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Practical approaches for applying thermoeconomic analysis to energy conversion systems: Benchmarking and comparative application

Sajjad Keshavarzian[a,*], Matteo V. Rocco[a], Francesco Gardumi[b], Emanuela Colombo[a]

[a] Politecnico di Milano, Department of Energy, via Lambruschini 4, Milan, Italy
[b] KTH Royal Institute of Technology, Department of Energy Technology, Brinellvägen 68, Stockholm, Sweden

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ABSTRACT

In the last decades, thermoeconomic analysis emerged as a combination of exergy analysis and cost accounting principles, widely used for multiple purposes: to account for the exergy and economic costs of energy systems products, to derive the structures of such costs for the design optimization purpose, and to perform system diagnosis quantifying the source and the impact of malfunctions and dysfunctions within the analyzed process. Traditionally, thermoeconomic analysis is referred to as Exergy Cost Analysis or Exergoeconomic Cost Analysis. The former is based on the so-called Exergy Cost Theory, focused on the evaluation of exergy cost of the system products, while the latter is focused on the evaluation of monetary cost following the same theory. Currently, many practical approaches are available in the literature for the application of thermoeconomic analysis and Exergy Cost Theory to energy conversion systems, while a comprehensive classification, benchmarking and comparison of such approaches is missing. This paper aims to fill this gap through the following activities: first of all, a brief but comprehensive literature review related to the theoretical developments and applications of thermoeconomic analysis method is performed. Secondly and for the purpose of benchmarking, the main practical approaches identified for the application of Exergy Cost Theory are presented and formalized, including the fundamental aspects related to the definition of auxiliary relations and the reallocation of the exergy cost of the residues. Finally, the identified approaches are comparatively applied to the standard CGAM problem, and the advantages and drawbacks of each approach are discussed.

It is found that the definition of the functional diagram and the numerical solution of the system through input-output analysis seem to be more straightforward with respect to the other approaches, leading also to the formalization of an unambiguous method to reallocate the exergy cost of the residual flows.

1. Introduction

Starting from the oil crisis in the 1970s, the efficient use of non-renewable energy resources becomes one of the main concerns related to the design and the operation of energy systems and industrial activities. Thermodynamic irreversibilities (i.e. *exergy destructions*) caused by energy conversion processes then become one common proxy for the assessment of resource consumption. [1], and *Exergy Analysis* (ExA) is currently adopted to support analysts in optimizing resources consumption of Energy Conversion Systems (ECS) [2]. The joint application of ExA and economic principles leads to the definition of the so-called *Thermoeconomic Analysis* (TA) [3], which is currently adopted for three main purposes:

- *Cost accounting*. TA establishes univocal rules based on exergy to account and to allocate the costs of products of each component of the system [4];
- *Design improvement*. TA allows to derive the structure of the costs of the products. Thus, the analyst is given the possibility to understand the role that thermodynamic endogenous factors (that is, irreversibilities) and exogenous factors (all the additional costs generated outside the system) have in increasing the costs of products. This information leads to the definition of indicators useful to perform the so-called iterative thermoeconomic design optimization [5];
- *Malfunction diagnosis*. Once the cost structure of the analyzed system has been derived, TA allows the direct and induced effects of a malfunction of one component inside the system on the costs of system products to be estimated [6];

TA is usually referred to as *Exergy Cost Analysis* or *Exergoeconomic*

* Corresponding author at: Via Lambruschini 4, 21056 Milan, Italy.
E-mail addresses: sajjad.keshavarzian@polimi.it (S. Keshavarzian), matteovincenzo.rocco@polimi.it (M.V. Rocco), gardumi@kth.se (F. Gardumi), emanuela.colombo@polimi.it (E. Colombo).

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Nomenclature

AC	air compressor
APH	air pre-heater
CC	combustion chamber
CCHP	combined cooling, heating and power
CDU	crude distillation unit
CHP	combined heat and power
COP	coefficient of performance
CRExA	combined risk and exergy analysis
ECS	energy conversion system
ECT	Exergy Cost Theory
EFA	Engineering Functional Analysis
ELCA	exergy life cycle assessment
ExA	Exergy Analysis
F	fuel
f	final demand vector
FI	fuel impact
GT	gas turbine
GT-MHR	gas turbine-modular helium reactor
HRSG	hear recovery steam generator
I	inlet
k	number of flows
L	loss
MF	malfunction
n	number of components
O	outlet
ORC	Organic Rankine Cycle
P	product
r	relative cost difference
TA	thermoeconomic analysis
I	incidence matrix
I*	cost matrix
R	resource vector, reallocated (if used as subscript)
SOFC	solid oxide fuel cell
U	unity matrix
W	residues production coefficient
X	total production vector
Z	transaction matrix
ex^*_F	unit exergy cost of the fuel (kW/kW)
ex^*_P	unit exergy cost of the product (kW/kW)
$\dot{E}x_D$	exergy destruction rate (kW)
Ex^*_D	exergy cost of exergy destruction (kW)
$\dot{E}x$	exergy rate (kW)
$\dot{E}x^*$	exergy cost (kW)
ψ	residues cost distribution ratio (–)
β	Szargut beta factor (–)

