Open Access Journal

Journal of Power Technologies 96 (2) (2016) 73–80

journal homepage:papers.itc.pw.edu.pl

Use of a gas turbine in a hybrid power plant integrated with an electrolyser, biomass gasification generator and methanation reactor

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Abstract

The main objective of this paper is to evaluate the thermodynamic potential of a complex hybrid power plant based on a gas turbine, integrated with an electrolyser powered by: a wind farm, a biomass gasification unit and a methanation reactor. The system serves as an electricity accumulator. The calculation methodology and the basic assumptions for the analysis are presented. The calculations provided the basic thermodynamic parameters of the streams in all the major points of the system. A gas turbine was selected and key thermodynamic indicators of the system operation were determined. The annual products were calculated and the influence of the size of electrolyser on the share of electricity supply from the wind farm was presented.

Keywords: Power to gas; SNG; Gas turbine; Hybrid power plant

1. Introduction

One major thread in energy-related research at present is focusing on energy storage systems, in particular electricity accumulators. This is due, among others, to a growing share in the power systems of sources characterized by discontinuous operation, mainly renewable energy sources (solar power and wind turbines). In the literature various storage solutions are proposed, of which the most popular are Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES) and Power to Gas (P2G) installations [1–4]. Power to gas technology is based on a conversion of excess electricity into gaseous fuel, which can be used, e.g., during energy peaks. The most common solution requires the use of electrolysis to produce hydrogen (and oxygen), which can be then introduced into a natural gas grid or used in industry or transport [5–8]. Another solution is to involve an additional methanation process in order to convert hydrogen obtained during electrolysis to synthetic natural gas (SNG), using carbon monoxide or carbon dioxide [9]. The gas can be injected into the gas grid or used locally to produce electricity and heat in cogeneration (e.g., based on gas engines or gas turbines) [4, 10]. For the production of SNG the carbon monoxide that is formed in the process of gasification of solid fuels can be used, in particular biomass [3, 11]. This is a relatively innovative solution, as it exploits the potential of gasification and makes use of a portion of the oxygen coming from the electrolyser in this process.

There is an increasing number of projects aimed at the production of SNG from hydrogen produced in the electrolysis process. The largest operational installation is the Audi e-gas project in Werlte [12]. This installation produces annually about 1000 metric tons of synthetic gas, which is injected into the gas network. Production of synthetic natural gas based on biomass gasification is carried out, for example, within the framework of a project conducted on an existing system for biomass gasification in Gussing (Austria). A methanation installation with a capacity of 1 MW, producing synthetic natural gas, was added to the existing plant [12]. The methanation technology used there is based on the methanation reactor developed in the Paul Sherrer Institute (PSI). A system is still in the construction phase in Gothenburg (Sweden) under the project GOBIGAS [13, 14]. This system should have capacity of 13 MW in the first phase, and 50 MW in the last phase. A detailed list of technologies and projects in which the methanation part is implemented is presented, among others, in the report [13].

The main objective of this paper is to evaluate the thermodynamic potential of a complex hybrid power plant [15] based on a gas turbine, integrated with an electrolyser supplied with energy from wind farms, a biomass gasification unit and a methanation reactor.

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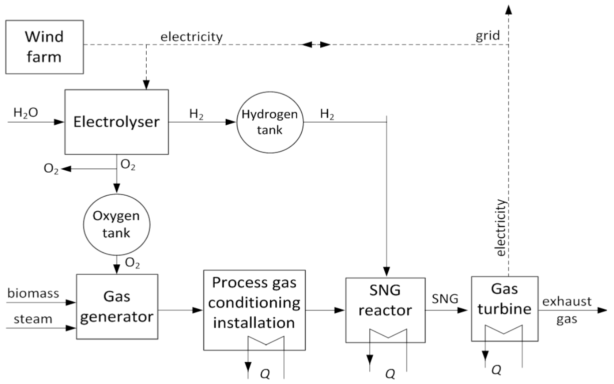

Figure 1: Schematic of technological links of the analyzed hybrid system

2. Description of the model and main assumptions for calculations

The concept of the analyzed hybrid power plant with gas turbine involves cooperation with a wind farm with an electrolysis installation, an oxygen biomass gasification system and a system for the production of synthetic natural gas (SNG). The main advantage of this solution is the production of SNG with a composition similar to that of natural gas, which has a greater potential for use in the available cogeneration systems (based on internal combustion engines and gas turbines) than pure hydrogen. No less important is the possibility of partial use of oxygen coming from the electrolyser in the process of biomass gasification and - economically - the possibility of government support mechanisms for electricity produced from renewable energy sources.

