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Introduction of an energy efficiency tool for small scale biomass gasifiers – A thermodynamic approach

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ABSTRACT

Modern gasification plants, should be treated as poly-generation facilities because, alongside the production of electricity and heat, valuable or waste materials streams are generated. Thus, integrated methods should be introduced in order to account for the full range and the nature of the products. Application of conventional hybrid indicators that convert the output into monetary units or CO_2 equivalents are a source of bias because of the inconsistency of the conversion factors and unreliability of the available data. Therefore, this study introduces a novel thermodynamic-based method for assessing gasification plants performance by means of exergy, entransy and statistical entropy. A monitoring campaign has been implemented on two small scale gasifiers and the results have been applied on the proposed method. The energy plants are compared in respect to their individual thermodynamic parameters for energy production and materials distribution. In addition, the method returns one single value which is a resultant of all the investigated parameters and is a characteristic value of the overall performance of an energy plant.

1. Introduction

As polygeneration facilities are defined the units that combine the production of electricity with heating/cooling applications and material recovery which may have various utilizations [1]. The numerous inputs and outputs along with the multi-objective nature of their operation complicate the decision-making and the policy development, especially in the energy production industry. The polygeneration technologies are very diverse and are becoming increasingly popular both in the scientific literature and in commercial applications. In addition, the utilization of renewable fuels, like biomass, in polygeneration plants is very interesting due to the mitigation of greenhouse gases and the simultaneous development of advanced green energy conversion technologies [2]. Cultivation and utilization of short rotation coppice biomass has extended commercial applications in EU countries. Pfeifer et al. analyzed techno-economically several scenarios of unused agricultural land for cultivation of short rotation coppice biomass. The results have been very promising for various aspects like land use, cover of local energy demand sustainably and positive impact in jobs creation [3].

Trigeneration plants are the polygeneration plants that combine the production of electricity, heating and cooling [4]. Balli et al. presented a TRIGEN system with a diesel-gas engine and an electrical power of 6.5 MW. The plant has a very energy efficiency due to the trigeneration which reaches 58.9% [5]. Cabalcanti and Perreira Motta introduced a solar assisted LPG fired superheater that improved the overall energy efficiency of the Rankine cycle from 50% to 78% [6]. Also other novel technological possibilities have made possible the upgrade of power plants that operate with standard Rankine cycles with the integration of cooling units and heat pumps [7]. Ifaei et al. showed that such configurations reduce the costs by up to 4.7% and the water losses by 18% [8]. Amirante et al. introduced a trigeneration system that is able to operate solely with biomass residues with an electrical output of 280 kWe and an overall efficiency of 71.8% [9]. Amirante and Tamburrano proposed novel designs of small scale biomass cogeneration plants which are based on an externally-fired combined cycle of Joule-Brayton and Rankine cycles. These designs are cost-effective and can reach electrical efficiencies of up to 25% and overall efficiencies of up to 70% [10].

The present study considers small scale biomass gasification units as great examples of renewable energy polygeneration facilities with high efficiency. Gasification can be primarily defined as the thermochemical conversion under sub-stoichiometric conditions of a carbon-rich substance into mainly a gaseous product

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Nomenclature

β	chemical exergy factor
Δ	difference between output and input (delta)
B, B_{ph}, B_{ch}	exergy, physical exergy, chemical exergy (J)
B_{out}, B_{in}	output exergy, input exergy (J)
c_i	concentration of substances (mg kg^{-1})
G, G_{eff}	entransy, entransy efficiency (J K)
G_{out}, G_{losses}	entransy output, entransy losses (J K)
H/E	heat exchanger
ICE	internal combustion engine
LHV_{biom}	lower heating value of biomass (J)
LHV_{gas}	lower heating value of producer gas (J)
M, $\dot{m}$	mass, mass flux (kg, kg h^{-1})
$\dot{m}_{biom}$	mass flux of biomass (kg h^{-1})
$\dot{m}_{gas}$	mass flux of producer gas (kg h^{-1})
IE	intergraded efficiency index
P	power (W)
P_{biom}	total energy input of biomass (J)
P_{biom}	total energy input of producer gas (J)
P_{el}, P_{th}	electric power, thermal power (W)
RSE_I, RSE_O	relative statistical entropy of input, output
S, s	entropy, specific entropy (J K^{-1}, J K^{-1} kg^{-1})
SEC	substance concentrating efficiency
SH, SH_{eff}	statistical entropy, statistical entropy efficiency
T, T_0	temperature, temperature of environment (K)

