression for an open system "exergy balance" (1), analytically formulated among others by Bejan in [18], can be derived by applying energy and entropy balances to the system shown in Fig. 2:

$$\frac{d\mathbf{E}}{dt} = \sum_{l=1}^{p}(\dot{\mathbf{E}}_{\mathbf{Q}})_l - \dot{\mathbf{E}}_{\mathbf{W}} + \sum_{j=1}^{q}(\dot{m}\cdot\mathbf{e}_{\mathbf{M}})_j - \sum_{k=1}^{r}(\dot{m}\cdot\mathbf{e}_{\mathbf{M}})_k - \dot{\mathbf{E}}_{\mathbf{des}} \tag{1}$$

In Fig. 2, system can exchange work ($\dot{W}$), heat ($\dot{Q}$) and mass ($\dot{m}$) with its reference environment, and with a heat sink R_h, a source R_i and an outlet reservoir R_r.

Notice that, since exergy – like entropy – is not conserved, the word "balance" is not strictly appropriate: indeed, the term $\dot{\mathbf{E}}_{des}$ in (1) is a virtual term introduced with the purpose of "closing the balance", and does not correspond to any physical "flux". Although a better denomination would therefore be "exergy accounting", in this paper the commonly accepted "balance" notation is adopted.

Following the classification proposed by Kotas, the terms in (1) are described below. The specific exergy of a stream of matter consisting of n components, $\mathbf{e}_{\mathbf{M}}$, is defined as:

$$\begin{aligned}\mathbf{e}_{\mathbf{M}} &= g(z_1 - z_0) + \frac{1}{2}\left(V_1^2 - V_0^2\right) + (u_1 - u_0) + P_0(v_1 - v_0)\\ &\quad - T_0(s_1 - s_0) + \frac{1}{MM_{mix}}\sum_{i=1}^{n}(\mu_{i,0} - \mu_{i,00})x_i\end{aligned} \tag{2}$$

where the first and the second terms in the rhs of (2) are respectively the potential and kinetic energy, forms that can be completely recovered into work:

$$\mathbf{e}_{\mathbf{pt}} = g(z_1 - z_0) \tag{3}$$

$$\mathbf{e}_{\mathbf{kn}} = \frac{1}{2}\left(V_1^2 - V_0^2\right) \tag{4}$$

Neglecting potential and kinetic components, the exergy of a stream of matter (2) is the sum of two main contributions, namely *physical* and *chemical* exergy:

$$\mathbf{e}_{\mathbf{Ph}} = (u_1 - u_0) + P_0(v_1 - v_0) - T_0(s_1 - s_0) \tag{5}$$

$$\mathbf{e}_{\mathbf{Ch}} = \frac{1}{MM_{mix}}\sum_{i=1}^{n}(\mu_{i,0} - \mu_{i,00})x_i \tag{6}$$

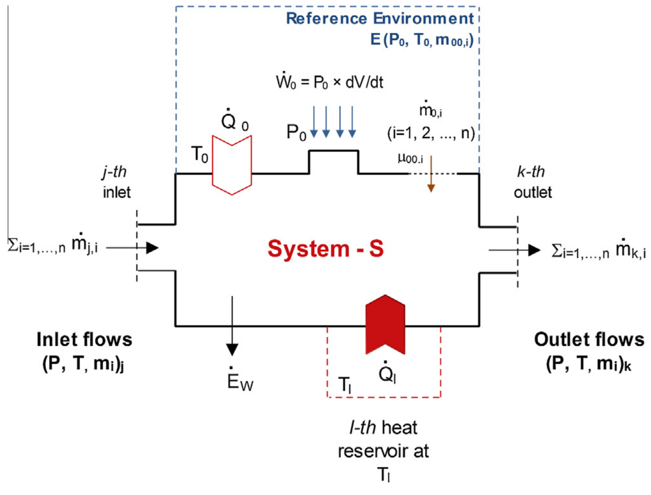

Fig. 2. Control volume for exergy balance. Adapted from Bejan [18].

If the system is closed with respect to its reference environment R_r (conventionally denoted as R_{00}), its final equilibrium state is called the *Environmental State* (subscript "0"), and this implies that complete thermo-mechanical equilibrium is attained ($T = T_0$, $p = p_0$). At such point, the chemical and/or phase composition of the system may be different from that of the environment. On the other hand, if the system can exchange mass with its reference environment, material exchanges may take place until the system reaches another thermodynamic state called *Dead State* (subscript "00") described by both thermo-mechanical and chemical equilibrium properties ($T = T_0 = T_{00}$, $p = p_0 = p_{00}$, $\mu_i = \mu_{i,00}$). The exergy of a system can also be modified through *immaterial* interactions, namely by exergy transfer associated with heat (in any form) or work (in any form) transfers through the system boundaries:

$$\dot{\mathbf{E}}_{\mathbf{W}} = \dot{W} - P_0\frac{dV}{dt} \tag{7}$$

$$\dot{\mathbf{E}}_{\mathbf{Q}} = \dot{Q}\cdot\left(1 - \frac{T_0}{T}\right) \tag{8}$$

There are additional terms that may appear in (2): for instance, the amount of exergy corresponding to nuclear energy of the material or to a flux of solar radiation [19]:

$$\mathbf{e}_{\mathbf{Nu}} = 19.3\times10^{12}\cdot\frac{1}{MM} \tag{9}$$

$$\mathbf{e}_{\mathbf{R}} = e_R\cdot\left[1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4\right] \tag{10}$$

Finally, it can be shown that the exergy destruction term, $\dot{\mathbf{E}}_{des}$, which is the irreversible (i.e., irrecoverable!) loss of work capacity experienced by the system during a thermodynamic process is equal to the so-called Gouy-Stodola lost work:

$$\dot{\mathbf{E}}_{des} = T_0\cdot\dot{S}_{irr} \tag{11}$$

In summary, exergy is a thermodynamic quantity capable of:

1. Measuring the conversion of material and energy flows into comparable terms on the basis of the capacity of such flows to generate mechanical work as a useful effect.
2. Identifying and quantifying the thermodynamic inefficiencies of a generic process by means of the exergy destruction term.

Because of its properties, exergy is a convenient tool for the calculation of the global resource consumption of both natural and engineering processes.

2. General overview of exergy-based methods for system analysis

2.1. Exergy accounting fundamentals

Traditional exergy analysis consists in the application of the exergy balance (1) to a defined control volume, with the scope of tracking and quantifying exergy destructions and efficiencies. The word *System* defines all of the possible objects susceptible of an energy analysis, ranging from simple stand-alone thermodynamic processes to more complex ones resulting from combinations of more processes and components. There is a general consensus today among System Analysts that the rational use of resources must be assessed with the aid of both energy and entropy concepts, since the presence of irreversibility in a process increases the amount of primary resource needed to attain the same design objective.

A set of general guidelines for performing an exergy analysis of a system is the following [20]:

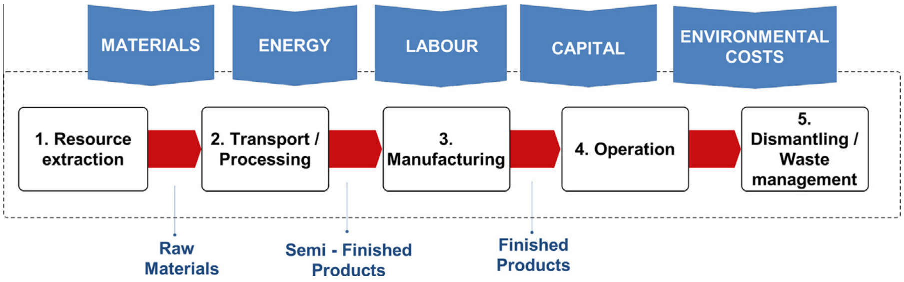

Fig. 3. Simplified and generic life cycle of a good/commodity (material or immaterial). The arrows represent all of the possible resources absorbed in all phases of the system life cycle.

- Univocally define the system by properly selecting the control volume.
- Define an appropriate reference environment, specifying whether it is steady and uniform or not.[1]
- Compute mass, energy and entropy balances of the system during the process.
- Apply the exergy balance to the system.