The hybrid system proposed in this paper consists of an electrolyser powered with electricity from a wind farm (and from the grid when the power from the wind farm is insufficient), an oxygen biomass gasification installation with fluidized bed reactor, a methanation reactor, a gas turbine operating on the basis of the produced SNG, and auxiliary installations and tanks for hydrogen, oxygen and SNG storage. The hybrid system is assumed to be in continuous operation, mainly due to the nature of the gasification reactor which does not allow for quick startups and shutdowns. In addition, the assumption was made that all the hydrogen produced in the electrolysis installation is used in the methanation process, thus, the individual components of the hybrid system are sized so as to ensure complete utilization of the hydrogen.

A schematic diagram of the analyzed solution is shown in Fig. 1. A description of the individual installations and the method used to model them are presented later in this chapter.

2.1. Wind farm

It was assumed in the analysis that the electrolysis installation will be supplied with electricity from a wind farm, and in the case of insufficient power production by the farm, from the power grid. No particular wind farm was adopted here, but on the basis of the available exemplary power characteristics of a wind farm, the power required to supply the electrolyser was assumed. A wind farm with an installed capacity of 100 MW was adopted, of which the power characteristics (N) for the annual cycle (τ) are shown in Fig. 2.

It was assumed that the electricity produced in the wind farm during peak demand is sold to the grid, while the electricity generated in the valleys of the demand is directed to the electrolysis plant. In particular, this takes place during the 8-hour night valley, between 22.00 and 6.00. In the case of reduced wind farm production, the difference between the electricity required to power the electrolysis plant and the production of the wind farm is covered by electricity taken from the grid. In the case of a surplus wind farm production in the period of operation of the electrolysis installation, the excess electricity is directed to the grid. Exemplary power characteristics for a daily cycle of the wind farm cooperating with the electrolysis installation with a capacity of 10 MW, with marked areas of electricity use, are shown in Fig. 3.

2.2. Electrolysis installation

The process of electrolysis is conducted during the period of the night valley. The products of electrolysis (hydrogen and oxygen) are directed to the particular technological installation (gasification and methanation rector) or to the oxygen and hydrogen tanks, in order to ensure continuous operation of the system during the day. The oxygen produced in the process is only partially consumed, the remaining part thereof may be used as a commercial product.

The efficiency of the electrolysis installation was assumed at 57%. This value is defined as:

$$\eta_{\mathrm{el}} = \frac{\dot{m}_{\mathrm{H2}} LHV}{N_{\mathrm{el}}}, \tag{1}$$

where: $\dot{m}_{\mathrm{H2}}$—stream of produced hydrogen, LHV—lower heating value of hydrogen (120 MJ/kg), N_{el}—electrical power of the electrolysis installation.

The assumed schedule of operation of the electrolysis installation and its efficiency were used to determine the product streams for the assumed power of the electrolyser.

2.3. Biomass gasification installation

The analysis assumes that the biomass gasification process will be conducted in the gas generator with a Bubbling Fluidized Bed (BFB). Reactors of this type are indicated in the literature as the most suitable for carrying out the process of methanation, primarily due to their simple construction and maintenance, high tolerance to the size of fuel particles, the uniformity of the temperature distribution and the course of chemical reactions in the bed, and ease of scaling [16–18]. In addition, generators of this type are classified as a medium temperature reactor, in which the product is a process gas containing a significant quantity of hydrocarbons (mostly CH_4), which favors the production of SNG. Gasifying factors in the gas generator are oxygen and steam (generated in the hybrid system), which facilitates the production of gas with the composition best suited for further

