PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

The future of Thermoeconomics: from industrial cost minimization toward cumulative resources accounting and sustainability assessment

Mauro Reini[a] and Melchiorre Casisi[b]

[a] *Dept. of Engineering and Architecture, University of Trieste, Italy, reini@units.it*
[b] *Polytechnic Dept. of Engineering and Architecture, University of Udine, Italy, melchiorre.casisi@uniud.it*

Abstract:
Thermoeconomics has been developed with the main object of first identifying, and then reducing the costs of the energy produced by industrial power plants. More recently, the same approach formalized in the Exergy Cost Theory has been recognized as a useful tool also in a wider field, like industrial symbiosis and sustainability assesment. To do this, exergy supply chains have been tracked backward and backward, to include in the primary resource consumption a more and more complete inventory of the indirect consumption. In Authors' opinion, the future of Thermoeconomics is to go on in this directions. If a very complete inventory of all indirect consumption were obtained, the sustainability assessment of a production process could be performed (at least in principle) by applying the idea that the lower its consumption (direct and indirect) of scarce primary resources, the more sustainable a production process is.
In this paper, the idea of the Thermoeconomic Environment (TEE) is summarized, to highlight as it is a consistent ultimate boundary of the exergy cost accounting, where the origin of the exergy supply chains can be properly placed. Then, the frame of the TEE is used to discuss some possible options for obtaining a more complete inventory of all indirect consumption, and to outline possible perspective connections with some relevant environmental models, coming from Biology, Dynamic of Populations, or Climatology.

Keywords:
Thermoeconomics; Exergy Replacement Cost; Exergy equivalent of capital and labour; Exergy costs of bioproducts; Sustainability.

1. Introduction

Thermoeconomics has been developed with the main object of first identifying, and then reducing the costs of the energy produced by industrial power plants (see, for instance [1-3]). From the beginning, the very fundamental ideas of this approach were:

- All *Fuels* (local resource consumed by a process, or by a component) have to be evaluated in term of the exergy of the streams entering (or leaving) the considered control volume, and the same for the *Products* (goods or commodities locally obtained for the usage in a different part of the system, or for the outside).
- For a process, or a component, the exergy cost of the Products have to be calculated taking all Fuels into account, with their specific exergy costs, disregarding if some Fuels come from the upstream, or the downstream part of the production chain.
- The total cost of the Fuels is allocated on the Products. If a process, or a component, obtains more than one Product at the same time, the total cost is allocated in proportion to the exergy content of each Product.

As a consequence of the previous assumptions, the exergy cost is a conservative magnitude, and the exergy costs obtained by aggregating contiguous control volumes, are consistent with the exergy costs obtained by the previous, smaller, control volumes. These are similar to the properties of the monetary cost, in a closed economy without profit. This analogy is at the basis of the name *Thermoeconomics*.

From the very beginning of Thermoeconomics, the problem arose of including in the exergy cost balance also the resources consumed for owning, operating and maintaining the hardware of the system, i.e. the capital costs of all its parts. The first solution found was consistent with the objective of limiting the Thermoeconomic Analysis to the control volume of a power plant, converting all input flows of resource in terms of monetary costs, using the known values of the unit costs of the energy carriers at the control volume frontier.

https://doi.org/10.52202/069564-0006

In the 80s, a lot of previous ideas about Thermoeconomics have been clarified and organized in an algebraic formulation, named the Exergy Cost Theory (ECT) [4-6].

More recently, the same approach formalized in the ECT has been recognized as a useful tool also in a wider field, like the Industrial Symbiosis [7] and the analysis of eco-industrial parks [8].

In the ECT formulation (as well as in other accounting methodologies, based on the input/output approach [9]) the space boundaries of the analysis are not defined in advance, but they can be adapted case-by-case. In this way, it should be possible, at least in principle, to extend the space boundaries of the analysis, so that the exergy supply chains can be tracked backward and backward, to reach the real primary resources, directly and indirectly consumed, like the raw minerals, the solar radiation, or the biomass in the living ecosystems. If a very complete inventory of all direct and indirect consumption were obtained, the sustainability assessment of a production process could be performed by applying the idea that the lower its consumption (direct and indirect) of scarce primary resources, the more sustainable a production process is. Notice that the idea of *scarcity* plays an important role for assessing sustainability, because the consumption of a certain amount of a very abundant, not renewable resource has to be regarded as more sustainable than the consumption of the same amount of a scarce not renewable one. If this concept is disregarded, we go towards a poor on/off evaluation of sustainability: Goods and process completely based on renewable resources (very few) are identified as sustainable, while all the others, completely, or partially, based on non-renewable resources, are identified as unsustainable!

In view of using the Thermoeconomic approach for cumulative resources accounting and assessing sustainability, a common boundary for the analysis of different goods and processes should be defined. Very recently, the idea of Thermoeconomic Environment (TEE) has been presented [10], highlighting that it may be regarded as a consistent ultimate boundary of the exergy cost accounting, where the origin of the exergy supply chains can be placed, consistently with different exergy accounting methodologies.

