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On the Future of Exergy-based Methods

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Abstract:

In 1984 the author coined the term *exergoeconomics* to replace the term *thermoeconomics* when *exergy costing* is used in the combination of an exergetic analysis with a cost analysis and to emphasize the role of exergy in the efforts to reduce the product cost. He also developed a general exergoeconomic methodology based on appropriate definitions of the “product” and “fuel” for each component of an energy conversion system and on exergy-based variables. These definitions and the application of exergoeconomics were generalized by A. Lazzaretto and the author in 2006 in an approach based on specific costs (*SPECO approach*).

Mayer and the author coined in 2009 the term exergoenvironmental analysis for a combination of an exergy analysis with a life-cycle analysis when exergy is used to assign environmental impacts to streams. An exergoenvironmental analysis uses the methodological background of the above exergoeconomic methods.

Starting in 2002, the author and later, in cooperation with T. Morosuk and co-workers at TU Berlin, developed the advanced exergy-based methods, which are based on the notion that the inefficiencies (exergy destruction and exergy loss), the costs, and the environmental impacts can be split into avoidable/unavoidable and endogenous/exogenous parts, to improve understanding of the formation process of inefficiencies, costs and environmental impacts within an energy conversion system, to reduce the limitations of the conventional exergy-based methods, and to facilitate system optimization.

As often happens, after their introduction, all the above terms and methods have been misused and misinterpreted by some other authors.

This paper very briefly reviews past contributions by the author and some other exergy practitioners and discusses future developments.

The exergy-based methods allow for a comprehensive and consistent simultaneous evaluation of the performance of an energy conversion system from the thermodynamic, economic, and environmental viewpoints. However, the advanced exergy-based methods need further investigations to be generalized, integrated and to reduce their subjectivity as well as the efforts and time required for their application. Development of appropriate software and short-cut methods will facilitate their use by researchers and engineers in industry and the applications of exergy-based methods in energy-intensive industrial processes for multiobjective optimization purposes.

Keywords:
Thermoeconomics; Exergoeconomics; Exergoenvironmental analysis; Advanced exergy-based methods; Optimization of energy systems.

1. Introduction

In the analysis, evaluation and optimization of energy-conversion systems (ECS), progress has been made every time the limitations of an existing method have been identified and solutions for overcoming at least some of these limitations have been developed. Thus, after realizing that an energy-based method can lead to misleading results and conclusions, the exergetic analysis, which combines the concepts of energy and entropy, was adopted as the appropriate method for analyzing and evaluating ECS from the thermodynamic viewpoint. All alternative terms used to characterize an exergetic analysis (e.g., the term “second-law analysis”) are not accurate, because this analysis combines the second *and* the first laws of Thermodynamics.

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An exergetic analysis identifies the location, magnitude and causes of inefficiencies within an ECS. The inefficiencies are measured in terms of exergy destruction and exergy loss [1]. Based on the results received by an exergetic analysis, changes in the design and operation of an ECS can be identified to improve its exergetic efficiency, which is the best variable for evaluating the thermodynamic performance of an ECS. An exergetic analysis can be applied also to very complex systems and is the most effective method for evaluating and improving the thermodynamic performance of a system. Various variables can be used to measure the performance of an ECS (for example, thermodynamic efficiency, cost of product(s), environmental impact, rate of return on investment, and payback time). An exergy-based method should be able to consider all of these measures of performance. Finally, an exergetic analysis can stimulate and guide creativity and innovation [2].

In order to predict future developments, we must first understand and evaluate what has happened up to now. Therefore, the following two sections refer to past contributions to the exergy-based methods by the author and his co-workers as well as by other authors, before in section 4 the needs for future developments are discussed. It is important to keep in mind that all analyses of an ECS should consider the entire life time of the system.