A key outcome of such an analysis is the *exergy efficiency* of the process. For a clearer understanding of this concept, it is convenient to rewrite the exergy balance (1) according to the Fuel-Product paradigm (F–P) as introduced by Tsatsaronis [7] the Fuel and Product categories were adopted in this paper, and defined in Section 1.1. According to this paradigm, and assuming that the system of Fig. 2 operates at steady state, the exergy balance (1) can be rewritten as follows:

$$\dot{\mathbf{E}}_{\mathbf{Fuel}} = \dot{\mathbf{E}}_{\mathbf{Product}} + \dot{\mathbf{E}}_{\mathbf{Loss}} + \dot{\mathbf{E}}_{des} \tag{12}$$

$$\eta_{ex} = \frac{\dot{\mathbf{E}}_{\mathbf{Product}}}{\dot{\mathbf{E}}_{\mathbf{Fuel}}} = 1 - \frac{\dot{\mathbf{E}}_{\mathbf{Loss}} + \dot{\mathbf{E}}_{\mathbf{Des}}}{\dot{\mathbf{E}}_{\mathbf{Fuel}}} \tag{13}$$

Is necessary to remark that the definition of Product does not necessarily coincide with the exergy fluxes exiting the system: in (12), the waste or byproducts exergy ($\dot{\mathbf{E}}_{Loss}$) represents the output streams that are not considered a product. Since such fluxes are, however, associated to an energy or material stream output, their exergy is in principle "recoverable". By contrast, the exergy destruction ($\dot{\mathbf{E}}_{des}$) constitutes an irrecoverable loss.

2.2. Life-cycle exergy based methods

A fundamental classification of system analysis methods can be made on the basis of the objective function adopted in the analysis: we shall treat the *monetary cost* approach first and subsequently proceed to the *resource cost* approach.

2.2.1. Common spatial and temporal domain for LC-based exergy analysis

The main benefits arising from the application of an exergy analysis are:

1. It locates and quantifies the real sources of inefficiency within the system.
2. It allows for a comparison of different energy systems on the basis of their respective Second Law efficiencies.
3. It expresses material and immaterial fluxes in homogeneous terms.

The traditional approach, adopted in all initial versions of the method from the 60s through the 80s, was to consider the steady-state operation of the process, obtain an "optimal" configuration under suitable boundary conditions, and extrapolate the solution to off-design and unsteady operation. Since most plants operate indeed for a substantial portion of their technical life at or near design point, this approach was perfectly functional. However, when the method was extended to more complex conversion chains that often do not operate at fixed point, a life-cycle approach became unavoidable [21,22]. The simplified and conventional life cycle representation of a generic commodity production line (Fig. 3) consists of five "operational phases" taken to represent a physical set of production steps sequentially ordered in time:

1. Resource extraction.
2. Raw materials transport and pre-processing.
3. Final manufacturing and assembling/packaging of the finished products.
4. Use of the product.
5. Disposal of the product and operation waste management. Possibly, plant decommissioning.

Traditional exergy analyses were applied almost exclusively to Phase 4, a very limited number of works included Phases 2 and 3, while Phase 5 was -until recently- typically ignored or considered of secondary interest.

In the life-cycle approach presented in Fig. 3, the control volume shown as a dashed line represents both the temporal and the spatial extension of the system domain; also, notice that in this scheme, the arrows indicate that there are other "possible resources" than material and energy that need to be accounted for: these "fuels" are called by Economists "Production Factors", and include, besides Energy, **E** and Materials, **M**:

- Labour, **L**.
- Capital, **C**.
- Environmental cost, **O**.

Starting from the biosphere-conscious approach pioneered by Daly, Costanza and Ayres [23–25], System Analysts began distinguishing between energy and materials resources, labour and monetary inflows. It is clear that the exergy method cannot be used "as is" for the evaluation of labour L and capital C: indeed, proper models are necessary to include them into exergy accounting. However, since in the current modern industrial society the monetary cost is the crucial decision variable, the obvious approach was to try to link Thermodynamics and Economics. The link is provided by a series of cost-balance equations, presented in Section 3.

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[1] If R_{00} is unsteady, a time integration is needed for the calculation of the exergy of the system: the state $R_{00}(t)$ is in this case the imposed boundary condition. If R_{00} is not uniform, the treatment becomes difficult, because non-equilibrium Thermodynamics concepts are required. An accepted simplification is to define a portion R_{IS} of R_{00}, denoted as "immediate surroundings", as the reference, and to neglect the interaction between R_{IS} and R_{00}.

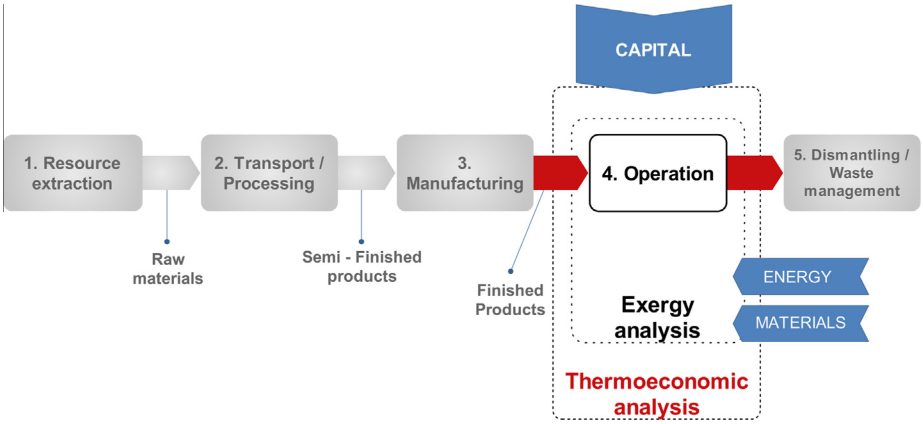

Fig. 4. Application of the Thermoeconomic method to a single production phase (here, operation).

2.2.2. Monetary cost approach

The "monetary cost" of a good or service is defined as the cumulative cost of all resources (fuels) used by the system in order to generate its desired output (products). According to Neo-classical Economics, the monetary cost of a commodity is expressed by an economic cost function (14) which contains the above defined Production Factors as relevant variables and time as an independent variable:

$$\mathbb{F}_c = f(M, E, L, C, O, t) \tag{14}$$

Since the cost function (14) is calculated on a monetary base, the problem arises of assessing the monetary value of each one of the Production Factors. While mass and energy flows can be easily translated into their monetary equivalent, and Labour can be prorated and included in the operating Capital, a monetary accounting of the environmental impact is difficult and uncertain, and results in a well known problem that goes under the name of "internalization of the environmental externalities".

In an exergo-monetary approach, the entire chain of Fig. 3 ought to be included in its time-dependent control volume: for practical purposes, most analyses are though performed separately (and often sequentially) on each phase. This is permitted by the conservative property of the concept of "Product cost", which is given by the sum of the cost of the Fuels, plus the cost of Materials and Energy used in the production line, plus the operating Capital (including Labour), plus the share of the Construction and Decommissioning costs pertaining to that phase. Thus, in a linear production chain like the one depicted in Fig. 3, the cost K_{fp} of the semi-finished products is a "fuel" for the Manufacturing phase, etc. For more complex production lines with feedbacks (recycles), proper iterative methods can be devised. The methods belonging to this category are collectively known as Thermoeconomics (Fig. 4), and have a common origin in the theory developed by Tribus and Evans in 1962 for the analysis of desalination processes [26]. The word "Thermoeconomics" was coined in 1961 by Tribus, and further fundamental developments were made by El-Sayed and Evans in [27] in the US and by Elsner, Fratzscher, Beyer and Brodjansky in Europe [28]. Later, in the '80s, Gaggioli extended the application of the theory to encompass a broader set of energy-intensive systems [29]. More recently, Tsatsaronis [30] and Valero et al. [31–33], were able to produce a complete and elegant formalization of the method, that is now known as thermoeconomic cost theory. For a review of the developments of the theory and of its applications, see [7,15,34–37].

Thermoeconomics is a monetary costing technique that combines second law principles with traditional cost accounting methods. It is founded on the so-called "exergy costing principle" [31], according to which exergy represents the real *use value* of goods,

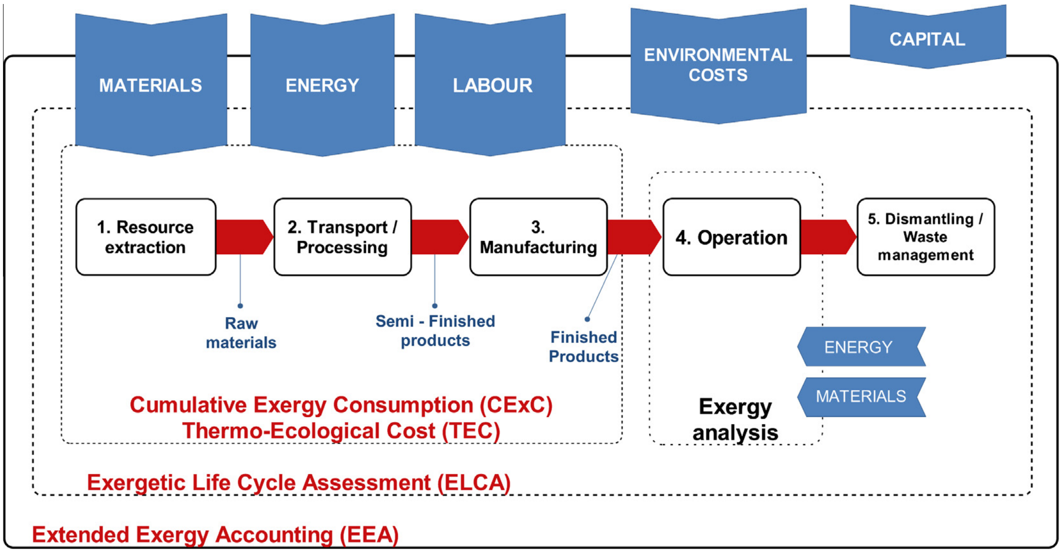

Fig. 5. Spatial and temporal domains for the life cycle resource cost approach methods.

and as such it is the only rational costing basis. Since Capital costs are in general an increasing function of the (exergetic) system efficiency while Operating costs are inversely proportional to it, the purpose of thermoeconomics is to determine the best tradeoff between efficiency and total system cost (Capital + Operating) in order to achieve the minimum economic cost of the products [38].