In the following, the idea of the Thermoeconomic Environment (TEE) is summarized and then it is used to outline some possible answers to the questions still under discussion in the scientific ambit of exergy accounting. In particular:

- the exergy cost embodied into money capital and human work,
- the proper specific exergy cost to be used for of non-fuel mineral resources,
- the proper approach to be used for the exergy cost accounting of externalities like polluting emissions,
- the proper specific exergy cost to be used for the products of biological systems, which cannot be regarded as supplied “for free” by the ecosystems, neglecting the consumptions and the environmental effects for the production of living stocks, or biomass, inside the ecosystem.

Finally, some possible perspective connections with some relevant environmental models, coming from Biology, Dynamic of Populations, or Climatology are also outlined.

2. The Thermoeconomic Environment

Ones the cost allocation rules have been defined, consistently with the conservative cost balances of all control volumes, the ultimate boundaries of the exergy cost accounting have to be defined, consistently with the purpose of assessing the impact in primary exergy resources of a good, or a service [11].

In the perspective of exergy cost accounting for assessing sustainability, it is evident that the Reference Environment, used in the basic exergy analysis [12], is not well suited for representing the ultimate boundary of the exergy cost accounting analysis. In fact, (i) it is perfectly homogeneous, (ii) its temperature and pressure cannot be modified and (iii) by hypothesis, it cannot be affected in any way by the interaction with the considered system, neither technological nor biological.

Although these characteristics are often considered mandatory for a precise definition of the exergy magnitude, it must also be recognized that they mean that:

- the Reference Environment does not contain any resource; in fact, it is perfectly homogeneous while a resource is generally a concentrated reservoir of some useful substance, or a localized energy flow, which is able to produce useful work while its thermodynamic state is transformed approaching the equilibrium with the defined reference conditions;
- the global warming cannot be accounted for, even in theory, because the temperature of the Reference Environment cannot be modified, in contrast with the evidence of a global temperature change that is happening as a consequence of the interaction of the real environment with the industrial system made by man [13];
- any polluting emissions from the considered production systems have no effect at all on the Reference Environment.

The last point in particular may be regarded as inconsistent, in Authors’ opinion, with the target of an appropriate exergy evaluation of the environmental impact of the industrial processes, at global scale.

https://doi.org/10.52202/069564-0006

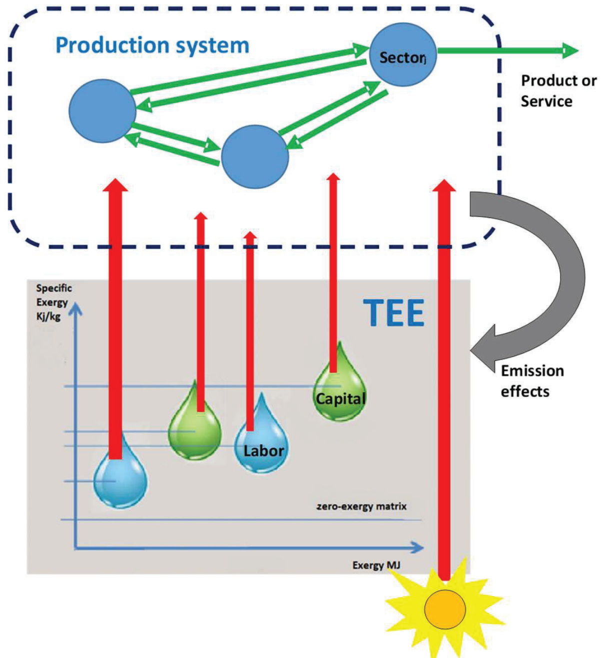

Fig. 1. A qualitative description of some reservoirs in the TEE [10].

To overcome the drawbacks highlighted previously, the TEE has been recently proposed. It is a model of environment, defined as a set of reservoirs, where different kind of natural resources are confined, consistently with the physical nature of the real-world energy systems, which do not operate in a homogeneous environment, but they are fully immersed in the biosphere. All reservoirs are surrounded by the zero-exergy matrix, which plays the role of the dead state for calculating the exergy of all flows inside the energy systems, as well as of all reservoirs (Fig.1). Notice that a specific exergy content greater than zero has to be assigned to each available resource.

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, directly or indirectly, by the production processes. In addition, it must be recognized that even the zero-exergy matrix may change its temperature T° and composition in consequence of some real-world phenomena, like the periodic oscillations of the availability of solar energy or the global warming, which is nowadays increasing as consequence of GHG emissions.

3. Extending the boundary of Thermoeconomic Analysis

If the history of Thermoeconomics and of all exergy-based cost allocation techniques is revised (see, for instance [14]), it clearly appears that this historical development may be regarded as a continuous effort to extend backward the exergy supply chains, toward the primary resources available in the environment (i.e. the reservoirs included inside the TEE).