This is a brief review paper. Because of space limitations no equations to describe the methods are given. The equations are available in the literature cited for each method. Also the mathematical cost minimization methods developed for an ECS are not discussed here (even the ones using exergy) because in these methods (a) we need to know the investment costs of components as functions of thermodynamic variables and such information is not readily available, and (b) we cannot include in the optimization considerations related to safety, maintainability, and operability of the plant, considerations that could be easier incorporated into an iterative improvement approach, such as the approaches discussed here.

2. Contributions by the author and his co-workers: From exergetic analysis to the advanced exergy-based methods

An exergetic analysis assists in the *thermodynamic* optimization of an ECS. In real-world applications, however, realization of the thermodynamic optimum would result in very high investment and product costs. Therefore, we are interested in a solution that minimizes the product cost and not in a solution that maximizes efficiency. Thus, an economic analysis must be considered in parallel and in addition to the exergetic one. From a combination of the two analyses, we obtain the maximum useful information, when both following conditions are fulfilled: (a) the two methods are combined using the exergy-costing principle [1], and (b) the analysis is conducted at the system component or a lower level. The term *thermoeconomics* was initially used for this combination (e.g., [3]). However, after noticing that the term "thermoeconomic analysis" was used also in publications that were not employing the exergy-costing principle, which is essential here, the author introduced in 1984 the term *exergoeconomics* (or *exergoeconomic analysis*) to more accurately characterize this combination, to emphasize the role of exergy in cost minimization, and to clearly distinguish the different approaches [4]. In the same publication, the terms *fuel* and *product* were generalized, the variables *cost per unit of exergy for fuel and product*, *cost difference* (which later was replaced by the *relative cost difference*) and *exergoeconomic factor* were introduced, and the formulation of the exergy balances and cost balances was generalized. These generalizations allowed later a consistent evaluation of the thermodynamic, economic, and environmental performance of an ECS. For a long time the terms thermoeconomics and exergoeconomics were used in parallel as synonyms by the author (e.g., [1]). Unfortunately the term exergoeconomics has been used in the past by some other authors in cases where only an exergetic analysis and an economic one were conducted without using the exergy costing principle and without using an appropriate combination of the two analyses, thus contributing to a certain confusion surrounding the meaning and use of these terms.

Purpose plays a central role in exergy-based analyses, where a *product* is defined unambiguously for every system component and process according to its purpose [4-8]. The ratio between *product* and *fuel* is the exergetic efficiency of the thermodynamic system being considered. An exergetic analysis provides the most rigorous definition of thermodynamic efficiency and the foundation for assigning costs (in an exergoeconomic analysis, e.g., [1, 4-9]) and environmental impacts (in an exergoenvironmental analysis [10,11]) to energy carriers. The definitions of exergetic efficiency have been generalized in the SPECO method [9].

The continuously increasing interest in environmental considerations in the last decades led to the development of the exergoenvironmental analysis, which identifies the location, magnitude and causes of environmental impacts associated with an ECS [10-12]. Thus, using an appropriate definition for *product* and *fuel* for each component of an ECS [9], engineers obtain *consistent*, informative, and powerful analyses and evaluations from the viewpoints of thermodynamics, economics and envirnmental impact.

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A conventional exergy-based method, however, does not assess (a) the parts of exergy destruction, cost and environmental impact that can be realistically avoided in a component or a process (by increasing the capital investment), and (b) the interactions among components with respect to exergy destruction, cost and environmental impact. These drawbacks of a conventional analysis are corrected in the *advanced exergy-based methods* (AEBM) (see, for example, [13-19]). By considering the avoidable/unavoidable values, the endogenous/exogenous values and their combinations (endogenous avoidable, exogenous avoidable, etc.) and by applying these concepts to the exergetic, exergoeconomic, and exergoenvironmental analyses, we obtain the most comprehensive set of analyses and evaluations of an ECS available today.

When dealing with exergy streams carrying a significant amount of *useful* chemical exergy, a distinction in the costs and environmental impacts associated with chemical and physical exergy might be meaningful. In addition, the chemical exergy should sometimes be split into reactive and non-reactive exergy [1] (e.g., in a gasification or chemical process), and the physical exergy, into thermal and mechanical exergy [20] (e.g., in a refrigeration process) to enable the definition of meaningful efficiencies, to improve the accuracy of calculations, to make fairer the calculation of costs and environmental impacts, and to improve the quality of conclusions drawn from the results of applications of exergy-based methods to an ECS.