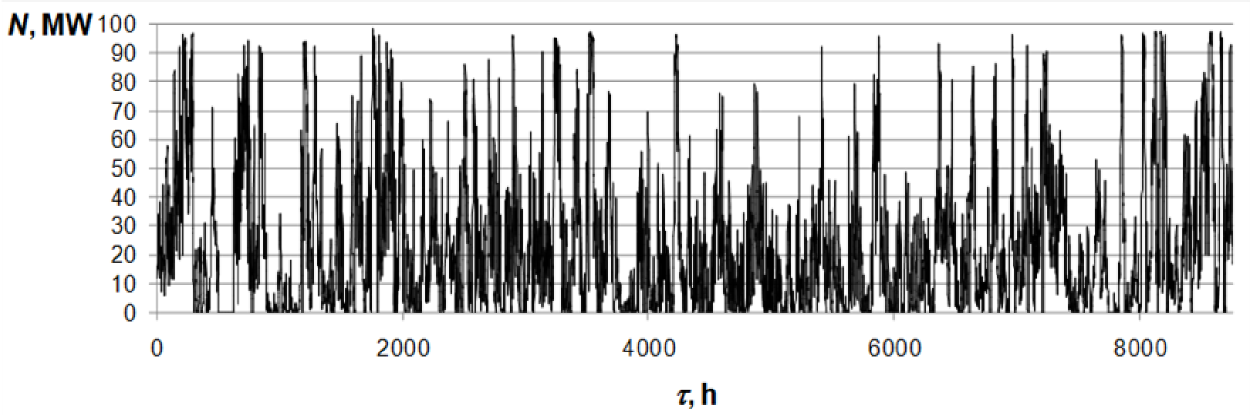

Figure 2: Power characteristics of the analyzed wind farm for annual cycle

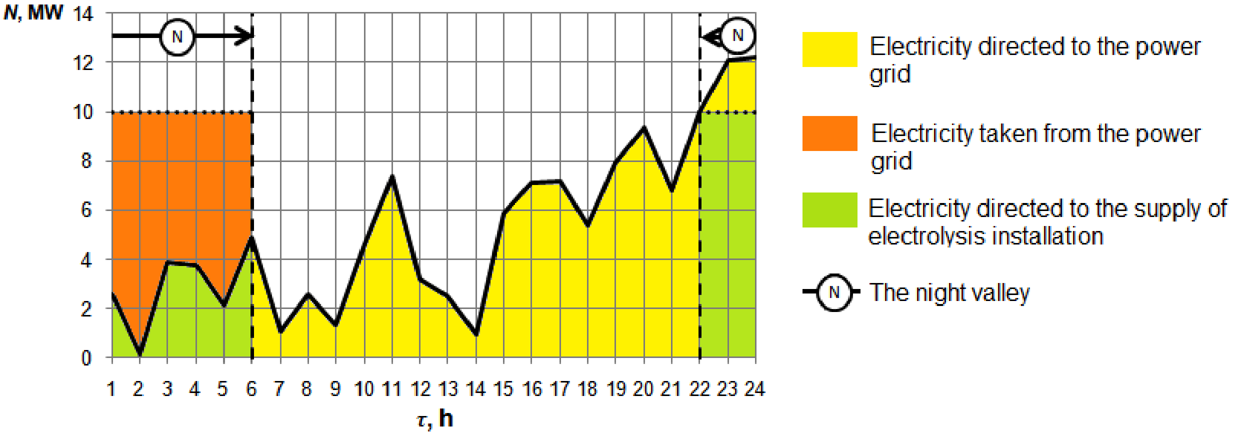

Figure 3: Characteristics of power of the analyzed wind farm for the daily cycle, cooperating with an electrolysis installation with capacity of 10 MW, with marked areas of the use of electricity

Table 1: Composition of gasified biomass

Parameter	Value
Ash, %	0.43
Carbon, %	48.75
Hydrogen, %	5.77
Nitrogen, %	0.19
Sulfur, %	0.04
Oxygen, %	44.75
Moisture content in wet biomass, %	14.60
Lower heating value of biomass (dry), MJ/kg	18.01
Biomass temperature at the inlet to the gasifier, °C	15

Table 2: Main parameters of the gasification process

Parameters of the gasification process	
Cold efficiency of the gasification process	0.66
Ratio $\frac{\dot{m}_{\mathrm{O2}}}{\dot{m}_{\mathrm{B}}}$	0.311
Ratio $\frac{\dot{m}_{\mathrm{pary}}}{\dot{m}_{\mathrm{B}}}$	0.515

