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Consolidating exergoeconomic and exergoenvironmental analyses using the emergy concept for better understanding energy conversion systems

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ABSTRACT

This paper aims at reformulating exergoeconomic and exergoenvironmental analyses using the emergy concept for a better understanding of the sustainable level of energy systems in the biophysical context. The proposed approaches substitute the solar emergy joule (sej) for the monetary term and the environmental impact score in the conventional exergoeconomic and exergoenvironmental analyses, respectively, to harmonize the dimension and scale of their outputs. This improves understanding and interpretations of the results obtained from these analyses. In both approaches, the emergy value is interfaced with exergy analysis in order to establish emergy-based exergoeconomic and exergoenvironmental balances for components of a given energy conversion system. The specific exergy costing (SPECO) methodology is then used to determine the solar emergy joule for each stream of the system. As a case study, a gas turbine-based cogeneration system is analyzed using the proposed methodologies. The results show that emergy-based exergoeconomic and exergoenvironmental analyses can be practical and powerful tools for appraising the long-term sustainability of energy systems compared with monetary- and life cycle assessment (LCA)-based exergetic approaches. Overall, the proposed emergy-based exergetic approaches are suggested as complements to available exergy-based techniques to help understand better and link thermodynamic, financial, and ecological aspects of energy systems.

1. Introduction

Interest in developing techniques to improve the performance of energy conversion systems has steadily increased in recent decades because of growing energy needs and increasing greenhouse gas emissions (Esen et al., 2006). Accordingly, the use of powerful engineering tools like energy and exergy analyses is essential for designing resource-efficient, cost-effective, and environmentally friendly energy systems (Dadak et al., 2016). Exergy analysis is a superior alternative to the conventional energy analysis due to its ability to identify highly irreversible energy conversion processes (Nasiri et al., 2017). Generally, exergy is the maximum amount of work that can be generated from a thermodynamic flow or system as it comes to complete equilibrium with a reference environment (Dincer and Rosen, 2013; Dowlati et al., 2017).

Nowadays, exergy analysis is an increasingly used engineering tool for improving the design and operation of energy systems and mitigating their impacts on the natural environment (Esen et al., 2007; Mojarab Soufiyan et al., 2016). This could be attributed to the multidisciplinary nature of the exergy concept, that incorporates sustainability and environmental facets, as elaborated by Dincer and Rosen (2005). Accordingly, numerous examples can be found in the literature where the exergy concept has been satisfactorily used to locate and quantify the thermodynamic losses (Mehrpooya et al., 2016; Zamfirescu et al., 2017). Most exergy analyses reported to date have focused on exergy destruction. Despite the fact that exergy destruction is a valuable thermodynamic measure, decision-making on the basis of exergy quantities alone might lead to inappropriate optimal energy systems. This can occur due to the fact that the standard exergy analysis is able to optimize the system with respect to exergy quantities (e.g., minimal exergy destruction) while such arrangements do not necessarily comply

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Nomenclature

$\dot{E}$	Exergy flow rate (MW)
f_m	Emergy-based exergoeconomic factor (–)
f_n	Emergy-based exergoenvironmental factor (–)
h	Specific enthalpy (kJ/kg)
m	Specific monetary emergy (sej/J)
$\dot{M}$	Monetary emergy rate (sej/s or sej/h)
n	Specific ecological emergy (sej/J)
$\dot{N}$	Ecological emergy rate (sej/s or sej/h)
r_m	Relative monetary emergy difference (–)
r_n	Relative difference of ecological emergy (–)
T	Temperature (K)
s	Specific entropy (kJ/kg K)
$\dot{U}$	Component-related monetary emergy rate (sej/s or sej/h)
$\dot{V}$	Component-related ecological emergy rate (sej/s or sej/h)
y^*	Exergy destruction ratio (–)

Greek letters

β	Scale factor (–)
η	Energy efficiency (%)
ε	Exergetic efficiency (%)
ψ_M	Overall emergy-based exergoeconomic efficiency (%)
ψ_N	Overall emergy-based exergoenvironmental efficiency (%)

Subscripts

0	Dead state
CI	Capital investment
CO	Construction phase
D	Destruction
F	Fuel
i, k	Numerator
OM	Operation and maintenance
P	Product
q	Heat
s	Sun
w	Work

with economic and environmental goals.

