Energy 150 (2018) 601–616

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Investment risk for biomass integrated gasification combined heat and power unit with an internal combustion engine and a Stirling engine

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A R T I C L E   I N F O

Article history:
Available online 27 February 2018

Keywords:
Waste biomass gasification
Combined heat and power
Stirling engine
Risk analysis

A B S T R A C T

In paper, the results of an analysis of the integration of a Stirling engine with a Biomass Integrated Gasification Combined Heat and Power system have been presented. The analyses were conducted for two systems: with and without Stirling engine. The priority for the power system is the utilization of waste biomass. In addition, the system produces electricity and heat for the municipal district heating network. The Stirling engine uses the high-temperature potential of the raw process gas. The use of an additional engine in the cogeneration system permitted an increase in the electricity production. Calculations were carried out for different degrees of gas cooling in the Stirling engine. The basic energy flows in the system, and the thermodynamic assessment indicators were determined. In the next step, the calculations were carried out to obtain the economic evaluation indices. The risk analysis was conducted using the Monte Carlo method. The main technical and economic risk factors concerning the implementation of the cogeneration technology were then identified. On the basis of the determined cumulative probability curves used for obtaining the specified values of the Net Present Value Ratio, the values of the defined indices of the investment risk assessment could then be obtained.

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1. Introduction

Currently around the world, including in the countries of the European Union (EU), technologies that allow the use of countries own energy resources, taking into account the criterion of minimizing adverse effects to the environment, are being promoted. All the technologies that enable an effective use of the potential of renewable energy sources perfectly fit this scope. At the end of 2016, throughout the world, such sources had an installed electricity generation capacity of 2017 GW, of which 1096 GW was power from hydropower plants. Among all the recently operating renewable energy sources, the most dynamically growing branches are the wind and solar power industries. Even though in the case of these technologies, the amount of installed electric power is relatively small, e.g., at the end of 2016, the installed electric power was only 487 GW for wind energy and 303 GW for solar energy, significantly high dynamics of development were observed as compared to that in the case of the water power industry. In 2016 alone, in the case of wind and solar energy, 54 GW and 75 GW of power were installed respectively, as compared to 25 GW of electric power installed in hydropower plants [1]. Wind and solar energy have an advantage over hydropower energy in that their occurrence is far more dispersed around the globe; therefore access to these energy resources is significantly more common. Unfortunately, both solar power plants and wind turbines are characterized by strongly varying potential over time, which adversely affects the functioning of the corresponding energy systems, including the risk of a lack of continuity in the energy supply, which may be the consequence of the weak structure of the generation sources and the lack of energy storage [2]. The problem primarily concerns systems in which power generation sources with poor regulatory properties are predominant, e.g., conventional coal-fired units [3]. Such a situation can be observed in Poland; in 2015 78.8% of electricity was produced using coal and lignite. In Poland the wind power industry is growing dynamically. In 2016, in this area, an increase in the installed power of 1.2 GW was noted, leading to a total installed power of 5.8 GW (a 27% increase compared to 2015) [4,5]. However, the development of wind energy in Poland has led to problems in the coal manufacturing sector, such as an increase in the number of forced shutdowns of the power units, which indirectly result from priority access to the network of energy produced using renewable energy sources. This situation has contributed to

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https://doi.org/10.1016/j.energy.2018.02.152
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the increase in the cost of the electricity generated and poses the threat of blackouts. The need to ensure the country's energy security forced the system operator to limit the number of concessions issued for connecting wind farms to the power grid. So that Poland can achieve a 15% share of energy from renewable sources in 2020 in electricity generation (in the first quarter of 2017, it was 13.5%), it is important to seek an alternative renewable technology that has the potential to be adapted.

A very significant energy potential for Poland lies in the possibility of acquiring biomass fuels. The technical potential for biomass energy in Poland is estimated at approximately 900 PJ/year, being one of the highest in Europe, and solid biomass is the primary source. The acquisition of primary energy in Poland from renewable sources in 2015 amounted to 376 812 TJ, of which 73.2% was in the form of solid biofuels. The most common types of solid biomass are waste wood from forests and from the wood industry, post-use wood and agricultural biomass, including orchard wood from care of parks and roadside trees, as well as undeveloped straw and hay. Additionally, it is possible to import biomass. Thus, the use of biomass for energy has a significant potential for further development [6,7].

