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Research Paper

Evaluation of the potential of the production of electricity and heat using energy crops with phytoremediation features

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HIGHLIGHTS

- Experimental research on gasification of the selected energy crops with phytoremediation potential was performed.
- Thermodynamic and economic analysis of integrated energy system was conducted based on the results of experimental study.
- The break even price of electricity ranges from 48.41 to 90.05 €/MWh depending on the system size.

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ABSTRACT

The use of biomass fuels is continually investigated, and the industry application possibilities are widely recognized. In the paper, an experimental investigation of gasification in a fixed-bed atmospheric reactor of selected energy crops is presented. These crops belong to the class of phytoremediation plants, and their potential to combine agroenergetics and active environment improvements is studied. The composition and characteristics of the obtained gas allow its use in an internal combustion engine. Composition of gas obtained from *Sida hermaphrodita* during the experimental study was used for thermodynamic and economic analysis of a CHP system with a gas engine. The system quality indices were calculated. For the economic analysis, the net present value method was adopted. The break-even price of electricity (c_{el}^{b-e}) was calculated. The paper includes a sensitivity analysis of change in the heat and biomass price. The power of the analyzed units was in the range of 1–5 MW in biomass chemical energy. The c_{el}^{b-e} ranges from 90.05 €/MWh (1 MW of supplied chemical energy in biomass) to 48.41 €/MWh (5 MW of supplied chemical energy in biomass).

1. Introduction

The modern power sector, as an important branch of the global economy, is facing changes that may, in the perspective of several decades, lead to thorough changes in the use of various energy sources. It is predicted that the fuel type with the highest increase of production by 2040 will be gaseous fuels [1]. They have certain advantages, mainly including a relatively small impact on the environment, no need for storage and ease of conduction and automation of the combustion process. One way to use the advantages of gas, while maintaining the diversity of sources of acquisition, is the use of unconventional gases in distributed cogeneration (CHP) systems, primarily systems based on gas engines [2–5].

1.1. Gasification background

One of the increasingly frequently used methods of obtaining gaseous fuel is gasification of various forms of biomass (including waste). As gasification agents, air, oxygen, water vapor or a mixture thereof can be used. The main components of the gas resulting from gasification in air (process gas) are carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. A method of conducting the process of gasification allows the composition of the gas to be influenced. The type of gasification medium has a significant impact on the content of flammable compounds in the process gas, which also determines its further use. An example of such a medium is water vapor, the presence of which may increase the amount of hydrogen in the gas [6]. The possibilities of the use of gas from the gasification process is widely analyzed in the literature [7–10]. The main applications are co-combustion in power boilers [11], the use as a reburning fuel [12,13] and, most frequently used, gas piston engines. There is quite a significant

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Nomenclature

c	price, €
CF	cash flow, €
CGE	cold gasification efficiency, –
$\dot{E}_{ch}$	chemical energy flux, kW
h	enthalpy, kJ/kg
i	unit investment costs, €/kW
J	total investment costs, €
K	costs in cash flow, €
L	salvage value, €
$\dot{m}$	mass flow rate, kg/s
NPV	net present value, €
$\dot{Q}$	heat flux, kW
N_{el}	electric power, kW
r	discount rate,%
S	sold production, €
T	temperature, °C
LHV	lower heating value, kJ/kg
λ	air equivalent ratio, –
ϑ	indicator of a relative change of the efficiency and temperature, –
η	efficiency, –

