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Complex thermal energy conversion systems for efficient use of locally available biomass

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A R T I C L E I N F O

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A B S T R A C T

This paper is focused on a theoretical study in search for new technological solutions in the field of electricity generation from biomass in small-scale distributed cogeneration systems. The purpose of this work is to draw readers' attention to possibilities of design complex multi-component hybrid and combined technological structures of energy conversion plants for effective use of locally available biomass resources. As an example, there is presented analysis of cogeneration system that consists of micro-turbine, high temperature fuel cell, inverted Bryton cycle module and biomass gasification island. The project assumes supporting use of natural gas and cooperation of the plant with a low-temperature district heating network. Thermodynamic parameters, energy conversion effectiveness and economic performance are examined. Results show relatively high energy conversion performance and on the other hand weak financial indices of investment projects at the current level of energy prices. It is however possible under certain conditions to define an optimistic business model that leads to a feasible project.

1. Introduction

Implementation of the concept of sustainable development and security of energy supply require rational use of available resources. It requires introduction of new technologies. Nowadays attention is payed to decentralized and on-site power production based on small-scale energy conversion systems optimized for locally available different dispersed energy resources, such as: biomass, municipal and agricultural wastes, industrial waste energy, energy of off-system gaseous fuels, solar energy, geothermal energy and energy accumulated in the soil. Interesting and technically possible option is the use the small-scale individual energy conversion technologies for design of complex hybrid and combined technological structures. Such systems can be nowadays configured using ORC (organic Rankine cycle), Striling engine, SOFC (solid oxide fuel cells) and MCFC (molten carbonate fuel cell) in combination with combustion engines, micro-turbines or turbo-expanders. The plants can also include fuel conversion reactors such as gasifiers and reformers as well as heat and electricity accumulators. The number of possible ways for integration of the available technologies is significant. Further improvement of the energy management effectiveness can be obtained in urban areas if such plants are integrated with local low-temperature district heating networks and low exergy heating systems [1].

The main source of locally available renewable energy in Europe is biomass [2]. It is currently used mainly in large scale steam plants in co-combustion installation or in small steam or ORC plants. The first option is connected with significant logistics issues due to fuel acquisition and transportation requirements. The second one faces a problem of low energy conversion efficiency. According to Mathiesen et al. [3] in the longer term bioenergy will become the key concern, as biomass is a limited resource and unsustainable use of it may cause serious challenges. On the other hand biomass technologies have a potential to improve performance of distributed generation systems with a high share of wind and solar power technologies. In comparison with these intermittent power sources biomass plants are able to work continuously so they are perfect candidates for base load technologies within optimised local energy systems.

Many complex concepts of biomass energy conversion plants have been presented in the literature. Usually, gasification technology is taken into account together with a gaseous fuel fired power generation equipment [4]. An interesting possibility results from the use of high temperature SOFC (solid oxide fuel cells) and

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MCFC (molten carbonate fuel cells) [5,6]. These technologies are now in the phase of intensive research and development. The effects of firing fuel cells with biomass derived syngas have been studied both theoretically [4–11] and experimentally at a pilot plant level [12–15]. There are several ongoing programs in Europe focused on the development of cogeneration technology with fuel cells and biomass gasifiers. The expected level of the energy conversion efficiency in such type of plant is $\eta_{el} = 0.27$ to 0.33 [6,8,9,12], where the efficiency is defined as follows:

$$\eta_{el} = \frac{P_{el}(1-\alpha)}{\dot{E}_{ch,bio}} = \frac{P_{el}(1-\alpha)}{\dot{m}_{bio} LHV_{bio}} \quad (1)$$

Further improvement of biomass to electricity conversion efficiency can be achieved in a hybrid and combined cycles configured using the gas turbine technology [12,15]. Fryda et al. [16] simulated the system with pressurised gasification reactor, SOFC and microturbine. They presented the value of efficiency $\eta_{el} = 0.406$. Proell et al. [17] examined the performance of gas turbine SOFC hybrid system integrated with allothermal FICFB (Fast Internally Circulating Fluidized Bed) gasification technology, that was applied in Güssing plant (Austria). Biomass chemical power input into the system was assumed at the level of 8 MW. For the assumed data of the Siemens Westinghouse tubular fuel cell, the obtained efficiency of electricity generation was $\eta_{el} = 0.435$ in the case of using a conventional steam cycle for waste heat utilisation and $\eta_{el} = 0.414$ in the case employing ORC bottoming technology.