Very few years after the first application of the Thermoeconomic thinking (1973), the effort of extending the control volume from the gates of the industrial plants, toward the primary resources was formalized by Szargut [15]. He 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 focused mainly on mineral resources, assuming an exergy cost equal to one for the chemical exergy of those resources, and it did not include any externalities. A list of CExC values for a large number of finished materials and energy vectors are available in literature [16].

At that point, it appeared as evident that the industrial plants do not consume only the conventional productive factors passing the gates of the plants. Also the polluting emissions, generated during the production process do consume natural resources, to be dispersed and neutralized in the biosphere. To consider this additional resource consumption, the Thermo-Ecological Cost (TEC) [17] was introduced by Szargut. In this last approach, a fictitious extension of the plant is considered, where the polluting emissions are treated in order of obtaining a completely neutralized effluent (or at least an effluent respecting the more restrictive prescriptions actually operating) which can be released in the environment without any damage. The resources expected to be consumed for the fictitious extension of the plant constitute the ecological cost for polluting emissions, which is used to complement the CExC and to obtain the TEC.

Notice that other Authors, too, use the same procedure for an exergy evaluation of polluting emissions, in particular Sciubba [11] in the Extended Exergy Accounting (EEA), where special emphasis is put in taking into account the entire life cycle of a good, or a service.

After including in the total consumption the effect of polluting emissions and all the main direct and indirect exergy resources supplied to the plant (being the exergy content of some non-fuel minerals quantitatively negligible) the picture could seem complete. Nevertheless, it is not. In fact, even if the hypothesis of a specific exergy cost equal to one for all reservoirs inside the TEE is accepted (as implicitly assumed by TEC and EEA), the operation of tracking back all supply chains towards the indirect primary exergy consumptions may be a very difficult task. In particular, when money capital and human work are considered among the production factors involved in those chains. Money links all sectors of an industrial economy to each other and is used at different stages in the construction and operation of manufacturing facilities. The availability of human work requires food, clothes, instruction, houses, transports, healthcare, etc. All of them are complex products in an industrial economy. To untie all these tangled links, the EEA introduces the exergy equivalent of work and the exergy equivalent of capital, which can be computed based on the Human Development Index (HDI) and the total quantity of circulating money and financial activities that can perform the same functions as money (M2) [18]. Notice that, in the frame of the TEE, this approach means that the TEE contains a reservoir of capital and another of human work and that the specific exergy costs of both resources is known.

4. The proper exergy cost of primary resources

Not only the specific exergy costs of capital and human work have to be known, but also those of all available resource inside the TEE have to be identified, in order of obtaining a meaningful set of product costs by applying the exergy accounting. A straightforward option is considering equal to one by hypothesis (see, for instance, [5]) the specific exergy costs of all exergy reservoirs present in the TEE. This approach expresses the idea that a certain exergy stock of non-renewable resources is available in the TEE at the present moment, jointly with a set of exergy flows of renewable resources (including the renewable part of all partially renewable reservoirs). It is consistent with the CExC and the derived approaches, and with the EEA, too. Then, the exergy cost of a good, or service, is the part of the exergy available in the TEE that is consumed directly or indirectly for obtaining it. This may be correct if the dynamic processes allowing the exergy accumulation inside the reservoirs can be neglected. This is possible, for instance, when the accumulation process is very slow, compared with the production process considered in the analysis, like for natural fossil fuel, or other mineral reservoir. Otherwise, if a dynamic exists inside the TEE and it provides an exergy accumulation inside the reservoirs at a time scale comparable with that of the considered good, or service, it should be taken into account. In fact, the exergy extraction from a certain reservoir may produce an exergy destruction in some other reservoirs of the TEE, in addition to the extraction up from the former reservoir. In this second case, two options can be immediately identified: (i) to extend the supply chain describing the indirect consumption of resources, or (ii) to define a set of specific exergy costs, not equal to one, which takes into account the effect of the mechanism of additional exergy resource consumption. As previously noted, this second option has been used for introducing the externalities of capital and human work consumptions into the EEA.

The meaning of the first option is that the TEE has its own internal production processes. In this case, the specific exergy costs of the exergy reservoirs should be determined by applying the same exergy accounting techniques considered for the manufacturing systems.

Various Authors, in particular Valero A. C. and Valero A. D. [19], have highlighted that, if the specific exergy costs of all exergy reservoirs present in the TEE were fixed at a value equal to one, a sort of inconsistency would arise: all non-fuel mineral resources would have a very low exergy cost, because of their poor chemical exergy content. This happens although some of them are quite rare and someone even valuable. Consequently, some industrial products appear to have an exergy cost that is extremely little dependent on the presence of rare materials and this is in strong contrast with the technological effort undertaken to reduce the presence of such materials, or to replace them with non-rare ones. This effort implies actions in parallel, or in competition with those for increasing the exergy efficiency of the modern production of goods and services, so that, it cannot be simply disregarded.