Indices

b	biomass
C	certificate
E	engine
eg	exhaust gas
el	electric
GC	gas cooler
GCI	gas cleaning installation
GU	gasification unit
HT	high-temperature heat
I	integrated CHP system
LT	low-temperature heat
Q,q	heat
T	temperature
η	efficiency

amount of theoretical and experimental research on the gasification of various types of biomass and the subsequent use of the resulting process gas in a combustion engine. One of the most widely known European plants using the gasification process is a system in Güssing (Austria), built in 2001, with power in the fuel of 8 MW_{th} [14,15]. Similar systems can be found, e.g., in Harbore (Denmark), Spiez (Switzerland), Kokemäki (Finland) or Skive (Denmark) [2,16,17]. In Poland, research has been conducted for many years at the Institute for Chemical Processing of Coal in Zabrze (Poland), which resulted in obtaining the structure of a fixed-bed gasifier, ensuring the stable operation of cogeneration systems regardless of the fuel used [18,19]. It can therefore be assumed that the process of gasification of biomass and further use of the process gas in gas engines is rather recognized, but there are few installations operating in a commercial environment that use different types of biomass to prepare the gas that is used to produce electricity and heat in cogeneration.

1.2. Energy crops for phytoremediation process

The production of biomass for energy purposes can be linked with the use of wastelands and polluted and degraded areas through the use of energy crops (species of plants that can be grown for the purpose of production of biofuels (solid, liquid and gaseous) and bio-components) with a phytoremediation potential [20]. The gasification of energy plants brings measurable environmental benefits. As a method of producing fuel, it is characterized by the potential of retention in solid products (slag) of some heavy metals and the disposal of pathogenic bacteria [21]. Research on the potential of energy plants to purify the soil is the subject of the European Phyto2Energy project [22]. Earlier phytoremediation results show [23] that *Miscanthus* x *giganteus* is a more tolerant species to the total contaminated soil with Zn and Pb to *Sida hermaphrodita.* Additionally, it was proven in [24] that *Spartina pectinata* and *Panicum virgatum* are also very suitable for heavy metals phytostabilization. This paper focuses on presenting the results of gasification test and aiming to develop mathematical model of the whole-chain process of converting biomass to electricity and heat.

In agroenergetics, three groups of perennial plants are mainly used: trees and shrubs (e.g., *Salix L.*), grasses (e.g., *Miscanthus x giganteus*) and perennials (e.g., *Sida hermaphrodita*). The subject of the use of energy crops in the gasification process appears in the literature; however, aspects of the use of *Miscanthus x giganteus* are mainly discussed [25–32] with attention rarely paid to *Spartina pectinata*, *Sida hermaphrodita* [29] or giant reed [26]. Lifecycle assessment of *Miscanthus x giganteus* gasification was performed and described in [32].

A number of energy crop species have been tested for their phytoremediation effects on heavy metals contaminated soils, however, further investigations are needed to prove their feasibility for large scale applications. Sida hermaphrodita has shown a high potential of phytoextraction of heavy metals (Ni, Cu, Zn, and Cd) in comparison to other species used as energy crops [33,34]. It was proven, that it is producing biomass that can be an excellent source of raw material for renewable energy [35].

1.3. Scope of work

A review of the available literature reveals that the gasification process can be an interesting method of energetic utilization of energy crops planted in the areas of wasteland for the purpose of phytoremediation of soil. The resulting process gas, after the removal of impurities, can potentially be used for the production of electricity and heat in a cogeneration system. However, in the literature, there is little research on the gasification of various types of energy crops and the cost-effectiveness of further use of the process gas for energy purposes; it is therefore justified to undertake work in this direction.

The main aim of this paper was to evaluate the usability of different types of energy plants for gasification and of the produced gas to generate electricity in a combustion engine. In this paper the whole process chain from fuel (biomass) to final product was analyzed, with special focus on evaluation of the thermodynamic and economic effectiveness of electricity and heat generation. To reach the stated goal, first, experimental research on gasification of the selected plant species in a fixed bed generator using air as a gasifying agent was performed. A thermodynamic analysis of the possibilities of using produced gas as a fuel for a cogeneration system with a piston engine was then performed. For the selected solutions, a thermodynamic and economic analysis was conducted. The main novelty of the paper lies in the complex, multicriterial analysis of the use of specific energy crops (having also phytoremediation potential) for electricity and heat production with the use of gasification process.