Table 3: Main assumptions for the analysis of SNG production installation

Quantity	Definition/unit	Value
Efficiency of Shift reactor	$\eta_{\mathrm{SH}} = \frac{\dot{m}_{\mathrm{CO,3}}}{\dot{m}_{\mathrm{CO,2}}}$	0.98
Efficiency of methanation process	$\eta_{\mathrm{MET}} = \frac{\dot{m}_{\mathrm{CO2,5}}}{\dot{m}_{\mathrm{CO2,4}}}$	0.98
Efficiency of SNG drying	$\eta_{\mathrm{OS}} = \frac{\dot{m}_{\mathrm{H2O,8}}}{\dot{m}_{\mathrm{H2O,5}}}$	0.997
Required H/C ratio in Shift reactor	$\frac{\dot{m}_{\mathrm{H2O,2}}}{\dot{m}_{\mathrm{CO,2}}}$	2
Required H/C ratio in methanation reactor	$\frac{\dot{m}_{\mathrm{H2,4}}}{\dot{m}_{\mathrm{CO2,4}}}$	4
Pressure in the methanation reactor	bar	5
Temperature in the methanation reactor	°C	250

use in the process of methanation: the use of oxygen eliminates nitrogen from the produced gas, the use of steam shifts the equilibrium of the reaction in which it takes part towards the production of hydrogen.

A detailed model of the gasification reactor was built in Aspen Plus software using components from the library of the program. The model of the generator was divided into three equilibrium reactors, corresponding to the process of pyrolysis, gasification and combustion. The composition and biomass parameters assumed in the calculations are shown in Table 1.

The gas obtained in the gasification process is highly polluted and needs to be purified in accordance with the requirements of the successive stages of its processing (chemical synthesis). The analysis assumes that the gas is purified with a certain degree of efficiency, but the energy input in this process is not taken into account. The process gas is also cooled and the high-temperature heat generated in the process can be usefully utilized. Table 2 presents the most important parameters of the gasification process adopted for the analysis.

2.4. Methanation installation

The process of methanation, leading to the production of synthetic natural gas from CO_2 and CO using hydrogen, is a catalytic process. The main reactions taking place in the hydrogenation of carbon oxides to methane (methanation) are as follows [18]:

$$\mathrm{CO} + 3\mathrm{H_2} \rightarrow \mathrm{CH_4} + \mathrm{H_2O} \tag{2}$$

$$\mathrm{CO_2} + 4\mathrm{H_2} \rightarrow \mathrm{CH_4} + 2\mathrm{H_2O} \tag{3}$$

Reaction (3) is called a Sabatier reaction and is the primary reaction used in the production of SNG. It is an exothermic, reversible reaction, taking place under the use of a catalyst. Both reactions are connected by the shift reaction which occurs whenever the process utilizes a catalyst:

$$\mathrm{CO} + 4\mathrm{H_2O} \rightarrow \mathrm{CO_2} + 2\mathrm{H_2} \tag{4}$$

While the technology of methanation of carbon monoxide into synthesis natural gas (reaction (2)) is quite advanced, most of the projects concerning the process of methanation of CO_2 (according to the reaction (3)), predisposed for the conversion of producer gas to SNG, are relatively new systems. A large part of them are projects in Germany, e.g., E-gas/PtG BETA plant, PtG ALPHA plant Bad Hersfeld and PtG ALPHA plant Stuttgart, with the PtG test plant Rapperswil just over the border in Switzerland [12].

To ensure a the methanation reaction takes place as desired (3), the ratio of hydrogen to carbon dioxide (H_2/CO_2) must be kept at at least 4 to 1. However, in the gas obtained from the gasification process, this ratio is typically in the range 0.3–2.0. Thus, the amounts of hydrogen need to be increased. This may be accomplished by applying the shift reactor (reaction (4)) or supply of an additional stream from the outside. The shift reaction is typically carried out at a temperature of 200–500°C, and the process efficiency (defined as the ratio of CO_2 in the gas stream after the methanation process to the stream of CO_2 in the gas before this process) increases as the temperature decreases. For the process it is important to maintain a the appropriate pressure, which is typically in the range of 1–30 bar. Methanation efficiency increases as pressure increases. Keeping the process temperature below 300°C and a pressure above 5 bar enables efficiency of well over 96% to be obtained [3, 4].