Paying attention to the rare or valuable characteristic of some minerals may seem irrelevant to the issue of accounting for exergy costs, and only meaningful in relation to the market economy. However, consider the conceptual example of an industrial economy fed by a TEE with only two non-renewable reservoirs, let's say coal and iron ore. That economy could obtain many technological products, but certainly not all the modern industrial goods. This example allows us to infer easily that the availability inside the TEE of many abundant reservoirs of *different* chemical nature is an asset for the industrial system, just like the availability of fossil fuels. In few words, the *Chemiodiversity* (that can be defined analogously to the most popular *Biodiversity*) of the TEE is a resource and has to be accounted for in the calculation of the exergy costs. In addition, consuming

 https://doi.org/10.52202/069564-0006

a scarce resources is different (less sustainable) that consuming an abundant one, even if they both were, for instance, not renewable.

The proper specific exergy cost to be used for non-fuel mineral resources has been proposed by Valero A. C. and Valero A. D. [19], by introducing the exergy replacement cost (ERC) of mineral resources. The ERC has to be regarded as the exergy cost required for producing a reservoir of a certain mineral resource, from the conditions defined for the Thanatia planet, where the confining constraints of all reservoirs have been destroyed and all mineral resources are mixed together. In other words, the reconstruction of the mineral deposits (i.e. the cradle of the resources consumed by the production process) requires an exergy expenditure, because real-world, irreversible technologies are used. An exergy cost greater than the mere content of chemical exergy can be identified in this way for all mineral reservoirs in the TEE. In its original formulation, the ERC calculation implicitly assumes that the input exergy is available for the ideal process of reconstruction of a mineral resource as it is in the real-world industrial system, being the process constrained only by the concentration of each chemical substance in the Thanatia environment. Notice that this makes sense (at least for an ideal experiment) if the replacement of a small sample of a certain mineral resource is considered. On the contrary, the replacement of *all the mineral resources consumed* by the global industrial system is not possible, neither in principle, because of the exergy losses in both cradle-to-grave and grave-to-cradle conversion processes. To make it possible (at least for an ideal experiment) an exergy source external to the bio-geosphere of the planet Earth should be considered.

4. The future of Thermoeconomics

In Authors' opinion, the future of Thermoeconomics must continue in the directions outlined above, in particular:

a) integrate the ERC concept into exergy cost accounting methodologies and sustainability assessment,
b) identify an appropriate specific exergy cost to be used for products of biological systems,
c) develop the exergy assessment of the environmental impact of industrial processes, on a global scale,
d) explore alternatives to evaluate the exergy cost embedded in money capital and human labour.

4.1. ERC integration

A first progress in the direction indicated in point a) has been recently obtained by integrating the ERC with the CExC approach, obtaining the new thermoecological-cost methodology [20].

When the object of the analysis is assessing the sustainability of a technology, or of an industrial sector, it is important to pay attention to the replacement of all the mineral resources consumed by the industrial sectors, directly or indirectly connected inside the global system.

As just mentioned, this is possible only if an exergy source external to the bio-geosphere of the planet Earth is considered. The only exergy input external to the geo-biosphere is solar energy (and possibly tidal and geothermal energy). Thus, the ERC may be understood as the exergy cost that should be payed to re-obtain a certain non-renewable resource by using additional renewable external exergy input [10], i.e. to allow its usage as it were renewable, excluding its exhaustion, on a human time scale. This interpretation does not require any conceptual modification of the ERC definition and is consistent with the idea that unit exergy costs greater than one can be considered for the reservoirs in the TEE. The numerical values of the ERCs of the different mineral resources may result amplified by a factor equal to the inverse of the exergy efficiency of the conversion process that produces the form of exergy required by the replacement process starting from solar radiation. Notice that this occurrence is implicit in the idea of using real-word technologies, so that, when the technologies change, also the values of the ERCs may change.

4.2. Products of biological systems

For what concern the direction indicated in point b), it has to be recognized as a difficult task, with few suggestions available in Literature. In fact, the products of the biological systems are resources of the kind having their own dynamic connecting many different reservoirs each other inside the TEE, for which a natural exergy accumulation may be present, at a time scale comparable with that of goods production by the industrial economy. Bakshi and co-workers [21] have proposed one of the few historical contribution in this direction. They have defined the approach named Ecological Cumulative Exergy Consumption (ECEC), that is identical to the CExC for what concern the contribution of mineral resources, whilst the exergy cost of the products of the biological systems are assumed to be equal to the emergy of the same products, calculated in the ambit of the EMergy Analysis (EMA) [22].