Recently R. Castillo developed the *thermodynamic cost accounting* (TCA) approach, a novel exergy-based approach to determine the cost formation process and the formation of environmental impacts within an ECS [21]. Compared to the approaches discussed above, this approach emphasizes the boundaries to the overall system (instead of the component level), takes a different approach to the interactions among components, extracts useful conclusions from the Castillo Paz diagram, and clearly reveals the importance of recirculating streams to the thermodynamic, economic, and environmental performances (see, for example, the application of the TCA to the CGAM problem [7, 21]).

3. Contributions by other authors

Based on the ratio between the cost per unit of exergy of a stream and the cost per unit of exergy of fuel to the overall ECS when only fuel costs (but no investment or operation and maintenance costs) are considered (cases the author studied, for example, in [6] and [22]), the Zaragoza group under the leadership of Antonio Valero developed the *exergetic cost theory* (ECT) [7, 23-24], which calculates the amount of exergy needed to provide each exergy stream in an ECS. The contributions of ECT complement the ones by the author and his co-workers. The group from Zaragoza also developed a method for the *diagnosis of malfunctions and disfunctions* around the operating point of an ECS [25-26].

The approach of *cumulative exergy consumption* (CEC) considers all thermodynamic inefficiencies that occur in the entire chain between the point where all natural resources used in the process are obtained from the natural environment to the point where the final product is generated [27]. This approach extends the system boundaries of the thermodynamic analysis to include all processes that previously were used to provide the feeds to the process under investigation. CEC accounts for how the inefficiencies of the process being analyzed affect the inefficiencies of the processes that provide the feeds, and vice versa. This information is used in calculating environmental impacts associated with the process that is being considered.

The *extended exergy accounting* (EEA) method is also based on the calculation of the cumulative exergy consumption, but takes into consideration additional aspects such as the exergy associated with capital (investment costs) and human activity (labor) [28-29]. The *extended cumulative exergy consumption* associated with the investigated system is minimized.

Environomics, *thermoecology*,and *exergoenvironmental analysis* deal with the reduction of the environmental impact. [30-37]. When more than one pollutant (e.g., CO2, CO, NOx, SO2, and solid particles) are considered in the analysis, the question arises how to compare (to establish the equivalence of) 1 kg of one pollutant with 1 kg of another. A common currency is needed here: In *environomics* [30, 31], monetary values (costs) are assigned to the environmental impact associated with each pollutant, then an exergoeconomic model is extended to include the costs of pollutants, and finally a cost minimization problem is solved. In *thermoecology* [32], or *exergoecology* [33], the depletion of non-renewable natural resources and the effects of pollutants are expressed in exergy terms. The resulting thermoecological (or exergoecological) cost (expressed in exergy units) is based on the cumulative consumption of non-renewable exergy, and includes the cost associated with the rejection of harmful substances to the natural environment. In the *exergoenvironmental analysis* [10-12, 34, 35], a one-dimensional characterization indicator is obtained using a *life cycle assessment* (LCA); this indicator is used in the *exergoenvironmental analysis* in a similar way as the cost is used in *exergoeconomics*.

An index (a single number), for example, the Eco-indicator 99 describes the overall environmental impact associated with each exergy carrier and with the manufacturing of each system component.

4. Future developments

Before discussing any future development we must point out that all methods mentioned in sections 2 and 3 have not yet received the same acceptance and reception by the scientific, engineering, and political communities as other methods, for example the pinch method and the method of LCA. The reasons for this lie probably in the facts that (a) exergy, not being introduced and discussed properly or sufficiently in engineering curricula, remains a variable and a concept that is not understood and used easily, and (b) the extraction of useful information from an exergy-based method requires good understanding of the limitations of the method being used and critical thinking, contrary to other more popular methods that can be applied as “recipes”. Finally, the disagreements among the exergy practitioners, the plethora of available approaches, the misinterpretations and misuses of these methods certainly have not contributed to their wider acceptance. In 2007 the author coordinated the responses received from several exergy practitioners in an effort to standardize the definitions and nomenclature in exergy-based methods [36]. The applications that followed showed a very limited success of this effort.