Various methanation reactor designs are used in the production of SNG. The most frequently used are fixed bed reactors and fluidized bed reactors [3]. Examples of technologies utilizing fixed bed reactors include the Lurgi process, TREMP^{TM} process, Hicom process, Linde process, RMP process and the a ICI/Koppers process. Fluidized bed reactors have been tested within the framework of projects such as: Bureau de Mines, Bi-Gas and Comflux [18, 19]. In existing installations SNG is more often produced from biogas (by-product of methane fermentation) than from synthesis gas (which is the product of biomass gasification). Currently, there are no commercial plants using gas from biomass gasification or hydrogen from electrolysis for production of SNG in the methanation reactor, but it is a future technology, with development potential.

In a view of the multiplicity of solutions proposed in the lit-

Table 4: Results of calculations of gas turbine supplied with natural gas (NG) and SNG

Characteristics quantity	Value	
	NG	SNG
Efficiency of gas turbine, %	43.92	44.02
Exhaust gas temperature at the outlet from combustion chamber, °C	1380.0	1380.0
Exhaust gas temperature at the outlet of expander, °C	420.8	420.7
Air temperature at the outlet of the compressor, °C	364.3	364.4
Maximum temperature of the material of the blades of the expander, °C	800.0	800.2
Pressure ratio	42.0	42.1
CMV index	0.7500	0.7533
Ratio of cooling medium	0.1750	0.1754

erature, it was decided that the methanation process would be preceded by a Shift reactor, where carbon monoxide is converted to CO_2 using water vapor present in the gas from gasification or supplied from the outside (if water vapor is absent). It was assumed in the analysis that behind the Shift reactor there is a process gas compressor, aimed at raising the pressure to the pressure required in the methanation process (5 bar). It was also assumed that the compressor is a two-section machine with interstage cooling, which achieves the temperature behind the second section equal to the temperature assumed in the methanation process. The heat obtained during the cooling process can be usefully utilized. The resulting SNG is dried to the desired moisture content at the final stage. The most important assumptions at this stage of the calculations are summarized in Table 3.

2.5. Gas turbine installation

Gas turbines are ideal interventional power sources. Very short startup times (for units with a capacity of 100 MW at increments of power even above 10 MW/min) predispose gas turbines to form part of energy storage systems designed to work in a daily cycle during periods of peak demand. Other advantages of gas turbines are the relatively low rates of investments and a wide range of solutions. Gas turbines are adapted to the combustion of different gaseous fuels, including synthesis gas with a higher concentration of hydrogen. All these features indicate a high predisposition of gas turbines as electricity generators for energy storage systems based on electrolysis, gasification and methanation.

In the presented analysis, the power of the gas turbine was selected in order to fully utilize the hydrogen generated in the night valleys. It was assumed that the machine operates at electricity peak demand for 4 hours a day and produces electricity and heat, which in this period may support the local district heating system. Although the size of the turbine was a subject to scaling in this analysis, the other parameters were chosen in order to map the GE LMS100 unit. The model of the gas turbine, which is described in [20], was used to determine the parameters of the turbine operation designed for the combustion of natural gas (NG) and supplied with SNG obtained in the system. The basic parameters of the turbine supplied with these two fuels, which were obtained during calculations, are shown in Table 4. The characteristics values obtained for the case of the gas turbine gas supplied with SNG were used in the course of analysis.

Table 5: Parameters of the streams at selected points of the hybrid system

Point number	4	5	7	9	10
CO_2	0.1643	0.3346	0.0051	0.0154	0.0154
CO	0.1738	0.0035	0.0026	0.0080	0.0080
H_2	0.2033	0.3736	0.0307	0.0936	0.0936
CH_4	0.0468	0.0468	0.2832	0.8623	0.8623
N_2	0.0063	0.0063	0.0048	0.0145	0.0145
H_2O	0.4056	0.2353	0.6736	0.0062	0.0062
molar stream, kmol/s	0.0081	0.0081	0.0107	0.0035	0.01400
mass stream, kg/s	0.1674	0.1674	0.1832	0.0540	0.2162
LHV, MJ/m_n^3	6.0596	5.7469	10.5000	31.9686	31.9686

Table 6: Results of calculations for the hybrid system integrated with gas turbine