The EMA allows overcoming the difficulties related to a detailed knowledge of the exergy flow network that is required to apply The CExC, or the ECT. In fact, only the inputs to the whole ecosystem have to be known in detail. Unfortunately, in the EMA approach, the ultimate boundary of the accounting analysis is placed in the solar energy that fed the whole geo-biosphere from the distant past to now, not in the TEE as it is at present time. In addition, special allocation rules (the Emergy Algebra), are used, which are only in part analogue to a conservative cost balance. In summary, the EMA has some characteristics that make energy engineers often sceptical about the option of incorporating the results of this approach inside the exergy cost accounting of goods and services [23].

The frame of the TEE offers an alternative for the calculation of the exergy costs of the products of biological systems, similar to the ERC of the mineral resources and consistent with the EEA approach. In this case, too, some information is required about the ecosystem dynamic, but it mainly consists of the parameters of natural growth rate and of extraction rate, which are not difficult to obtain (see, for instance [24]).

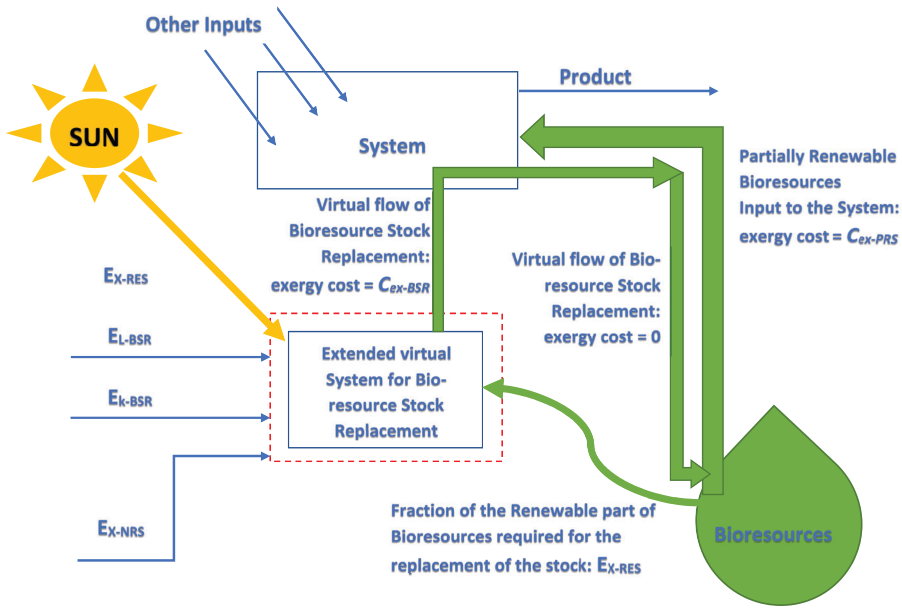

Fig. 2 The concept of Bioresources Stock Replacement Cost [10].

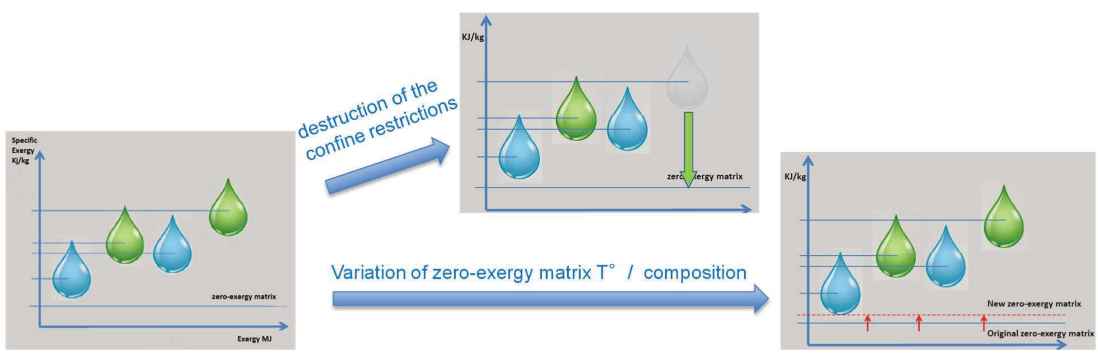

Fig. 3 A qualitative description of possible depletion of the exergy stock inside the TEE.

An extension of the system is considered (see Fig. 2), the function of which is to replace the stock of the bioresource reservoir in the TEE, if the stock has been affected by the operation of the system. In fact, if the bioresource is consumed at an extraction rate lower than (or equal to) its growth rate, the stock is not affected and the input to the production system can be regarded as completely renewable, like solar radiation, and its exergy cost can be equal to one as that of the solar radiation. On the contrary, if the extraction rate is greater than the growth rate, the exergy stock of the TEE is consumed and the extended system has to cultivate the ecosystem, to produce the biomass required to replace the original stock. The bioresource stock replacement cost (BSR) can be calculated because the exergy costs of the inputs of the extended system can be known [10, 25].