Because of its solid theoretical foundation and formalized structure, thermoeconomics is currently a standard tool in both academic studies and industrial applications, and continues to provide substantial contributes to the improvement of the economic cost efficiency of energy systems.

However, TE is affected by some critical drawbacks:

1. The assumption of a rigidly monetary basis introduces a strong dependence of the results on market considerations, which influence the monetary price structure (in a TE perspective, the monetary cost) of the Fuels (especially of the natural resources).
2. It is difficult to formulate a TE analysis of scarce resources, since TE considers as "fuel cost" the product of the flow rate of a certain input stream multiplied by the specific exergy of the flow, and the latter is assumed to be zero when the stream is directly extracted from the environment.
3. The evaluation of the costs associated with the environmental remediation activities suffers of the lack of a thermodynamically and physically correct link between the exergy of an effluent and its toxicity [39]. Specific attempts to solve this problem, like the so-called Environomics [40] or the more recent "Thermo-Ecological Cost" [22] do not seem to fully solve the problem.
4. In a complex production chain, the exergetic efficiency of a component influences the performance of all other components, so that the final product cost is a non-linear function of the cost of all components, their efficiency and of the connectivity of the plant: a correct assessment of these effects on the optimal cost structure is inevitably depending on some "design decisions" made by the analyst (this is known as the "allocation problem", see [7,41]). The "Advanced Exergo-Economics" recently proposed by Tsatsaronis [42] does not seem to completely eliminate the arbitrariness in the allocation decisions.

2.2.3. Resource cost approach

The limitations caused by the use of the monetary proxy in system assessment have been known for a long time, and already in 1973 Szargut [6] proposed an accounting method based solely on exergy, and properly named it "Cumulative Exergy Consumption" (CExC): its objective is to compute the cumulative consumption of natural resources, quantify this consumption in units of exergy, and attribute the total "resource cost" to the products. In its original formulation, CExC did not include the externalities; later, the theory was complemented by the addition of an "ecological cost" calculated on a remediation basis [43]. Somewhat later but independently, Valero in 1986 realized that his formalization of TE made it possible to evaluate the "cost" of the product by using the "exergy costing": if all "fuels" were attributed an exergy cost rather than a monetary one, the cost of the final product turns out to be in the same units (J per kg or per unit).

Later, Szargut introduced the Thermo-Ecological Cost (TEC) [44]: based on CExC concept, TEC expresses the cumulative consumption of non-renewable exergy of natural resources, extending the applications of exergy analysis into the field of environmental analysis. More recently, the two methods (CExC and Exergy Costing) were unified into a formally complete costing paradigm to account for the natural resources consumption, leaving out though all monetary costs (capital, labour and the monetary portion of environmental costs).

It is noteworthy that embodied exergy paradigm is not an entirely new concept: already in the '70es, Costanza, Herendeen and Berry [45,46] had formulated a theory of "embodied energy", in which the "cost" of a product was obtained as a space and time integral of all of the energy fluxes that constitute the "fuels" of the production process. However, Embodied Energy is a First Law based quantifier, and as such cannot account for the inherent thermodynamic difference between chemical, thermal and mechanical energy inputs or outputs.

A life-cycle extension of exergy costing method was proposed by Cornelissen in 1997 [47]: his Exergy Life Cycle Assessment, ELCA, is an extension of CExC in time, in which materials and energy uses are computed for the entire life cycle of the system, including operation and dismantling. Unlike CExC, ELCA assumes as the environmental cost indicator the global exergy destruction

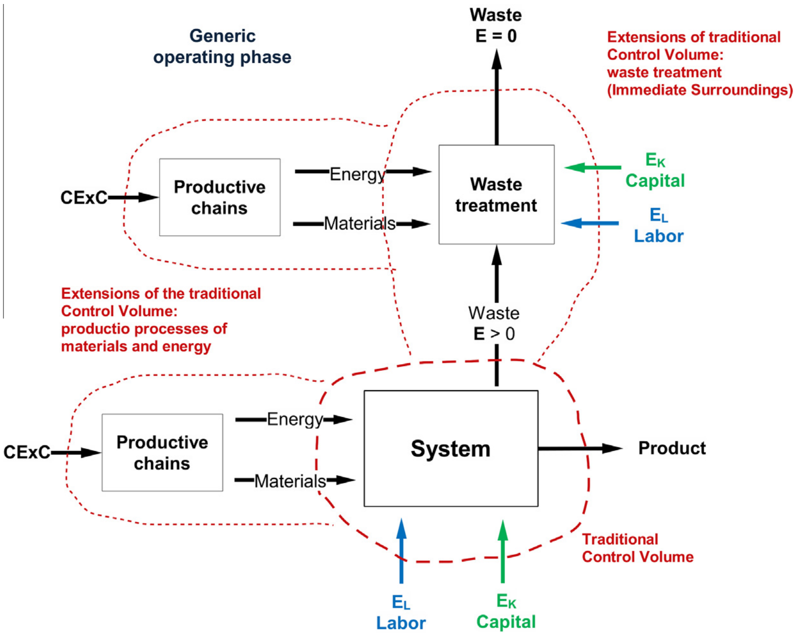

Fig. 6. The expanded control volume for EEA (only the operational phase is represented here).

over the considered life cycle, but, as CExC, it does not include labour and capital externalities.

At about the same time, a very original line of thought was devised by Odum and Scienceman [48] in their Emergy method: they adopted an embodied energy paradigm, but measured all types of "fuels" by a conventional equivalent amount of solar radiation, which they called Solar EmJoule (SEJ). This approach is also First Law based [49], but it contained another ground-breaking idea: that the monetary circulation in a society is in fact supported by the cumulative amount of SEJ that the society could avail itself of.

To address the problem of the inclusion of all externalities into an exergy-based analysis, a paradigm shift is needed: this was provided in 1999 by the formulation of the Extended Exergy Accounting method, EEA [50]. The most recent formulation of EEA method can be found in [11]. In the EEA approach, reversing the traditional perspective of the monetary cost accounting, all terms in the production cost function (14) are converted to exergy terms, to obtain an exergy cost function (15) in J per unit or per kg:

$$\mathbb{F}_{ex} = \bar{f}(M, E, L, C, O, t) \tag{15}$$

EEA adopts both the embodied energy and the emergy paradigms, but proposes to express each one of the cost factors by means to their specific exergy content multiplied by a proper extensive property (kg/s for mass, W for energy, workhours/s for Labour, €/s for capital, kg/s of removed effluent for environmental costs).

To clarify the analogies and discrepancies among the *Embodied Exergy* methods, in Fig. 5 control volumes and the time-frame of CExC, ELCA and EEA are displayed.

3. Extended Exergy Accounting (EEA): a theoretical review

3.1. Definition and objectives

The concept of EEA was coined in 1998 [50,51]. The attribute "extended" is a reminder that the resulting product cost includes materials, energy and externalities, and that the calculation is done along the whole life cycle of the system. There are fundamental similarities between EEA and the previously mentioned exergy methods [52]:

- EEA implements the use of exergy as in a traditional exergy analysis, as a quantifier of the real amount of resource consumption of a system.
- Like thermoeconomics, EEA results in a system of cost equations in which though inhomogeneous quantities like labour, material and energy flux, capital are all homogeneously expressed in primary exergy equivalents.
- Like Cumulative Exergy Consumption, EEA computes the cumulative primary exergy "embodied" in a product over its entire production process.
- Like Exergy Life Cycle Assessment, EEA computations cover the entire life cycle of the considered system.

