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Thermoecological cost of electricity, heat and cold generated in a trigeneration module fuelled with selected fossil and renewable fuels

Sergio Usón [a], Wojciech J. Kostowski [b,*], Wojciech Stanek [b], Wiesław Gazda [b]

[a] Centre of Research for Energy Resources and Consumptions (CIRCE), Department of Mechanical Engineering, Universidad de Zaragoza, Zaragoza, Spain
[b] Institute of Thermal Technology, Silesian University of Technology, Gliwice, Poland

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ABSTRACT

The paper presents a thermoecological evaluation of a trigeneration module based on an Internal Combustion Engine fuelled with selected fuels of various origin: domestic/mixed-origin natural gas, CMM (coal mine methane) and biogas. The generated products comprise: electric energy, heat available in hot water and cold generated in an absorption chiller. Transformations of energy and exergy in the trigeneration module have been analysed, and the TEC (thermoecological cost) of the products has been determined. The decomposition of TEC into the cost of resources, the contribution of process irreversibility and the equivalent cost of noxious substances has been shown. The chosen gaseous fuels reflect four different cases: a fossil, non-renewable resource (1 – domestic, 2 – mixed origin) 3 – a by-product from the extraction of a fossil resource and 4 – a renewable resource. It has been demonstrated how the TEC of final products depends on the chosen resource, on the process irreversibility, and on the waste contribution. TEC of electricity produced in the trigeneration module varies from 0.30 (biomass syngas) to 3.11 (mixed origin natural gas), and the TEC of the generated heat and cold varies from 0.61 to 6.46 (heat) and 3.37 and 35.5 (cold) accordingly.

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1. Introduction

Consumption of energy, especially electricity, is the basic factor deciding about the development of humankind civilisation. Many economists maintain that the increase of the consumption is necessary for further economic growth [1,2]. Simultaneously, the growing global consumption of energy and other useful goods accelerates the depletion of non-renewable resources [3]. Sustainable development requires a much more rational management of these resources to provide the next generations with resources they will need to exist. For this reason, two problems are especially important nowadays:

1. development of resource-efficient *systems* for energy transformations,
2. development of *methods* for efficient natural resources management.

* Corresponding author.
E-mail addresses: suson@unizar.es (S. Usón), wojciech.kostowski@polsl.pl (W.J. Kostowski), wojciech.stanek@polsl.pl (W. Stanek), wieslaw.gazda@polsl.pl (W. Gazda).

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Two well-known and relevant system solutions for effective energy transformations are *cogeneration* and *trigeneration*. Both options ensure a highly efficient utilization of resources, moreover, they can additionally be improved by the introduction of renewable resources or by the application of low-cost fuels obtained as by-products from many industrial technologies, as demonstrated by numerous recent publications [4–8].

In the case of trigeneration, it is possible to utilize low-grade heat to drive an *absorption chiller*. Absorption refrigeration chillers have been gaining popularity because they use environmentally friendly working fluids with zero global warming potential e.g. mixture of water-lithium bromide or ammonia-water. In addition, the absorption chillers may be applied with renewable energy sources, such as solar energy [9,10] or waste heat, especially in cogeneration systems [11–13]. The current development concerns the selection of working fluids as refrigerant/absorbent e.g. n-butane/n-octane [14], ionic-liquid/mixed refrigerant [15]. Also, research is done on combined system configurations, e.g. ejector-double effect absorption refrigeration systems [16], ammonia–water refrigerating system powered by industrial waste heat or a gas turbine exhaust gas [17].

The trigeneration system analysed in this paper is based on a commercially available single–effect lithium bromide-water chiller. The main components of a typical single-stage absorption chiller are: a generator, an absorber, a condenser, an evaporator, a solution heat exchanger, a refrigerant pump, a solution pump, and expansion devices [18,19]. In the indirect-fired chillers heat is supplied to the generator in the form of hot water, causing the weak absorbent solution to boil. The desorbed refrigerant vapour (in the studied case: water vapour) flows to the condenser, where it is condensed by a flow of cooling water from a cooling tower. The cooling water is also used to cool the strong absorbent solution inside the absorber. The condensed refrigerant enters the evaporator, where the liquid refrigerant boils. In the evaporator, the chilled water cools as it releases the heat required to boil the refrigerant. Apart of the driving heat, absorption chillers also consume a small amount of electricity to drive the refrigerant and solution pumps.