Cost Analysis, depending on the kind of costs accounted for, respectively exergy or monetary costs. More specifically, the *exergy cost* is a concept introduced by *Valero* through the *Exergy Cost Theory* (ECT) [7], and it is defined as the amount of exergy required by one component to produce its product (measured in J/J). On the other hand, the exergoeconomic cost accounts for the monetary cost of the system products (measured in $/J) [8]. These two kinds of costs are evaluated through the same accounting structure and allocation rules, unequivocally defined by TA.

The number of publications focused on theoretical developments and applications of TA (either based on exergy or exergoeconomic costs) is continuously increasing, and the applications of TA cover a wide range of energy conversion systems and industrial processes. Different approaches may be followed to define and to solve the system of equations required to perform a TA. The definition of the system of equations can be made just by classifying the exergy flows in terms of inlets and outlets (i.e. the *physical* approach, also called *inlet-outlet* approach) or by collecting exergy flows according to their "economic" purpose (i.e. the *functional* approach, also called *Fuel-Product-Loss* approach) [9]. Once the system of equations has been defined, it can be numerically solved through the *Direct method* or the *Input-Output method* [10]. Different combinations of these approaches may lead to discrepancies in final results: therefore, a comparative view of them may be useful to understand their similarities and differences, weaknesses and strengths. This paper provides a comparative investigation of such approaches from both the theoretical and the practical standpoints, with the aim to provide a better understanding of their capabilities and drawbacks.

The rest of the paper is structured as follows: a brief literature review about TA including its theoretical advancements, fields of application, and kind of analysis is presented and summarized in Section 2. Afterward, the most relevant approaches identified for the application of ECT -as a basic theory behind the TA (either for exergy or exergoeconomic costs)- to a generic energy system are presented in Section 3, and then applied to the CGAM problem in Section 4. Discussion of the obtained results and concluding remarks are respectively enclosed in Sections 5 and 6.

2. Thermoeconomic analysis: a literature review and fields of application

This section provides a literature review of the journal articles published in the field of thermoeconomics between 1970 and 2016. For this purpose, original research and review articles have been looked for in the *Scopus* archive, filtering the following keywords: "*Thermoeconomic/s*", "*Exergoeconomic/s*" and "*Exergy cost*". Other kinds of publications such as conference papers and books have been disregarded. The number of papers found for each year is reported in Fig. 1, revealing the exponentially growing interest in the field of TA devoted to the literature. To our best knowledge, such exponential growth is initiated by the increasing installation of the Co/Tri-Generation industries (CHPs, desalination, etc.), together with the concern of depletion of the fossil fuel resources, and fluctuation of the resource price. In order for the aforementioned industries to resist in a highly competitive market, it is necessary to take care not only about the thermodynamic aspects of the system, but also to the economic issues at the same time.

In the following, the initiation of the concept of TA, its evolution, and applications are presented. Afterwards, some of the most cited publications in different fields have been summarized and tabulated in

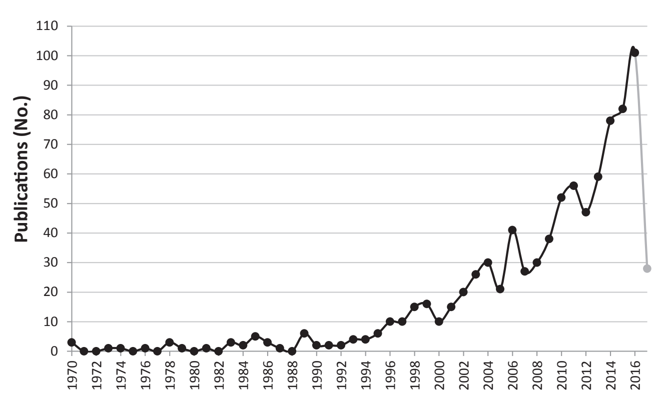

Fig. 1. Numbers of publications directly related to thermoeconomic analysis.