4.3. Environmental impact

To develop the exergy assessment of the environmental impact of industrial processes (point c), it is worth noting that the remediation cost for neutralizing the chemical and physical exergy of waste (the cost considered by both the CExC and the EEA, among others) may be the same whether or not waste treatment strategies

https://doi.org/10.52202/069564-0006

are actually applied. In fact, part of the costs are actually incurred within the real plant, while the other part (so as, to have virtually neutralized emissions) is incurred in the fictitious extension of the plant. In other words, the cost charged on the plant products because of polluting emissions may independent by the degree of emission cleaning actually operated. Moreover, the cost for the actual treatment may be even higher, because real processes are generally 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. To avoid this inconsistency, an alternative approach has been suggested in the frame of the TEE [10, 25], where the actual exergy cost of polluting emissions has to be defined as the real exergy stock depletion produced by the polluting emissions. Bearing in mind the definition of TEE, it is easy to deduce that a certain depletion of the exergy stock can be caused, besides consumption, also by:

- destruction of the confine restrictions of reservoirs (see Fig. 3),
- variation in the zero-exergy matrix temperature or composition(see Fig. 3),
- dilution of substances inside the reservoirs, reducing their concentration,
- 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).

It is worth noting that the suggested alternative approach requires an inventory of the effects of the identified polluting emissions and then the translation of those effects in terms of depletion of the exergy content of the reservoirs inside the TEE. The effort of the first step is similar to that required by the LCA [26] of a process, whilst the second step requires an appropriate evaluation of the specific exergy cost attributed to each reservoir, in order of obtaining the total exergy cost of the polluting emissions [27]. Moreover, the evaluation of the exergy stock depletion produced by some pollutant may vary, because new effects may be discovered. This may be regarded as a negative point, because the evaluation is, to some extent, dependent on the historic moment. Or as a positive point, because new discoveries can be integrated in the evaluation, allowing well supported decision for improving the sustainability of the production processes. It is worth noting that this alternative approach define a connection among Thermoeconomics and the ecological models developed in different scientific fields, in particular with the climatic models, that have assumed increasing importance in the recent years [13] because of the arising of the global warming.

4.4. Money capital and human labour

The final topic (d) of the future development of Thermoeconomics will be, in Authors opinion, the development of alternatives to evaluate the exergy cost embedded in money capital and human labour. The exergy equivalent of money capital and of human work following the methodology of the EEA have been presented in the previous sections. Rocco and Colombo [28] have proposed an alternative approach, which can be regarded as an exergy extension of the input/output analysis, originally formulated by Leontief [9]. 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 cost accounting of each flow in the model is obtained considering the exergy of all inputs coming from the environment and feeding the sectors (the nodes) of the production network. The exergy equivalent of capital has not to be evaluated explicitly in this procedure and (if it is evaluated *a posteriori*) it may result different for the different production sectors considered.

As far as the exergy cost accounting of human work is concerned, the suggestion by Rocco and Colombo [28] is again a direct extension of their exergy input/output analysis. Human labour is embedded as an additional sector, without the need of any arbitrary assumption. Obviously, additional information is required, in particular the quantitative evaluation of the inputs required by the human working activities from each one of the other sectors and, likewise, the human working hours required by each of them.

It has been previously highlighted that the development of the exergy assessment for the environmental impact of polluting emissions will imply a more strict connection with the ecological models developed in different scientific fields. In conclusion, it is worth noting that, in the same way, the identification of a detailed information about the exergy cost embedded in money capital and human labour will imply a strict integration with the input/output models coming from the economic analysis.

5. Is Thermoeconomics a science?

This question has been always present, even not explicitly asked, from the very beginning of the exergy based cost accounting methodologies:

Is Thermoeconomics a science?

The question may appears as inappropriate, out of place, and even insulting. Thermoeconomics comes from the exergy analysis that means from the Second Law of Thermodynamics. It has to be close to the holy hart of Physics.

https://doi.org/10.52202/069564-0006

Unfortunately, the exergy cost cannot be measured like mass, or energy. In fact, these magnitudes can be measured independently from the thesis to be demonstrated. By using the measured values of two masses, it can be demonstrated that the gravitational attraction between them is proportional to the product of the two masses. By using the measured value of the potential energy of a body, the Joule experiment can be performed, demonstrating the energy equivalent of heat. On the contrary, the exergy cost cannot be measured independently by the cost allocation rules, the inventory of the flows regarded as relevant (whilst a lot of others are disregarded), the hypotheses about the exergy equivalent of money capital and of human labour, and so on. Ones the cost allocation rules are defined, together with all other required information, the calculated exergy costs cannot be wrong, *they are right by hypothesis*. They may be more or less useful from an engineering point of view (this is true), but this is far from a clear scientific result.

To claim Thermoeconomics as a science, it should be shown that the exergy costs (or the specific exergy costs) are involved in some physical phenomena different from their calculation procedure. Perhaps, this could be investigated referring to a process without any requirement of money capital or human labour, and with a clearly identified environment, where all resources come from. Such a process could be a network of chemical reactions, where reactants and products could be identified for each reaction, or better, the metabolic network of a simple bacterium in a Petri dish.