Co- and trigeneration systems produce simultaneously energy carriers of different type. For this reason, their evaluation by means of energy analysis is not enough, and in order to determine their global effectiveness, *exergy analysis* has to be applied. However, exergy analysis of a system is complex. The local exergy efficiency of a system or component characterises the irreversibility appearing within the assumed boundary but it fails to take into account the interaction between system components. So an important question remains unanswered: *how does the exergy cost cumulate along the production process?*. This problem can effectively be addressed by the theory of Thermoeconomic Analysis (TE Analysis, TEA) [20–23]. Basing on the concept of Exergy Cost, which is similar to the CExC (Cumulative Exergy Consumption) [24], TE input–output analysis has been developed in order to trace the exergy cost formation process in complex energy conversion systems and to decompose the final product cost according to irreversibility along the productive process. Hence, TEA is a suitable tool for exergetic diagnosis of production systems.

The 'classic' TEA is performed within some assumed boundary of the analysed system and it assumes the unit cost of unity at all system entry points (i.e. all resources entering the system have the exergy cost equal to one). However, from the point of view of natural resources management, the boundary should reach the level of extraction of non-renewable resources from nature. This kind of analysis is possible thanks to the application of the TEC (Thermoecological Cost). According to J. Szargut [25], the TEC is defined as the cumulative consumption of non-renewable exergy connected with the fabrication of a particular product, increased by the additional consumption required to compensate for environmental losses caused by rejection of harmful substances to the environment. For this reason, TEC can be applied as a method of evaluating the sustainability of any production system from the point of view of non-renewable resources management. The dimensionless TEC can be applied as an indicator of sustainability [27]. As demonstrated in Ref. [28], TEC can be applied for both non-renewable and renewable resources; for the latter it is usually less than unity, yet not equal to zero due to various auxiliary costs.

The original mathematical formulation of TEC by Szargut is suitable for relatively simple systems. For more complex cases, like the trigeneration system studied in this paper, it is convenient to integrate both TEA and TEC method. The integration of both methods allows one to analyse how the dimensionless TEC increases through the production system due to irreversibility in its components and due to the emission of harmful substances. This concept was demonstrated by the authors' previous work for a natural gas transport system [29], which was limited to a chosen fossil fuel.

As it was proven in Ref. [28] in order to evaluate the systems fed with a mix of non-renewable and renewable resources, the external evaluation should be done basing on the TEC value. However, the detailed decomposition of cost formation has to be done based on the classic TEA methodology. The aim of this paper is to formulate a new mathematical framework for the integration of the TEA-TEC methods for systems supplied with both non-renewable and renewable external resources. The approach is able to combine advantages of TEC and TEA. Although a preliminary formulation was presented in Ref. [29], in the present paper, it is improved in order to deal with inputs with thermoecological cost lower than unity. Furthermore, its applicability is demonstrated by using an example of a trigeneration system.

The analysed system is based on an ICE (Internal Combustion Engine) fuelled with selected gaseous fuels of various origin: natural gas, CMM (coal mine methane) and syngas obtained from biomass. The generated products comprise: electric energy, heat available in the hot water used for space heating and cold generated in an absorption chiller. The paper trances the transformations of energy and exergy in the system and demonstrates the method of calculating the TEC of products.

2. Methodology

The applied methodology comprises: the thermoecological cost, thermoeconomic analysis, and their integration (TEA-TEC).

2.1. Thermoecological cost

The TEC proposed by Szargut [25,26] is an evaluation tool applied to measure the efficiency of natural resources management. It combines exergy as a resource's quality indicator and cumulative calculus. TEC of a product fulfilling the rules of exergy cost theory is expressed in units of exergy per unit of product, and is defined as the cumulative consumption of non-renewable natural resources burdening this product, increased by a supplementary term accounting for the necessity to abate or compensate the negative effects of harmful wastes rejection to the natural environment [25,27].

Within this paper, the notation TEC stands for the general term 'thermoecological cost' without specifying the unit (i.e. kJ/unit product) while the symbol r is used for the value of the dimensionless TEC (kJ/kJ).

The value of TEC can be calculated from the balance of cumulative non-renewable exergy consumption. The total value of TEC_j burdening the products of the j-th process results first of all from the direct consumption of non-renewable exergy resources supplied to the process. Also, TEC_j results from the consumption of intermediate exergy carriers and/or materials with known TEC index. Additionally, the product of the process j has to be burdened with the TEC resulting from rejection of harmful substances to the environment. If the j-th process is a multi-product one, TEC of the main product is decreased by TEC of all by-products. The detailed description of the balance method with relevant examples is given in Ref. [25]. The balance equations are mutually dependent if some useful product is applied as raw material in another production process. In that case, a system of balance equations should be formulated. In the case of final products for consumption, the balance equations are mutually independent and can be solved by means of a sequence method, beginning with the product and going back through all the production steps. The general form of the balance equation determining the total TEC has been widely presented and discussed in Refs. [27,30].

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