3.2. Extended Exergy (EE) and extended exergy content (eec)

As previously mentioned, Extended Exergy (EE) measures the amount of primary exergy absorbed by a system throughout its life cycle. In addition to material and energy flows, it includes externalities, all expressed in terms of exergy (Joules, or W if a flux is considered). EE is computed as the sum of:

- Exergy cost of materials and energy flows (renewable and non-renewable), absorbed by the system under consideration. This contribution is identical to the Cumulative Exergy Consumption (CExC) of material and energy flows.
- An externality term $\mathbf{E_{Ext}}$, including labour, capital and environmental cost contributions, expressed by means of their primary exergy equivalents, respectively $\mathbf{E_L}$, $\mathbf{E_K}$, $\mathbf{E_O}$.

In analytical form:

$$\mathbf{EE} = \mathrm{CExC} + \mathbf{E_{Ext}} \tag{16}$$

$$\mathbf{E_{Ext}} = \mathbf{E_L} + \mathbf{E_K} + \mathbf{E}_O \tag{17}$$

The result of (16) must be evaluated over the whole life cycle of the system. Conventionally, the life cycle of a system is divided into three phases: *construction*, *operation* and *decommissioning,* and in this context, (16) can be rewritten as follows:

$$\mathbf{EE} = \mathbf{EE_{const.}} + \mathbf{EE_{op.}} + \mathbf{EE_{dis.}} \tag{18}$$

In other words, the Extended Exergy absorbed by the system throughout its life span is equal to the sum of Extended Exergy contributions during its main life stages:

$$\mathbf{EE} = (\mathrm{CExC} + \mathbf{E_{EST}})_{const.} + (\mathrm{CExC} + \mathbf{E_{EST}})_{op.} + (\mathrm{CExC} + \mathbf{E_{EST}})_{dis.} \tag{19}$$

And each term can be calculated by direct integration over the corresponding time window, e.g.:

$$(\mathrm{CExC} + \mathbf{E_{EST}})_{const.} = \int_{t_0}^{t_{const.}} (\mathrm{CExC} + \mathbf{E_{EST}})dt \tag{20}$$

It is obviously possible to express the Extended Exergy in specific terms: the *extended exergy content* (eec) is indeed defined as the extended exergy required for the generation of a single unit of product:

$$\mathbf{eec}_i = \frac{\mathbf{EE}}{n_i}\left[\frac{\mathrm{J}}{\mathrm{kg}};\frac{J}{J};\frac{\mathrm{J}}{\mathrm{unit}}\right] \tag{21}$$

In (21), n_i is the cumulative amount of the product i in the period of interest, expressed in units of mass, energy or number of units.

3.3. Definition of spatial and temporal domains

As we have seen, the calculation of the overall exergy resources use throughout the life cycle of the system is one of the key features of EEA.

3.3.1. Spatial domain

Referring to Fig. 6, the choice of the system boundaries is made in EEA under three general criteria:

- Material and energy fluxes must cross system boundaries in their raw state, without having been subjected to any previous pre-processing. This implies that the "traditional" control volume should be expanded to include all the upstream phases up to the original reservoir.
- Labour and capital flows absorbed by the system are considered as primary resource flows (for their calculation, see Section 3.4).
- Both material and energy waste flows must cross the system boundaries at their respective zero exergy level. This means that the "traditional" control volume should be expanded in order to include all the "downstream" processes needed to reduce the exergy level of the effluents [53].

3.3.2. Time domain

Fig. 7 represents the exergy cost function (15) and the EE absorbed by the system throughout its life cycle (the integration domain on the abscissa represents the time window of the analysis). Such graphs are useful to compare the "*degree of unsustainability*" of alternative production lines and/or to assess how unsustainable

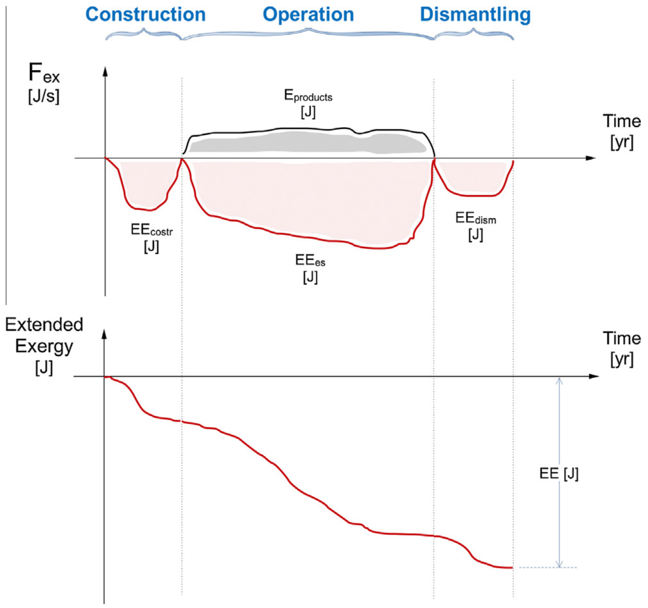

Fig. 7. The time window for extended exergy accounting.

a certain product is (i.e., how large an amount of primary non-renewable resource exergy is embodied into it).

In all phases of its life cycle, an ECS absorbs EE. In particular, the resource consumption measured by EE during the operational phase increases in time even if the "product" (the useful effect) remains constant, due to the inevitably decreasing overall efficiency: this essential feature of real plants is thus correctly captured by the method.

The area subtended by the exergy cost function in the upper part of Fig. 7 represents the net EE absorbed by the system. The total amount of EE absorbed by the system throughout its life cycle corresponds to the rightmost ordinate of the lower graph.

3.4. Calculation of the extended exergy EE

The Extended Exergy absorbed by a generic system over its life span, associated with the production of useful products, is computed by solving (18) and (21). The method for calculating each contribution is explained below.

3.4.1. Material and energy fluxes

In the exergy cost function framework, the exergy content of material and energy fluxes is calculated in analogy to the concept of embodied energy and CExC: these fluxes are computed by EEA as the sum of all direct and indirect exergy contributions required to produce each one of them. The "embodied approach", introduced by [54] and transposed into exergy terms by Szargut [6], is schematically illustrated in Fig. 8.

From Fig. 8 it is clear that the calculation of the CExC of energy and material flows requires a rather detailed bookkeeping. A sufficiently disaggregated database is not always available in practical applications, and suitable approximations are often necessary.

The graph of Fig. 8 sheds also some light on the crucial difference between direct and indirect exergy consumption:

- Direct exergy consumption is represented by level 1 processes: this is the amount of primary exergy directly employed in the production of the product. For instance, direct exergy consumption in the electricity production from coal is the amount of coal and auxiliary exergy necessary to produce one Joule of electricity.
- Indirect exergy consumption is represented by all upstream levels, and is the amount of primary exergy consumed in order to produce each one of the material and energy inputs to the system. Taking again the example of electricity production from coal, indirect contributions are the primary exergy needed to produce and transport coal; build, operate and decommission machines, buildings, trucks, etc.

The CExC is the sum of direct and indirect exergy consumptions. Notice that CExC values of the same flux may assume different values depending on the production chains of origin. As an example, two streams of superheated steam at the same p and T, one produced by a gas-fuelled steam generator and the other by a heat recovery boiler, have two different CExC values. Lists of CExC values for a large number of finished materials and energy vectors are available in literature [6,43].

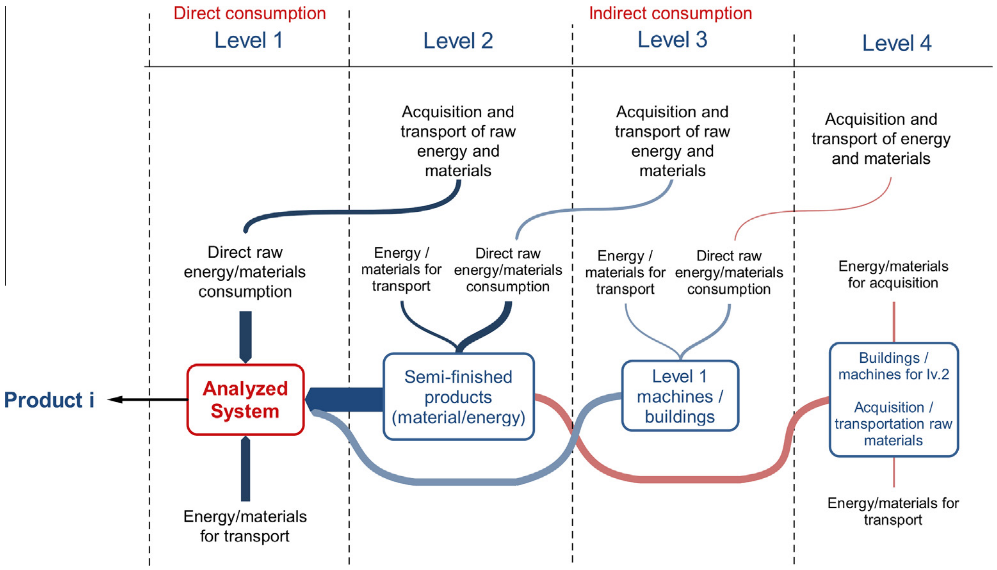

Fig. 8. Process method for CExC calculation.