This investigation line is nowadays under development [29, 30]. The object is to show that, under well-identified conditions, the minimization of the specific exergy costs of the products plays a role [31, 32] analogous to the Constructal Principle, formulated by Bejan [33] and often considered to be a physical principle of the same rank of the First and Second Law of thermodynamics [34]. If this hypothesis were confirmed, it would be definitely demonstrated that Thermoeconomics is more than a useful engineering tool, but a real scientific field.

6. Conclusions

In the paper the history of Thermoeconomics is quickly summarized, highlighting how its development may be regarded as a continuous effort to extend backward the exergy supply chains, toward the primary resources available in the environment. In fact, this allows including in the economic and sustainability assessment a more and more complete inventory of direct and indirect consumption. If a very complete inventory of all direct and indirect consumption were obtained, the sustainability assessment of a production process could be performed by applying the idea that the lower its consumption (direct and indirect) of scarce primary resources, the more sustainable a production process is. In spite of being apparently a simple idea, this effort is still not completed.

In Authors' opinion, the future of Thermoeconomics will be going on in the direction of improving the inventory of all direct and indirect consumption related to a production process, in order to supply a more complete information to the decision-makers in the field of industrial sustainability. In the paper, some specific directions have been identified, like:

a) The integration of the Exergy Replacement Cost of rare mineral resources into the exergy cost accounting methodologies and sustainability assessment.
b) The identification of an appropriate specific exergy cost to be used for the products of the biological systems. In this direction, the exergy Bioresources Stock Replacement Cost has been presented as an alternative to other approaches, keeping the consistency with the exergy cost accounting and the Exergy Replacement Cost formulations.
c) The continuous improving of the exergy assessment for the environmental impact of industrial processes, on a global scale. In this direction, the frame of the Thermoeconomic Environment may help overcoming a drawback of the exergy assessment of pollution, in which a highly polluting plant may appear to be less resource-consuming (more sustainable) than a plant that obtains the same product cleanly.
d) The exploration of alternatives to evaluate the exergy cost embedded in money capital and human labour.

Is worth noting that the development of the exergy assessment for the environmental impact of the production processes will imply a more strict connection with the ecological models developed in different scientific fields. In the same way, the identification of a detailed information about the exergy cost embedded in money capital and human labour will imply a strict integration with the input/output models coming from the economic analysis. In addition, all these improvements of the inventory of direct and indirect consumption have to be integrated into a unique frame. For instance, the exergy cost embedded in human labour should be accounted for in the Exergy Replacement Cost of rare mineral resources, and Bioresources Stock Replacement Cost should be accounted for in the assessment for the environmental impact of industrial processes, if even distant ecosystems are affected by their emissions.

In conclusion, the question if Thermoeconomics has to be regarded as a science, or not, is briefly discussed and a possible path to demonstrate that Thermoeconomics is more than a useful engineering tool, but a real scientific field, is outlined.

https://doi.org/10.52202/069564-0006

Acronyms

BSR Bioresource Stock Replacement Cost,

CExC Cumulative Exergy Consumption CExC,

ECEC Ecological Cumulative Exergy Consumption,

ECT Exergy Cost Theory,

EEA Extended Exergy Accounting,

EMA EMergy Analysis,

ERC Exergy Replacement Cost,

GHG Greenhouse Gases,

LCA Life Cycle Assessment,

TEC Thermo-Ecological Cost,

TEE Thermoeconomic Environment.

References

[1] Fehring T. H., Gaggioli R. A., Economics of feedwater heater replacement, Trans. ASME, J. Eng. Power, vol. 99, pp. 482-489, July 1977.

[2] Gaggioli R.A. and Petit P.J., 1977, Use The Second Law First, Chemtech, 7, 496-506.

[3] Rodríguez L. S. J., Gaggioli R. A.,1980, Second law of a coal gasification process, Can. J. Chem. Eng., vol. 58, p. 376.

[4] Valero A, Lozano M A, Munoz M., A general theory of exergy savings - 1. On the exergetic cost, Proc. ASME Computer-Aided Engineering of Energy Systems, v. 3, Second law analysis and modelling, pp. 1-8, Anaheim, Ca., 1986.

[5] Valero A., Serra L., Uche J., Fundamentals of Exergy Cost Accounting and Thermoeconomics. Part I: Theory, Journal of Energy Resources Technology, March 2006, Vol. 128.

[6] Lozano M, Valero A. Theory of the exergetic cost. Energy 1993, 18, 939–960.

[7] Usón S, Valero A, Agudelo A, Thermoeconomics and Industrial Symbiosis. Effect of by-product integration in cost assessment, Energy Vol. 45, Issue 1, September 2012, Pages 43-51.

[8] Valero A. et. Al., Thermoeconomic tools for the analysis of eco-industrial parks, Energy, Volume 62, 1 December 2013, Pages 62-72.