An alternative way for hybridisation is design of modular systems based on independent equipment components [18]. In the hybrid system that consists of allothermal wood gasifier, solid oxide fuel cell, bottoming internal combustion engine fired with the anode exhaust gas and ORC for waste heat recovery the net biomass energy conversion efficiency into electricity in cogeneration mode was found at the level of 37% [17]. On the other hand the results of economic evaluation of the proposed technology revealed that although financial attractiveness of the projects was weak a profitability could be reached under certain circumstances. Due to emission reduction and energy policies, there are nowadays available financial and legal mechanisms that significantly support new investment initiatives. There is an opportunity for implementation and further development of thermodynamically effective emerging technologies in the field of energy conversion from local resources.

In this work the concept of a modular cogeneration plant with wood gasification integrated with MCFC, conventional natural gas fired MGT (micro-turbine) and IBC (inverted Bryton cycle module) is presented and assessed. As the natural gas fired MGT is proven and commercially available technology it can provide electric power independently on the performance of the other equipment. There is also possibility to switch the fuel cell into natural gas operation mode. It can be an advantage in the case of gasification or gas cleaning system failure. The MGT selected for the study can be also fired with biogas from farm digesters, sewage treatment plants and landfills. Therefore the characteristic features of the proposed system are flexibility in fuel type, reliability of power supply and potential to be 100% renewable.

One of the conditions for development of energy systems with a high share of intermittent renewable energy sources is availability of flexible energy conversion technologies [19]. In this context the proposed system, if it is integrated with water electrolysis [3], can provide ancillary services to the system such as electricity accumulation.

In the proposed system configuration the MCFC operates at near ambient pressure and its cathode is fed with exhaust gas from the natural gas fired MGT. This is the main difference from the systems studied so far in the literature. Additionally the flue gas from the fuel cell afterburner expands in the IBC to a pressure lower than the ambient one. The plant delivers heat to the LTHN (low temperature heating network) that allows for condensation of water from syngas in the IBC heat exchanger.

The study also demonstrates the use of commercial software for performance modelling of the complex energy conversion process. The model was built using the Cycle-Tempo software [20]. Characteristics and input data of individual elements of the investigated systems are adopted form the literature.

2. Sample system description

The gasification technology taken into account uses an allothermal process with steam, that takes place in a double fluidised bed reactor with separated combustion and gasification zones. There are several possibilities for integration of the gasification island with MGT, MCFC and IBC. Due to high oxygen content in MGT exhaust gas the turbine can provide oxidant for gasification system combustion section. It can also provide oxygen and carbon dioxide for the MCFC cathode. In this case however, due to relatively low CO_2 content in the MGT flue gas there is expected low MCFC efficiency [21]. Alternatively a mixture of MGT and gasification reactor exhaust gasses can be considered as the cathode inlet gas [11]. The final configuration of the technological structure should result from a detailed techno-economic optimisation in given location and local constraints. As the purpose of this work is a general presentation of the concept and discussion of the critical issues related to its attractiveness it does not include the optimisation study.

In this paper a relatively simple configuration of the system is taken into account. The main design assumption was modularity of the system. The entire plant model has been built within the Cycle-Tempo environment. Fig. 1 presents the simplified flowsheet diagram of it. The picture was imported from the Cycle-Tempo but for clarity it has been simplified in a graphics software. Figs. 2 and 3 present sections of the original flowsheet that is too large to be included in the paper.

Wet biomass is dried and fed into gasification section of the reactor where it is gasified in steam using heat delivered from combustion zone by circulating bed material. The raw syngas is cleaned and cooled down to the near ambient temperature. A portion of heat from gas cooling is released to the LTHN. High temperature gas cooler is used as regenerative heat exchanger where the product gas is heated back to the high temperature and send to the fuel cell reformer. Steam required for both gasification and reforming processes is generated in heat recovery steam generator fed with flue gas from combustion section of the reactor. Heat required for syngas reforming is generated in the anode offgas afterburner. Exhaust gas from the reformer goes through the heat exchanger to the IBC module expander. There is located the regenerative heat exchanger. Useful heat is being releases to the LTHN at low pressure in the IBC cooler where condensation of water takes place. Therefore the flow of gas through the compressor is smaller than the one through the expander. The exhaust gas is compressed to the pressure slightly higher than the ambient one (for compensation of pressure drops). After compression the gas is partly recirculated and partly used as drying medium in the drier. Recirculation allows for increase of CO_2 content in the MCFC cathode inlet gas.

3. Plant performance modelling

The aim of the modelling process is identification of possibilities. Therefore a detailed modelling study was not undertaken. The plant has been modelled using the Cycle Tempo simulation software [20]. The model represents a steady state plant operation. In

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