One development is certain for the future: The number of cases in which exergy-based methods could be applied will be lower because more electricity will be generated using direct energy conversion, for example, photovoltaics, wind energy, and hydropower, and more electricity will be used in the sectors of transportation, industry, and buildings in every future year. Thus, the exergy-based methods, which show their strength and are more useful when thermal energy is involved, will follow the decline in relative importance we have experienced for thermodynamics and thermal sciences in the engineering curricula in the last years.

The diversity of the methods mentioned in sections 2 and 3 indicates that there is not a single generally accepted method for evaluating the design and the performance of an ECS. All methods have weak points: For example, the *advanced exergy-based methods* often use some subjective estimates, *the exergetic cost theory* does not explicitly consider the investment cost, the assignment of costs to environmental impacts in *environomics* is more or less arbitrary, as is the conversion of monetary values (e.g., capital investment and salaries) and environmental impact into exergy values in the *extended exergy accounting method*. In addition, it is very time consuming to apply most of the above methods. All these weak points reduce the usefulness of the corresponding methods. In the future we should expect developments that will reduce the weak points associated with each approach.

It should be emphasized that the evaluation of costs, which will incur in the future, and of environmental impacts will always be somehow subjective and associated with limitations because of the uncertainties involved in their estimation. However, even the imperfect information extracted from an exergoeconomic or an exergoenvironmental analysis is always useful for reducing the costs and the environmental impacts associated with an ECS.

The *advanced exergy-based methods* are expected to be further developed in the future, so that their subjectivity and the time required for their application will be reduced. Through applications to different ECS, we should expect a higher degree of method generalization and the development of short-cuts to reduce the time required for their application. Also the development of new software specialized in the application of these methods will facilitate application of the methods to many different energy-intensive processes. Because environmental considerations will become more important on future applications, a further integration of these methods (see, e.g., [37, 38]) will enable a fast and consistent multiobjective optimization of an ECS, for example an optimization (improvement procedure) that will simultaneously consider costs and environmental impacts in the optimization to reveal actions that could decrease the cost(s) of the overall product(s), while, at the same time, enhancing the efficiency, and decreasing the environmental impact of the ECS being evaluated. Finally, decision making procedures referring to an ECS will be further improved through applications of advanced exergy-based methods.

5. Conclusions

Various methods have been developed using exergy for the evaluation and improvement of an ECS from the viewpoints of thermodynamics, economics and ecology. Brief reviews of the methods show that all of them have some limitations while focusing on specific aspects of the ECS being considered. The *advanced exergy-based methods* provide the most comprehensive and powerful set of methods available today for evaluating and improving an ECS. All these methods have not yet received from the industry and politicians the recognition they deserve as tools for decision making.

Future work is expected to include the reduction of the limitations associated with each method, a generalization and integration of the methods and the development of appropriate software and short-cut approaches to reduce the time required for the applications.

Abbreviations

AEBM	Advanced Exergy-Based Method(s)
CEC	Cumulative Exergy Consumption
CGAM	An energy-conversion system used to compare the application of exergoeconomic methods in [7]. The name was formed by combining the first letters of the first name of the four main contributors to [7]: **C**hristos Frangopoulos, **G**eorge Tsatsaronis, **A**ntonio Valero and **M**ichael von Spakovsky.
ECS	Energy-conversion system(s)
ECT	Exergetic Cost Theory
EEA	Extended Exergy Accounting
LCA	Life-Cycle Assessment
SPECO	Specific Cost (method)
TCA	Thermodynamic Cost Accounting (method)

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