[9] Leontief W. W., The structure of the American economy, 1919–1939, 2nd Ed., Oxford University Press, New York, 1951.

[10] Casisi M., Khedr S., Reini M., The Thermoeconomic Environment and the exergy-based cost accounting of technological and biological systems, Energy 2023, Volume 262, Part A (available on line: 14 August 2022).

[11] Sciubba E, Bastianoni S, Tiezzi E., Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy. J Environ Manage 2008;86:372–82.

[12] Kotas T., The Exergy Method of Thermal Plant Analysis, New Publisher, 2021.

[13] Giorgi F., Coppola E. and Raffaele F., A consistent picture of the hydroclimatic response to global warming from multiple indices: Model sand observations, J. Geophys. Res. Atmos. (2014), 119,11,695–11,708, doi:10.1002/2014JD022238.

[14] Sciubba E., Wall G., A brief Commented History of Exergy From the Beginnings to 2004, Int. J. of Thermodynamics ISSN 1301-9724, Vol. 10 (No. 1), pp. 1-26, March 2007.

[15] Szargut J., Morris D. R., Steward F. R., Exergy analysis of thermal, chemical, and metallurgical processes. Hemisphere; 1988.

[16] Szargut J., Exergy method: technical and ecological applications. WIT Press; 2005.

[17] Szargut J., Ziebik A., Stanek W., Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. Energy Convers Management 2002; 43:1149–63.

[18] Sciubba E., A revised calculation of the econometric factors □- and □ for the Extended Exergy Accounting method. Ecological Modelling 222 (2011) 1060–1066.

[19] Valero A. C., Valero A. D., Thanatia-The destiny of the earth's mineral resources - a thermodynamic cradle-to-cradle assessment, Ed. World Scientific Publishing Company, 2014, 670 pp.

https://doi.org/10.52202/069564-0006

[20] Valero A., Valero A., Stanek W., Assessing the exergy degradation of the natural capital: From Szargut's updated reference environment to the new thermoecological-cost methodology. Energy 2018, 163, 1140–1149.

[21] Hau Jorge, Bhavik L., Bakshi R., Expanding exergy analysis to account for ecosystem products and service, Environ. Sci. Technol. 38 (2004) 3768-3777.

[22] Odum H.T., Environmental Accounting: Emergy and Environmental Decision Making (1st edition). John Wiley & Sons, New York, 1996, 370 pp.

[23] Sciubba E., Ulgiati S., Emergy and exergy analyses: Complementary methods or irreducible ideological options? Energy, Volume 30, Issue 10, July 2005, Pages 1953-1988.

[24] Cordier M. et al., An Input-output Economic Model Integrated Within a System Dynamics Ecological Model: Feedback Loop Methodology Applied to Fish Nursery Restoration, Ecological Economics Volume 140, October 2017, Pages 46-57.

[25] Khedr S., Casisi M., Reini M., The Thermoeconomic Environment Cost Indicator (iex-TEE) as a One-Dimensional Measure of Resource Sustainability, Energies 2022, 15, 2260.

[26] Klöpffer W., Life cycle assessment. Environmental Science & Pollution Research 4, 223–228 (1997). https://doi.org/10.1007/BF02986351.

[27] Dewulf J. et al., Cumulative Exergy Extraction from the Natural Environment (CEENE): a comprehensive Life Cycle Impact Assessment method for resource accounting, Environ. Sci. Technol. 2007, 41, 8477–8483.

[28] Rocco M., Colombo E., Internalization of human labor in embodied energy analysis: Definition and application of a novel approach based on environmentally extended Input-Output analysis, Applied Energy 182 (2016) 590–601.

[29] Assal S., Malfatti F., Giani M., Reini M., Exergy and exergy cost analysis of biochemical networks in living systems far from equilibrium, Proceedings of the 9th International Conference on Bioinformatics Research and Applications - ICBRA '22, September 2022 Pages 36–40 https://doi.org/10.1145/3569192.3569199.

[30] Assal S., Application of exergy analysis in living cells: A case study with Escherichia coli as a biofuel source, Journal of Fundamentals of Renewable Energy and Applications, 2023, Vol. 13.

[31] Reini M., Constructal Law & Thermoeconomics, International Journal of Heat and Technology, Volume 34 (January 2016), Special Issue 1, pp. S141-S146. Presented at the Constructal Law & Second Law Conference 2015 CLC 2015, Parma (Italy), 18 - 19 May 2015.

[32] Reini M., Casisi M., Is the evolution of energy system productive structures driven by a physical principle?, Front. Sustain., 25 March 2021, https://doi.org/10.3389/frsus.2021.599173.

[33] Bejan A., Evolution in thermodynamics, Applied Physics Reviews, Vol. 4, No. 1, 011305, 2017.

[34] Reis A. H., Use and validity of principles of extremum of entropy production in the study of complex systems, Annals of Physics 346 (2014) 22–27.

 https://doi.org/10.52202/069564-0006