In order to fill this gap, various combinations of exergy concepts with economic and environmental considerations have been proposed over the last few decades as summarized and reviewed by Meyer et al. (2009). In addition, several other approaches like exergoenvironmental (Meyer et al., 2009), exergoenvironment (EXEN) (Caliskan, 2015), and exergoenviroeconomic (EXENEC) (Caliskan, 2015) analyses have been developed and used in recent years. Among the approaches, exergoeconomic and exergoenvironmental methods have been relatively widely used for component-level optimization of energy conversion systems. These techniques have proven to be more powerful than the standard exergy analysis because of their capabilities for comprehensively revealing economic profitability and environmental impact of energy conversion processes.

In exergoeconomic and exergoenvironmental analyses, monetary values (e.g., USD, EURO) and weighted environmental impact scores (millipoints), respectively, are systematically assigned to the exergetic values of various energy flows of a given energy conversion system. Even though the same methodology, i.e., specific exergy costing (SPECO), is used in both approaches in order to establish the required balances and auxiliary equations, their outcomes are presented in different dimensions and scales. That is, units of USD/h and mPts/h are often used for the cost rate and environmental impact rate of an energy flow, while its specific cost and specific environmental impact are frequently given in units of USD/GJ and mPts/GJ. Therefore, understanding, evaluating, and interpreting the results obtained from these analyses are somewhat difficult for engineers and researchers unfamiliar with economic and environmental impact assessment concepts. In a multi-objective optimization study, this issue becomes even more problematic since bridging the objectives of both approaches simultaneously in order to find a global optimal point is complex and challenging. Therefore, a solution to address this issue is needed by researchers.

The emergy concept provides a promising alternative to the conventional monetary term and environmental impact assessment score for dealing with such complexity and diversity. In simple terms, the kinds of energies and resources required directly or indirectly in the biosphere in order to make a specific product or service can be regarded as emergy or "energy memory" (Odum, 1996). The main hypothesis involved in this concept is that life in the biosphere is created and sustained by a flow of high-quality solar energy. It is worth mentioning that any flow of matter, energy, and even money can be expressed on a common basis using the emergy paradigm, e.g., solar emergy joule (sej). Using this concept, the monetary and environmental costs of a given energy flow can be presented on a consolidated basis, i.e., sej/h. In addition, specific monetary and environmental costs can be expressed in terms of sej/J. These in turn not only facilitate the interpretation of data emerging from exergoeconomic and exergoenvironmental analyses but also easily bridge the objectives of both approaches concurrently in multi-objective optimization.

To the best of authors' knowledge, there appears to be no framework for systematically consolidating and harmonizing exergoeconomic and exergoenvironmental approaches. Accordingly, this paper aims at reformulating exergoeconomic and exergoenvironmental analyses using the emergy concept for a better understanding of energy conversion systems from thermodynamic, economic, and environmental viewpoints. More specifically, the present work is devoted to developing emergy-based exergoeconomic and exergoenvironmental analyses to investigate energy systems for the first time. After presenting the theoretical concepts, the developed approaches are applied to a well known gas turbine-based cogeneration system as a typical example. This example elucidates how emergy-based exergoeconomic and exergoenvironmental analyses allow us to scrutinize energy conversion systems at a component level. It is envisaged that energy conversion systems may be better understood thermodynamically, economically, and environmentally using the developed emergy-based exergetic methods.

2. Theoretical considerations

2.1. Concept

The proposed emergy-based exergoeconomic and exergoenvironmental analyses are performed in three successive steps, as shown in Fig. 1. In the first step, exergy analysis is applied to the considered energy system. In the second step, the emergy values of