commonly known as syngas or producer gas. This fuel is usually combusted in a Combined Heat and Power engine, i.e. CHP, in order to generate electricity and heat. Small scale gasifiers also produce char, a solid product that resembles graphite but also several other by-products like tar compounds. Although char is primarily made of carbon, a series of heavy metals can potentially be trapped in the mineral fraction. Although these products may or may not contribute to the production of electricity or heat, they can potentially have negative environmental impacts. Alongside small scale gasification plants, there are several other energy production units that could be defined as poly-generation, units but identifying the whole spectrum of these facilities is beyond the scope of this study.

This wide range of output streams/products from poly-generation plants has denoted the necessity of an integrated evaluation of these facilities because the standard CHP efficiency analysis does not reflect the whole spectrum of products [11]. Several methods have been developed in order to cope with this issue, all of which include the integration of hybrid indicators. According to Brunner and Rechberger, the most representative ones are the sustainable process index (SPI), the material intensity per service unit (MIPS), the Swiss ecopoints (SEP) but also the more widely applied methods of Cost-Benefit Analysis (CBA) and Life Cycle Assessment (LCA) [12]. The utilization of these methods has a dual scope. On the one hand it deals with the rationalization of the results, by converting energy units into more meaningful values for policy-making. On the other hand, these methods provide a (partial) solution to the inability of traditional "input-output ratios" to analytically describe complex systems. The plurality of these methods results to outcomes that may be vague and sometimes confusing. The data reliability and consistency for even well-established methods like Life Cycle Assessment are issues of concern [13]. Tokarski et al. utilized thermodynamic indicators for assessing the conversion of fuels in relation to the component loads and suggested that these indicators can be used also for further environmental and financial analyses [14]. Finally, Song et al. used a data based method to compare objectively different efficiency indexes [15]. The variety of several methodologies with the application of hybrid indicators denote the necessity for developing an objective framework for assessing energy efficiency and including all the different input and output streams at the same time, whether they are nergetic steams or material streams.

The scope of this study is to introduce a methodology that utilizes solely thermodynamic parameters and can compare different poly-generative gasification plants. Thus, facilities with different levels of electricity and heat output and quality of materials could be directly compared for their performance and their environmental impact. This approach comes along as a further development of several other novel methods, which increasingly integrate thermodynamic parameters in indicator-methodologies for evaluating material or energy flows. Rechberger and Graedel used statistical entropy analysis for the evaluation of the European copper cycle flows [16]. Kaufman et al. used statistical entropy for the analysis of waste management systems [17] and Bakshi et al. integrated exergy in LCA [18]. Li et al. developed a "theoretical framework" for exergy analysis in biomass boilers [19]. But except conventional biomass boiler systems, exergy has also been used for the analysis of more complex energy conversion facilities. Characteristically, Mehrpooya et al. [20] used exergy analysis for an ethane recovery plant and Li and Lin [21] for the analysis of liquid from coal (LFC) is a pyrolysis technology plant. Finally, Ozturk and Dincer [22] applied exergy analysis for the thermodynamic assessment of a poly-generation energy production unit that was consisted by an integrated solar power tower coupled with a coal gasification system.

The suggested methodology in the framework of this manuscript, combines the following: the assessment of the ability for work production (mainly electricity generation) by means of exergy analysis, the assessment of the ability for heat transfer by means of entransy analysis and, finally, the assessment of the ability of a process to dilute or concentrate a range of substances by means of statistical entropy. The aim is to provide an integrated thermodynamic efficiency index by combining these three parameters and provide one single number that is characteristic of a plant or the technology. A numerical example is provided by applying this integrated thermodynamic efficiency for the comparison of two small scale gasification plants which have been monitored in the framework of a previous work [23].

2. Materials and methods

This section is separated in two major subsections. The first describes the developed methodology, the thermodynamic parameters that are utilized and how this methods merges these thermodynamic parameters in order to return a single integrated efficiency index. The latter subsection describes the two gasification technologies that were selected and the monitoring campaign that was implemented on these gasifiers in order to apply real data to the suggested methodology.

2.1. Development of the method

As mentioned in the Introduction section, the methodology consists of an integrated calculation of exergy, entransy and statistical entropy. The methodology does not consider the whole life cycle of the input material. In fact, it should be denoted that the scope of

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