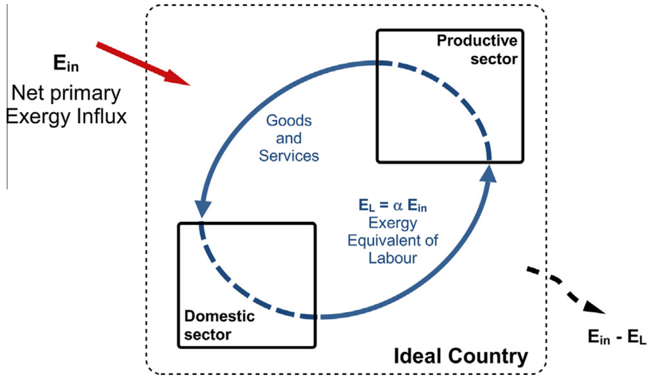

Fig. 9. Exergy analysis of a macroscopic human society.

3.4.2. The Labour externality

The calculation of the exergy equivalent of the human labour and capital flux is based on two postulates. The first postulate is necessary since the labour externality cannot be translated as such into cumulative exergetic costs for the society. The First postulate of EEA reads:

«*In any Society, a portion of the gross global influx of exergy resources* $\mathbf{E_{in}}$ *is used to sustain the workers who generate Labour*». [55].

Using $\mathbf{E_{in}}$ as a “fuel”, the society generates labour whose rate, measured in workhours per unit time, is its unique “internal” product. This postulate is equivalent to the assumption that a human society may survive only as long as it absorb a net flux of resources that sustain its population. Fig. 9 shows the macro-scale exergy analysis of a generic human society. The net exergy rate globally absorbed by the society ($\mathbf{E_{in}}$) consists of:

- Exergy of the net solar radiation incident on the surface occupied by the society.
- Exergy of the net contributions related to raw material and primary energy (excluding solar) inputs.
- Cumulative exergy of the net material fluxes flowing into the society (fuel, food and all other material products).

The first postulate states that the primary product of the society is exergy embodied into labour $\mathbf{E_L}$, which is the exergy globally used by the entire population (workers + unemployed), $\mathbf{E_{Used}}$. This exergy flow rate is a fraction α of the net exergy input ($\mathbf{E_{in}}$):

$$\mathbf{E_{used}} = \alpha \cdot \mathbf{E_{in}} \Rightarrow \mathbf{E_{used}} = \mathbf{E_L}[\mathrm{J/year}] \tag{22}$$

$$\mathbf{E_{dis}} = \mathbf{E_{in}} \cdot (1-\alpha)[\mathrm{J}] \tag{23}$$

This model assumes that all the members of a society, including those who consume resources without generating any work (minors, elderly, unemployed, etc.), thrive on the production of labour: they survive by using goods and services produced and supplied, in end effect, by the workers.

The exergy absorbed by the population ($\mathbf{E_{Used}}$) can be calculated from the exergy flow diagram of the society under consideration: these diagrams are available only for a few Countries (Italy, Norway, England, Turkey, China, etc.), and in all other cases some form of approximation is needed. A formula frequently employed in EEA studies is:

$$\mathbf{E_{used}} = f \cdot \mathbf{e_{surv}} \cdot N_h \ [\mathrm{J/year}] \tag{24}$$

where f is a consumption amplification factor, N_h is the population numerosity and $\mathbf{e_{surv}}$ represent the minimum exergy amount required for the metabolic survival of an individual ($\approx 1.05 \times 10^7$ J/(person × day) [55], corresponding to 2500 kcal/day per person). The amplification factor f can be in turn calculated on a statistical basis: in modern societies the exergy consumption per capita $e_{used} = \mathbf{E_{used}}/\mathbf{N_h}$ can be orders of magnitude higher than the metabolic rate ($\mathbf{e_{surv}}$), and this is reflected in correspondingly high values of f.

In the absence of statistical data, it is possible to estimate the amplification factor by investigating possible correlations between well-established socio-economical indicators and the Total Primary Energy Supply of a countries (TPES). In some of the first applications of the method, the *Human Development Index* (HDI) was adopted: it is an indicator widely used in social-economic sciences, computed for all countries on annual basis, and it takes into account life expectancy, health and education levels [56]. An approximate guess for the exergy consumption per capita can be extracted, in the absence of more detailed data, from the formula:

$$f = \frac{HDI}{HDI_0} \tag{25}$$

where HDI_0 is the *Human Development Index* of a pre-industrial society (≈ 0.055) [55].

3.4.2.1. The first econometric coefficient α. The dimensionless coefficient α is called *first econometric coefficient*. It represents the fraction of primary exergy absorbed by the society and converted into labour (workhours). Starting from (22) and (24), the first econometric coefficient can be computed as:

$$\alpha = \frac{f \cdot \mathbf{e_{surv}} \cdot N_h}{\mathbf{E_{in}}} \tag{26}$$

The calculation of α is thus solely based on the macroeconomic indicators of a country, and this provides an opportunity to check the internal coherence of the first postulate: in fact, since the exergy consumed by population ($\mathbf{E_{Used}}$) cannot be greater than the total net exergy input ($\mathbf{E_{in}}$), the acceptable range for α is limited to the open interval $(0,1)$.

3.4.2.2. The exergy equivalent of labour ee_L. For a given society, if Wh represents the average annual working hours of one worker [h/(year worker)] and N_W is the number of workers, the total number of workhours N_{wh} generated in a year is:

$$N_{wh} = N_w \cdot Wh[\mathrm{h}] \tag{27}$$

It is then possible to calculate the *exergy equivalent* of labour ($\mathbf{ee_L}$), or embodied exergy of labour, as the ratio between the fraction of exergy converted into labour and the total number of hours cumulatively produced by the society:

$$\mathbf{ee_L} = \frac{\alpha \cdot \mathbf{E_{in}}}{N_{wh}}[\mathrm{J/h}] \tag{28}$$

3.4.3. The Capital externality

The calculation of the exergy equivalent of the capital flux requires a second fundamental postulate: «*The amount of exergy required to generate the net monetary circulation within a society is proportional to the amount of exergy embodied into labour*» [55].

The analytical formulation of the second postulate is:

$$\mathbf{E_K} = \beta \cdot \mathbf{E_L} \quad \Rightarrow \quad \mathbf{E_K} = \alpha \cdot \beta \cdot \mathbf{E_{in}} \quad [\mathrm{J/year}] \tag{29}$$

Consider again a simplified society shown in Fig. 10 consisting of only two sectors, domestic (DO) and productive (PR). Two “circulations” can now be identified between these two sectors: the first is a material one (goods, services and workhours), while the second is monetary (wages, compensations and purchases). These two circulations, represented in Fig. 10, are mutually dependent: the labour flux from DO to PR – expressed in exergy equivalent $\mathbf{E_L}$ – is necessary for the production of goods and services; however, these products are made available to DO only because of the parallel monetary

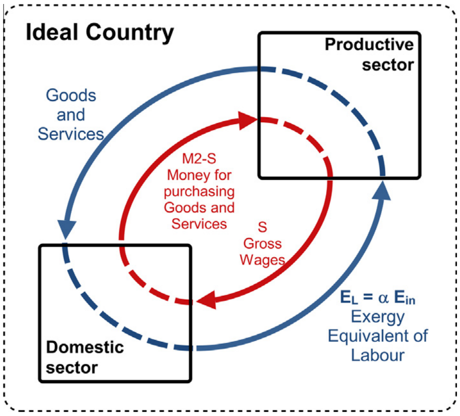

Fig. 10. Scheme of the internal structure of an ideal society used in the calculation of β and $\mathbf{ee_K}$.

circulation required for their purchase. In this simplified model, PR "generates" a monetary flux equal to the workers cumulative wages (S), which are in turn fully reinvested by DO by purchasing goods and services form PR. Notice that in this simplified model there is no monetary or material accumulation.