Parameter	Value
Heat flux from synthesis gas cooling, kW	189.2
Heat flux from cooling of gas in Shift reactor, kW	52.7
Heat flux from cooling of gas in the interstage cooler, kW	66.1
Heat flux from SNG cooling, kW	377.5
Total useful heat flux generated in the process of SNG synthesis, kW	685.5
Heat flux needed for production of steam supplied to gas generator, kW	139.0
Gas compressor power, kW	67.1

3. Results of the analysis of the integrated hybrid system

It was assumed in the analysis that the gasification and methanation installations operate continuously while the electrolyser and gas turbine operate in a discontinuous manner. It was assumed that the electrolysis installation operates 8 h per day, but during this time they produce the quantity of hydrogen which is necessary for continuous operation of the hybrid system. The hydrogen and oxygen in the amount required for gasification and the methanation process, and the SNG used in the gas turbine system are stored in the tanks and used when needed. Nominal power of electrolysis installation was assumed at 10 MW (5.7 MW in hydrogen produced), which enables operation of the gasification system with a power of 1.65 MW in biomass fuel.

The mathematical model of the hybrid system was used to calculate the basic parameters of streams in all important points of the system. The main results of the analysis are presented in the diagram shown in Fig. 3.

Parameters of gases at selected points of the system, according to denotations from Fig. 4, are shown in Table 5.

In the hybrid system heat flows are generated, which, because of the high temperature of the medium (gas), may be usefully utilized. The main sources of heat are: cooling of the process gas after the gas generator, cooling (including drying) of gas behind the methanation reactor, cooling of the gas in the Shift reactor and compressor intercoolers (before the methanation reactor), and cooling of the exhaust gas from the gas turbine. The most important values of the streams of energy produced or supplied to the system are summarized in Table 6.

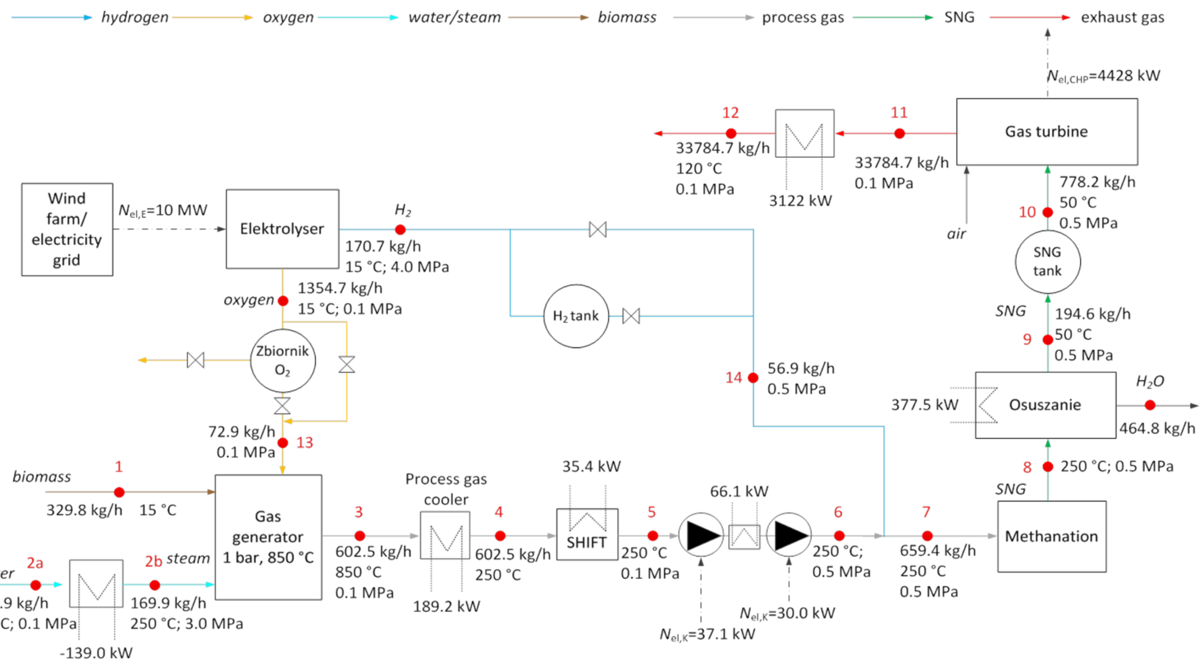

Figure 4: Results of the analysis of the hybrid system

Table 7: Results of calculations of the system integrated with gas turbine

Quantity	Value
Chemical energy flux of SNG fuel, kW	10058.5
Electric power of gas turbine, kW	4427.7
Heat power of gas turbine, kW	3122.2
Overall efficiency of gas turbine, -	0.7506
Efficiency of electricity generation in gas turbine, -	0.4402
Temperature of exhaust gases leasing gas turbine, °C	420.7

