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Energy and environmental assessment of integrated biogas trigeneration and photovoltaic plant as more sustainable industrial system

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HIGHLIGHTS

- Biogas cooling, heating and power and photovoltaic systems were studied.
- Biogas and solar energy for production of energy carriers were used.
- Primary energy savings for trigeneration and photovoltaic plants were examined.
- Reduction of CO_2 emission were estimated.

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ABSTRACT

The biogas fired tri-generation system for cooling, heating and electricity generation (BCCHP + PV) supported by a photovoltaic system (PV) is discussed and analyzed from energetic and ecological effectiveness point of view. Analyzed system is based on the internal combustion engine and the adsorption machine. For the evaluation of primary energy savings in the BCCHP aided by PV system, the indicators of the total primary energy savings (*TPES*) and relative primary energy savings ΔPES were defined. Also an analysis is carried out of the reduction of greenhouse gases emission. In the ecological potential evaluation, the environmental impact as an indicator of the total greenhouse gasses reduction (TGHGR) is taken into account.

The presented detailed algorithm for the evaluation of the multigeneration system in the global balance boundary can be applied for the analysis of energy effects (consumption of primary energy) as well as ecological effect (emission of greenhouse gasses) for real data (e.g. hour by hour through the year of operation) taking into account random availability of renewable energy. It allows to take into account a very important factor characterized for renewable energy systems (RES) which is the variability or random availability (e.g. in the case of photovoltaic – PV) of primary energy. Particularly in the presented work the effects of the analysis and the application of the discusses algorithms have been demonstrated for the hour-by-hour availability of solar radiation and for the daily changing availability of chemical energy of biogas. Additionally, the energy and ecological evaluation algorithms have been integrated with the methods offered by exergy analysis. In the case of cogeneration systems there is a problem of the allocation of fuel between useful products (heat and electricity). The commonly applied methods of "energetic division" don't take into account different quality of products generated in the cogeneration unit. Moreover, these methods require subjective assumptions and it can lead in some cases to non-physical results of fuel allocation. It is commonly known that exergy losses decide on the amount of consumed energy driving the production process. If in the considered process two or more products are generated these losses should be proportionally allocated between these products. For this reason the correct allocation also should be done with the application of the exergetic allocation, what has been proposed in the algorithm presented in the paper.

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Nomenclature

B	exergy
GB	gas boiler
Con	converter
GHG	greenhouse gasses
$GHGR$	greenhouse gasses reduction (ton CO_2/a)
$\Delta GHGR$	relative greenhouse gasses reduction (%)
F	area (m^2)
E	energy
$\dot{E}$	energy flow (kW)
ICE	internal combustion engine
G	generator
$GRID$	electric gird
h	enthalpy
HT	hot storage tank
$\dot{I}_\beta$	global solar radiation reaching photovoltaic panels with inclination angle β (W/m^2)
p	primary
PES	primary energy savings (GJ/a)
ΔPES	relative primary energy savings (%)
t	temperature (°C)
T	temperature (K)
Q	heat (cooling)
$\dot{Q}$	heat (cooling) flow (kW)
f	primary energy conversion factor

Greek symbols

α	the ratio of chemical exergy of fuel per unit of lower heating value
τ	time (h)
η	efficiency
μ_{CO2}	CO_2 emission conversion factor

Subscripts and superscripts

AD	adsorption chiller
GB	gas boiler
bg	biogas
c	cooling
CT	cooling tower
$BCCHP$	biogas cooling, heat and power plant
d	delivery
el	electricity
$GRID$	electric grid
HT	hot storage tank
ng	natural gas
p	primary energy
PV	photovoltaic
RS	reference system
t	thermal
tr	transmission

1. Introduction

One of the ways to decrease global primary energy consumption and the corresponding greenhouse gas emissions is the application of the combined cooling, heating and power generation technologies. Both in the industrial and the residential sector there are objects and technological processes in which at the same time there is a need for some energy carriers (chemical energy of fuels, as well as electricity, useful heat and cooling medium for final consumers). In such cases the use of the systems for the combined production of energy carriers is preferred. A typical solution to the combined production of energy carriers is the cogeneration heat power plant (CHP), producing electricity and heat in the same process. In the case of additional demand for electricity and heat in the analyzed object (or technological process) there is a demand for cooling it is possible to use the trigeneration power plant (CCHP). It should be emphasized that small and medium CCHP plants represent an interesting solution for decentralized or distributed energy systems [1].

Different technologies generating heat and power as well as cooling carrier have been considered in the literature to serve as prime movers for the CCHP applications. The review on combined cooling, heating, and power systems summarizes the previous methods used to perform energy and exergy analyses, system optimization, performance improvement studies, and development and analysis of CCHP systems, is reported in [2]. Moreover, the performance assessment of a small size CCHP supported by numerical modeling can be found in [3].

The heat and power technologies are commercially mature including reciprocating engines and gas turbines with a wide availability in the market, while others are still at the research and development stage with limited commercial systems finding their way to the market including the Stirling-based units, the organic Rankine cycle (ORC) based systems and the fuel cell-driven units [4]. A large number of studies have been presented in the literature investigating different aspects related to the internal combustion engine or gas turbine as prime movers in the trigeneration systems. For example, a simulation of the performance of CCHP system with an internal combustion engine supplied by natural gas and diesel is discussed [5]. Recent publications focus on the connection of the CCHP systems with the energy conversion system which use renewable energy sources. Example of such combined cooling, heating, and power system supplied by biomass as a sustainable distributed energy system to reduce fossil energy consumption and carbon dioxide emission is presented and discussed in details by the authors of [6]. In the case of CCHP systems fed or supported with renewable resources the effects should be determined in the global level. For this reason the authors of [7] propose a comparison of primary energy savings due to the CCHP with the results from the LCA analysis. The influence of the different composition of gas supplied to the CCHP system on its thermodynamic performance assessment in [8] is reported. The performance of CCHP plants are dependent on the changes in load during the operation season. Such aspects can be included in the analysis of the influence of CCHP on primary energy savings or environmental effects using the sensitivity analysis as has been proposed in [9]. Review of the characterization of the emissions from the small-scale natural gas fueled cogeneration systems, with specific reference to the micro-turbines and internal combustion engines for the evaluation of local and global environmental impacts is presented in [10]. Another option of CCHP system is a small tri-generation plant supplied by geothermal and solar energies whose performance is more dependent on the availability of the geothermal than the solar energy [11]. The environmental impacts of microgeneration integrating with solar photovoltaic panels, combined heat and power plant and battery storage use life cycle assessment has been investigated in [12]. The life cycle assessment as optimization methodology to optimize the configuration and variable load operation of the solar-assisted CCHP system to minimize the life cycle environmental impact is proposed in [13]. The production of cooling in the CCHP system can be developed using sorption refrigerators i.e. the absorption or adsorption