3.4.3.1. The second econometric coefficient β. Eq. (29) states that the amount of primary resources embodied in the net monetary circulation (the exergy flux $\mathbf{E_K}$) is related to the exergy of labour $\mathbf{E_L}$ through the coefficient β. This second econometric coefficient indicates the capacity of a society to generate monetary circulation in addition to wage compensation and is defined as the ratio between the monetary circulation due to financial activities (M_F) and the gross cumulative wages (S):

$$\beta = \frac{M_F}{S}[ad.] \tag{30}$$

where S ($S = s \cdot N_W \cdot W$) is the gross yearly wage of all of the workers' body [€/yr]. M_F is a fraction of $M2$,[2] a monetary aggregate that represents, at a given time in the considered economic system, the total quantity of circulating money and financial activities which can perform the same functions of money. The second econometric coefficient in a simplified society devoid of financial activities would obviously be equal to zero, because the monetary circulation due to financial activities would be equal to zero. However, in current societies, β is always greater than zero, because of the extra monetary circulation generated by financial activities (M_F). So, the second econometric coefficient can be expressed as a function of circulating capital due to financial activities:

$$M2 = S + M_F \Rightarrow \beta = \frac{M2 - S}{S} \tag{31}$$

Its definition suggests to consider β as a *"financial ratio"* or *"financial amplification factor compared to the gross cumulative wages".* Indeed, from the definition it follows that the higher β, the higher the ability of the society to generate financially-leveraged monetary circulation.

Similarly to α, β depends on the spatial context (geographical location) and on the considered time window (historical period and technological level), but also on some socio-economic parameters and the societal organization of the considered country.

3.4.3.2. The exergy equivalent of capital ee_K. For a given society and time window, it is possible to compute the exergy equivalent of capital ($\mathbf{ee_K}$) as the ratio between the exergy that generates monetary circulation ($\mathbf{E_K}$) and the global net monetary circulation of the society:

$$\mathbf{ee_K} = \frac{\alpha \cdot \beta \cdot \mathbf{E}_{in}}{M2}[\mathrm{J}/€] \tag{32}$$

Values of α, β, $\mathbf{ee_L}$ and$\mathbf{ee_K}$ have been computed for 23 OECD countries and for 54 developing and emerging countries in [55].

3.4.4. The Environmental externality

3.4.4.1. The exergetic concept of "pollutant". The exergy of a generic system is a measure of the thermodynamic disequilibrium between the system and the reference environment [57]: in other words, it represents the real potential of a system to cause an effect on the environment, linked to alterations of the latter, in terms of resource consumption (and not related to any concept of toxicity). If the material is appropriately confined, like the oil in a reservoir, a flammable mixture in a combustion chamber, etc., its exergy could be considered as a resource, since its potential can be exploited to produce a useful effect (such as work or heat or chemical reaction). However, if the same mass is not physically confined, it represents a potential environmental alteration because it may affect the environmental equilibrium, at least at a local scale. Therefore, because of the non-zero exergy content of the stream, EEA classifies it as "a pollutant". Thus, without introducing any considerations about toxicity or greenhouse effect or bio-diversity, the sum of the physical and chemical exergy of a stream is taken by EEA as the sole indicator of the potential environmental "modification" that the stream may generate upon its release.

3.4.4.2. Calculation of the environmental remediation costs in EEA. Issues about environmental impact of energy systems are gaining primary importance in policy assessments: both public opinion and policymakers show an ever stronger sensitivity to this issue, recognizing the environment as a valuable asset that must be maintained within its natural evolutionary path.

Currently, the conventional assessment of the environmental impact of a system is based on estimates of the "damage" caused by its effluents, and subsequently translated into an estimated remediation cost expressed in monetary terms.

EEA proposes a different, original and more pragmatic approach, namely the calculation of the avoidance cost of pollutant emissions: this method consist in the calculation of the additional consumption of Extended Exergy that would allow the system to release effluents in the environment with zero exergy content (see Fig. 11). Since it is convenient to make the treatment as general as possible, it is stipulated that the effluents are brought to equilibrium with the environment by state-of-the-art processes and technologies for which the extended exergy can be reliably calculated.

$$\mathbf{E_O} = \mathbf{EE}_{RP} + \mathbf{E}_{buffer} \tag{33}$$

where $\mathbf{E_0}$ is the exergy equivalent of environmental costs [J], $\mathbf{E_{RP}}$ is the Extended Exergy absorbed by the effluent treatment system [J] and $\mathbf{E_{buffer}}$ is the exergy expenditure of the environmental buffering capacity [J]. Eq. (33) expresses a physically realistic feature of the treatment process: the Extended Exergy content (**eec**) of a generic product will be charged by the extended exergy cost of the effluent treatment system needed to discharge all of the effluents at zero exergy level throughout its life cycle.

However, Second Law negates that any real system can emit effluents in perfect thermodynamic equilibrium with the surrounding environment. Therefore, in EEA the unavoidable residual exergy (thermal, chemical or of any other type) of the stream is "charged" to the buffering capacity of the environment (also named environmental or biological limit buffer). This buffering represents though a "load" on the environment, because to

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[2] The European Central Bank (http://www.ecb.int) defines M2 as "the aggregation currency in circulation, overnight deposits, deposits with maturities of up to two years, and deposits redeemable with notice of up to three months".

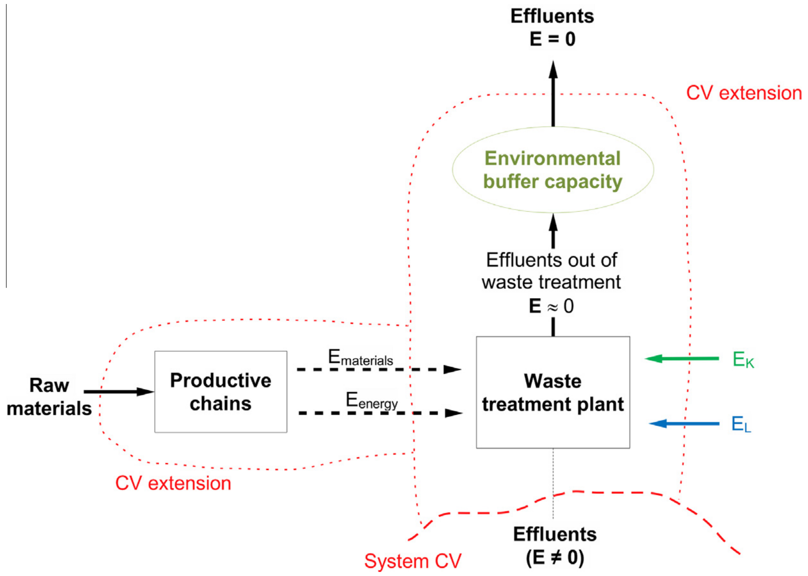

Fig. 11. Addition of a virtual waste treatment plant to compute the environmental costs of pollutants.

perform it, some of the exergy of natural processes must be devoted to this purpose ($\mathbf{E_{buffer}}$ in (33)).

Therefore, the maximum amount of exergy with which the pollutants can be released in the environment (a design specification) can be exactly calculated on the basis of this buffer capacity, which is a site-dependent variable. As a general rule for the choice of the residual buffer capacity, it is reasonable to assume the temperature and concentration limits imposed by law.

Thus, the practical rules for the calculation of the environmental cost are:

- If the exergy level of the effluents is below the upper limits imposed by regulations applicable at the plant site, no effluent treatment process is required: however, it is necessary to include in the environmental costs the exergy of the natural buffering, i.e. the exergy expenditure required of the immediate surroundings to annihilate the exergy level of the effluents by means of natural processes, and (33) becomes:

$$\mathbf{E_O} \approx \mathbf{E}_{buffer} \tag{34}$$

- If the chemical and physical state of the effluents do not meet the local regulatory limits, the environmental cost is calculated from (33):

$$\mathbf{E_O} = \mathbf{EE}_{RP} + \mathbf{E}_{buffer} \tag{35}$$

- If for a specific process and for a certain effluent there exists no real plant capable of performing the exergy abatement, it is necessary to devise a reasonably feasible chemical, thermal or mechanical process that performs this task. The environmental remediation cost will in this case be based on fictitious data that must be carefully checked and compared with all of the possible suitable alternatives.

4. Advantages and drawbacks of EEA

A complete review of the Extended Exergy Accounting method has been presented in the previous paragraphs: in the present section, we highlight some advantages and drawback of EEA, and suggest some possible ways to increase the effectiveness of the method and to improve its applicability to real, complex systems.

4.1. Advantages

The above review confirms that EEA may be considered as a step forward in evaluating the overall resource consumption of a generic system because it is able to include social, economic and environmental externalities expressed in homogeneous exergy terms and because it is founded on a life-cycle formulation.

In line with the accepted LC-based methodological taxonomy, it can be concluded that the extended exergy cost (**eec**) represents an appropriate resource cost function compared to other possible indicators (exergy cost, CExC, ELCA): in this respect, EEA offers a deeper insight than simple exergy analysis and all other LC exergy based methods.