In Poland the development of power engineering for renewable energy sources has commenced using biomass of a plant origin on a large scale. For nearly two decades, this was accompanied by the considerable turbulence associated with the changes in the legally binding definition of biomass for energy purposes along with the restrictions imposed on the protection of forests, making investments in this area high risk. The other significant risk factors were the considerable changes in the biomass price and the prices of the so-called green certificates, which in Poland are received by producers of energy that is generated using renewable sources. Risk minimization was achieved by adapting solutions with the lowest possible investment cost, which led to the development of a model based on the use of biomass in large blocks of a power plant, by direct co-firing with coal [8,9]. The centralization of the use of biomass, including forest biomass, started in 2005 and contributed to the devastation of the local forest areas. Restrictions on the possibility of using forest biomass and insufficient development of the potential of agricultural biomass producers contributed to decreased interest in centralized production based on biomass fuel. Currently, a decentralized energy generation market model is rightly being promoted.

In the absence of the possibility of integrating the large capacities of the hydropower plants into the energy system and because of the problems posed by the dynamic development of wind and solar energy, biomass energy is expected to become increasingly important in Poland. The data collected during the use of the technology while directly co-firing biomass with coal in the biggest domestic power stations has revealed the need for a more profound diversification in the field of applied power and the types of biomass used. Where economically viable, mainly in the areas conducive to the development of large surface biomass crops, the centralized use of biomass as energy should be made, e.g., in 100% solid biomass-fired units. Furthermore, it should be noted that the Polaniec power station in Poland, one of the world's largest 100% biomass energy generators capable of generating a power of 205 MW, was launched in 2013.

Moreover, the right direction for development seems to be the support and the construction of dispersed sources, where the waste biomass from production plants, reclamation of post-industrial areas, and green areas could be used. The segregation of municipal waste could also yield biomass. All of these areas of biomass energy collection fit the *Circular Economy* idea that has been actively promoted within the EU. The economic effects of the use of biomass energy, which thus far has been regarded as waste, will represent the sum of the benefits identified in categories such as economics, ecology, health, and employment.

A considerable amount of harmful substances, including heavy metals, may be present in waste biomass. The issue of identifying such pollutants was addressed in several studies [10–13]. The main problem for using of this type of biomass for energy production is the limited number of technologies which will not contribute to environmental degradation during operation. A desirable feature of such technologies is a high efficiency of binding the harmful substances in the solid products during the combustion process, which will then require further processing; e.g., the separation of these elements that can constitute a valuable product. The issue of emissions of inorganic elements formed during the combustion of biomass in the various types of boilers was discussed in the literature [14]. The problem is even more serious in relatively small-scale systems. The gasification of biomass can be an efficient technology in eliminating inorganic elements, irrespective of the project scale. This feature can give the gasification technology an advantage over the combustion technology in terms of the dispersed investments related to waste biomass utilization.

The paper has presented thermodynamic and economic analyses for the integration of a Stirling engine with a biomass integrated gasification combined heat and power system. The studies were conducted with two options: with and without a Stirling engine. The aim of this study was to assess the profitability of the construction of systems with various economic and thermodynamic conditions.

1.1. Biomass gasification

The gasification process for solid fuels is a thermal process carried out in a controlled atmosphere, constituting of the gas mixing with a quantity of oxygen allowing only partial oxidation of the combustible part of the fuel. Biomass gasification is performed at an elevated temperature in gasification reactors that have been specially constructed for this purpose. In the case of dedicated solutions for dispersed power generation, the gasification process can be carried out using reactors with a fixed or fluidized bed, but fixed bed reactors are more often used in relatively small installations [15,16]. Another popular type of reactor is the entrained bed, where the dust with a size of up to 0.1 mm is subjected to the gasification process; however, due to this not suiting the milling characteristics of biomass, it is not used for gasification [17]. The choice of the type of the gasification reactor and the type of oxidant, as well as the selection of the thermodynamic parameters at which the gasification process is performed, determine the composition of the obtained process gas and thus, its energy qualities. To obtain a process gas with a high calorific value, it is necessary to eliminate the inert ballast from the gasifying medium, which for air is nitrogen. For example the results of the analyses conducted for biomass gasification generators, where the process was focused on the provision of a high hydrogen content in the process gas, have been presented [18,19]. In the case of waste biomass utilization, the high binding efficiency of the harmful components of biomass, including heavy metals in the solid products of gasification, should be ensured [11,20].

A significant aspect of a project using biomass is adequate infrastructure from the harvesting stage, through to transport and storage, to the final preparation of the biomass. In the literature the authors [21] pointed to some difficulties in the different stages. In the case of the biomass harvesting stage, the efficiency and cost-effectiveness depended on many factors, for example, the type of biomass and its yield, local weather conditions, the prosperity of the state, etc. The main problems in the transport stage included: the physical nature and structure of the biomass, the moisture

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