Furthermore, the extended exergy cost function can be used within the traditional and well formalized Thermoeconomic framework, replacing the economic cost function in order to evaluate and optimize the consumption of natural resources of a system. Indeed, some recent studies show that EEA may be used to analyze both traditional energy systems and complex systems (complex networks and societies) [58]. The results demonstrate that EEA is a tool for performing design and configuration optimization, and that its results may give additional insight to the analyses when compared to those of a thermoeconomic analysis.

4.2. Drawbacks and possible further developments

EEA is a relatively young methodology which still needs further validation and the inclusion of some supporting tools before it may become a standard within engineering analysis. The path toward its dissemination displays an interesting similarity with the fate of LCA: at its early stages, the latter was not supported by a sufficiently accurate database for evaluating the life cycle energy consumption of many industrial processes or products. A similar trend seems to apply to EEA which might become in the future an alternative methodology for investigating resource consumption (including externalities such as money, labour and environmental effects) of processes and products. Therefore, in this section, some of he known drawbacks of the method are critically analyzed, with the specific intent of indicating some high-priority research directions.

4.2.1. The Extended Exergy method needs a real standardization and formalization

The EEA method would greatly benefit from a precise and detailed set of application guidelines. Some formalization will be published soon by the same authors and the main steps to consider are:

1. Choice of the system object of the analysis: definition of temporal and spatial boundaries.
2. Definition of the relevant system parameters.
3. Data collection, mass, energy and exergy balances of the system/environment interaction, including the related material and energy supply chains.
4. Exergy analysis of the country in which the life cycle of the considered system takes place: calculation of the exergy equivalents of labour ($\mathbf{ee_L}$) and capital ($\mathbf{ee_K}$).
5. Calculation of Extended Exergy (**EE**).

In this formalization, possible double accounting and cost allocation for different products are relevant issues that need to be addressed.

A very general consideration is indeed linked to the nature of EEA which is a holistic approach and, if not supported by a sufficiently disaggregated database, is subject to double accounting problems.

Another consideration is linked to the allocation of the costs of fuel to different products produced by the same systems (e.g. electricity and heat from a cogeneration plant). It is apparent from the published EEA applications to societies with different structures that the general criteria adopted for the allocation of inputs in a multiproduct system (which are basically the same used in Thermoeconomics, but offer the possibility of a higher flexibility thanks to the disaggregation of the monetary costs in their specific primary exergy equivalents) still need clarification and there is a need for systematization.

4.2.2. Extension and improvement of the CExC database

The need to include material and energy supply chains in the EEA method leads one to wonder whether the additional modelling and computational burden arising from their inclusion is compensated by a real advantage in terms of information content. Furthermore, in some publications it seems that there is no clear agreement on how the primary cumulative resource consumption of these fluxes are to be computed: for instance, in [59,60] (EEA applications to nations or large complex systems) material and energy fluxes are accounted only as for their chemical and physical exergy, neglecting the cumulative exergy needed to produce them. This seems to be more a problem of consistency than of methodological correctness.

The correct calculation of primary cumulative resource consumption of a system allows analysts to make more extensive, relevant and significant evaluations. For example, while traditional exergy analysis provides insight only into the analyzed system, an EEA analysis allows to make space and time dependent evaluations. But to reach its goal, an EEA evaluation requires additional detailed information:

- Where materials and energy fluxes come from.
- Where (in time and space) the system is located (economic and politic situation of the country).
- How long the life cycle window is.

This features confirm that the results of EEA depend on the local and temporal context in which the system operates. This theoretical advantage comes however at a cost, namely the calculation effort necessary to perform complete and detailed process analysis of all of the supply chains.

The EEA method uses the CExC to calculate the primary cumulative resource consumption of materials and energy. There are though some open problems with such an approach: Fig. 12.

- System boundaries: research in CExC analysis should define general criteria to determine, in practice, where the regression in CExC calculation can be stopped. Referring to Fig. 8, a reasonable choice would be that of backtracking the CExC analysis to the level at which the additional contributions are comparable with the uncertainties in the contributions from preceding levels [6,54].
- Coherence between EE and CExC: shows a simplified energy production chain. In EEA, this kind of system must be included in the CV extensions for each material or energy flow. CExC accounts for materials and energy only. Therefore, the use of CExC in EEA should be supplemented with the necessary labour, capital and environmental costs, expressed with their exergy equivalents, incurred by in the entire set of materials/energy production chains.

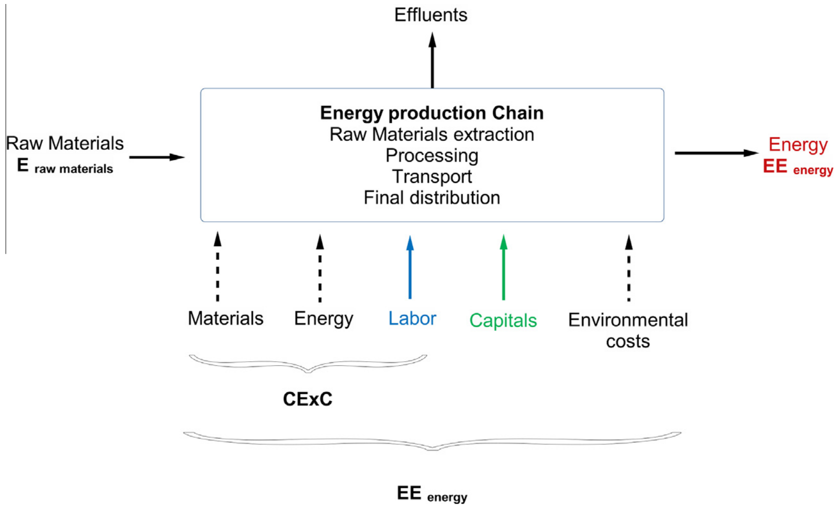

Fig. 12. CExC and EEA calculation schemes of a production chain.

The above reinforces the idea that EEA needs an adequate database that can be built only on the basis of an extensive number of exergy flow diagrams of all the relevant technological systems and conversion processes that represent the current state of the art.

4.2.3. *Exergy equivalent of Labour and Capital*

The definitions of the exergy equivalent of labour and capitals needs some further investigation which must be performed with an open mind, perhaps reassessing the coherence of the simple socio-economic model hitherto adopted for the reference society. This task requires most likely a close cooperation with macroeconomist and/or development economists, which is lacking to-date.

Some weaknesses of the current formulation are related to the relationship between E_{in} and e_{surv} and more specifically to the factor f. While relation (24) implies a linear correlation between HDI and TPES, analysis of these values for different countries clearly shows that HDI does not increase linearly as the energy resource consumption increase.

Moreover the model adopted by EEA for the calculation of the exergy equivalent of the monetary unit, while representing a relevant novelty, it is prone to criticism as well. Indeed, there is no general agreement on the admissibility of calculating an exergy equivalent of capital; the debate on this topic is still in progress.

One important issue concerns the choice of the monetary circulation indicator. The EEA original formulation requires the use of monetary aggregate M2, but there are other monetary aggregates and econometric indicators that may be suitable for this purpose. A brief list is presented below [61]:

- M1 (narrow money): comprises currency in circulation (banknotes and coins) and balances that can immediately be converted into currency or used for cashless payments (overnight deposits).
- M2 (intermediate money): comprises M1 and, in addition, deposits with original maturities of up to two years and deposits redeemable at notice of up to three months. Depending on their degree of liquidity, such deposits can be converted into components of narrow money, but in some cases there may be restrictions, such as the need for advance notification, delays, penalties or fees.
- M3 (broad money): comprises M2 and large and long-term deposits.

There are cases in which none of the above indicators can be used: for example, in their EEA of Chinese society [62] Chen et al. adopted the Gross Domestic Product (GDP) indicator instead of M2, on the contention that the M2 of Chinese society is not representative of the real capital circulation. To avoid the use of different metrics that obviously distort the results and impair reproducibility, it is probably necessary to perform a detailed macroeconomic study to clarify and rationalize the $\mathbf{ee_K}$ calculation model.

Finally, a last problem is originated by the socioeconomic model that the EEA somehow subtends. Indeed, the way in which the exergy equivalent of labour $\mathbf{ee_L}$ is calculated seems to promote the development of less labour intensive system, i.e., of systems with the lowest "social resource" consumption. This statement must be better defined to avoid unduly interpretations, and may lead to different assumptions in the evaluation of the exergy equivalent of labour (28).

$$\mathbf{ee_L} = \frac{f \cdot \mathbf{e_{surv}} \cdot N_h}{W \cdot N_w} [\mathrm{J/h}] \tag{36}$$

where N_w/N_h represents the employment rate of a country and depends on the economy of the country and the contingent welfare condition, while W denotes the annual working hours per worker. By renormalizing the workload to represent the employment condition of the country we obtain:

$$\mathbf{EMPL} = \frac{\nu \cdot W}{8760} \tag{37}$$

In the assumption, valid in a first approximation, that α does not depend on $\nu = N_w/N_h$, for a constant $\mathbf{E_L}$ EMPL grows if the exergy equivalent of labour $\mathbf{ee_L}$ decreases, which implies a reduction in the resource consumption of the individual (average) worker, and indicates that N_h as a whole "consume" less. A little reflection shows that there are two ways to obtain this reduction:

1. By increasing the employment rate, keeping W constant.
2. By decreasing (or keeping constant) the employment rate and increasing W.

Since it is unlikely that α remains constant for the two above scenarios, a socioeconomic evaluation of the effect of applying the above considerations to real societies is needed in order to link them to the local welfare policies and their effectiveness.

5. Numerical example: design analysis of electric power transmission wire

Consider the energy system depicted in Fig. 13: an arbitrary device C absorbs a certain amount of electricity (Pc) from a power source. The electricity feeds the device C through a copper wire of a defined length, represented in Fig. 13 by the component L. After the construction phase, the complete system (C + L) operates for one year. After the operation, the system is dismissed and dismantled. Each one of these phases (construction, operation and decommissioning) absorbs material and energy resources, as well as labour and capital, and generates pollutant emissions.

During the operation of the system, the copper wire L dissipates energy by Joule Effect (steady state operation is assumed). The objective of the thermoeconomic design analysis is to determine the optimal diameter of the copper wire, finding the best tradeoff between investment, operating and dismantling costs.

The numerical example discussed in this section can be used for testing the applicability of EEA and its added value compared to other methodologies. Different cost functions are adopted here: Economic Cost (EC), Cumulative Exergy Consumption (CExC) and

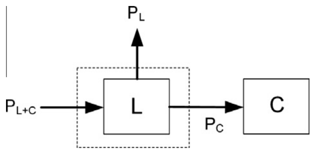

Fig. 13. Electric power transmission line L and electric final user C.

Table 1
Data for the cost analysis.

Data	Units	Value	Description
P_C	W	1000	Nominal power
R_C	ohm	10	Electric resistance
r_L	ohm*m	1.68E−08	Copper electric resistivity
ρ_L	kg/m^3	8940	Copper density
a_L	m	20	Wire length
t_{op}	y	1	Operative life
f	yr_op/yr	0.6	Load factor
h_{op}	h	5364	Operative hours
ee_L	MJ/h	85.33	Exergy equivalent of labour
ee_K	MJ/€	4.58	Exergy equivalent of capital

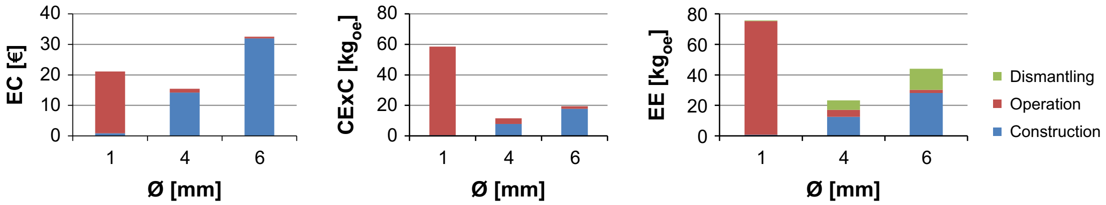

Fig. 14. Results of a EC, CExC and EEA analysis for different wire diameters.

Extended Exergy cost (EE). The investment and dismantling costs represent respectively the costs for producing and dismantling the copper wire, whereas the operating cost is the cost of the electric power dissipated by the wire due to the Joule effect. The data for the thermoeconomic analysis are presented in Table 1.

The following assumption have been made:

- All raw materials and energy flows are accounted for by their chemical and physical exergy, computed according to Szargut's data [6]. The CExC values of copper wire, electricity and other equipment are mainly computed relying on Ecoinvent database [63].
- Where possible, labour and capital costs are directly extrapolated from industrial data.
- Exergy equivalents for labour and capital are taken from [55].
- The decommissioning phase takes into account also the exergetic costs related to the recycling of the copper wire.
- The environmental remediation costs for the pollutant emissions are taken from [64] and determined based on the monetary remediation costs of the best available technology.

Fig. 14 presents the results of a standard engineering economics (EC), a Cumulative Exergy Consumption (CExC) and an Extended Exergy (EE) analysis for three different wire diameters: 1, 4 and 6 mm.

The cost sensitivity to the wire diameter (assumed to be a continuous variable) are displayed in Fig. 15, whereas the results of the optimization procedure are shown in Table 2. The following consideration can be made:

- The total EE is always higher than the CExC: this results was expected, since the EE takes into account additional cost factors (labour, capital and environmental costs).
- An optimal diameter can be identified for each cost function. Is noteworthy that the minimum EE cost is between the minimum Economic and CExC costs. This indicates that the added exergy inputs considered by EEA (capital, labour and environmental costs for all the life cycle phases) modify the balance between the investment and the operative costs.

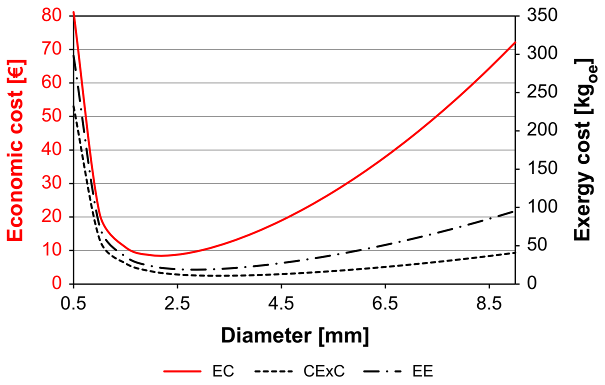

Fig. 15. Sensitivity analysis.

Table 2
Economic, CExC and EE cost for the three identified optimal diameters.

Value	Units	ECO	CExC	EE
d_{opt}	mm	2.19	3.29	2.83
CE	€	8.48	11.48	9.63
CExC	kg$_{oe}$	14.51	10.71	11.21
EE	kg$_{oe}$	21.16	19.49	18.63
ΔECO	€	–	3.01	1.15
ΔCExC	kg$_{oe}$	3.80	–	0.50
ΔEE	kg$_{oe}$	2.53	0.86	–

The above results provide useful information for decision makers: for example, if a standard monetary cost approach is preferred, the optimal diameter will minimize the overall economic costs. But this choice leads to an increase of the global resources consumption: 3.80 kg$_{oe}$ with respect to CExC and 2.53 kg$_{oe}$ with respect to EE, as in Table 2.

Since economic costs need in any case to be considered and cannot be neglected, it is interesting to note that the EE optimum represents a sort of a "compromise" between the other two (Table 2): indeed, the increase in the economic cost for the EE and the CExC optima are different (respectively 1.15 € and 3.01 €).

The example, albeit extremely simplified, shows that EEA is a cost indicator that provides more information than a purely monetary approach, but also generates more realistic results than CExC, with respect to which it has the advantage of embedding the exergy equivalents of the externalities.

6. Conclusions

In this paper a thorough review of the Extended Exergy Accounting method has been presented and revised and a new asset is presented showing its double nature and potential: from one side, EEA can be presented as a general theory with a global validity once that a proper knowledge of the cumulative exergy consumption of different supply chains, economic; from the other, EEA can be viewed as a space and time dependent methodology since economic and labour costs can only be included in the Extended Exergy balance via their exergy equivalents which require the first and the second postulates. The two natures of the EEA may provide relevant information for comparative analysis of energy systems at a global as well as local level.

This review confirms that EEA may be considered as a step forward in evaluating the overall resource consumption of a generic system because it includes social, economic and environmental externalities expressed in homogeneous exergy terms and because it is founded on a genuine life-cycle formulation and is in line with the accepted LC-based methodological taxonomy.

Furthermore, the Extended Exergy cost function can be used within the traditional and very well formalized Thermoeconomic framework, replacing the economic cost function. The EE optimal design, as demonstrated in the numerical example provided in the paper, corresponds to a set of operating parameters that lead to a reduction of the overall resource consumption when compared to economic optimum, and a monetary saving when compared to CExC optimum.

Some drawbacks have been identified in the current EEA formulation, and they point to potential research directions to improve the methodology both from a theoretical and practical point of view. They fall under three major categories: need for standardization, refinement and extension of the CExC database and possibly a more accurate socio-economic model to measure the exergy equivalence of labour and capital.

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