Table 8: Annual quantities of the raw materials and products

Quantity	Value
Chemical energy of biomass, GJ	41578
Chemical energy of hydrogen, GJ	47880
Chemical energy of process gas, GJ	27644
SNG chemical energy, GJ	63368
Electricity directed from the wind farm to electrolyser, MWh	17142
Electricity directed from the grid to electrolyser, MWh	6191
Electricity generated in gas turbine, MWh	7748
Useful heat obtained in the SNG synthesis process, GJ	17275
Useful heat obtained in gas turbine, GJ	19670
Heat needed for steam generation, GJ	3503

The analysis reveals that for the nominal assumptions (10 MW of power of the electrolyser) the chemical energy of the derived SNG gas is equal to 2541.6 kW. Gas is directed to storage and when the gas turbine is operating all of the gas is used for electricity and heat generation.

The hybrid system integrated with the electrolysis installation, biomass gasification, methanation, and gas turbine unit can be considered in two variants, which differ in the continuity of gas turbine operation. In the first variant, the gasification and methanation system operates continuously, the electrolysis plant for an 8 h night valley, and a cogeneration system for 4 hours during a peak demand. This solution requires the storage of hydrogen and oxygen, but also of the produced SNG. The main feature of this solution, however, is the production of electricity when there is a real need. The second variant of work differs from the first variant in that the gas turbine system operates continuously, which obviates the need for installing a SNG storage or for choosing a gas turbine with a lower nominal power. In this paper the first variant of operation of the hybrid system is considered, because from the point of view of the power system it is a more favorable solution.

The main results obtained from the modeling of the cogeneration unit with gas turbine working in a discontinuous manner are summarized in Table 7.

For the purpose of evaluating the hybrid system and possibly producing an economic analysis it is useful to determine the annual quantities of raw materials and products. These values were determined on the assumptions that the hybrid system works for 7000 h per year and that heat is produced in cooperation with a heating network with parameters of 90/70°C. The results are summarized in Table 8.

The presented results concern the case in which the hydrogen generator installed in the hybrid system for energy storage has a capacity of 10 MW. Selection of power generators for the existing wind farm is a key optimization issue in terms of investment in the energy storage system. Maximization of the power consumed by electrolysers might allow for advantageous provision of lower rates of unit investment costs for such components of the system as the gasifier, methanation generator and gas turbine. However, the higher the power needed to supply hydrogen generators, the higher

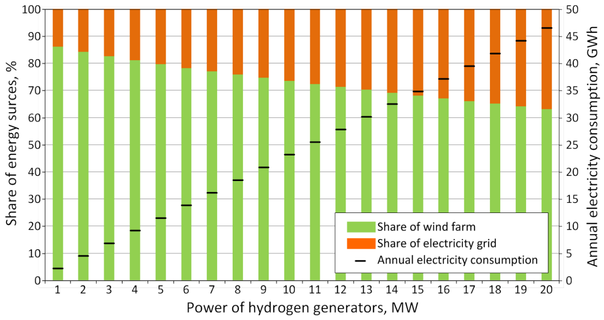

Figure 5: The influence of the installed power of hydrogen generators on the share of the two sources of electricity to cover electricity demand required for the realization of the electrolysis process

the ratio of power received from the grid to power from the wind farm. Fig. 5 shows the influence of the installed capacity of the electrolysers on the share of these two sources in terms of annual supply of the electrolysis process. The figure also shows the size of the overall consumption of electricity.

4. Summary and conclusions

This paper analyzes the concept of energy storage in the form of the use of hydrogen produced in electrolysis powered by electricity from a wind farm for the production of synthetic natural gas. The carbon dioxide required in the process of methanation comes from the process of biomass gasification in a fluidized bed reactor. The primary advantage of this solution is the ability to produce SNG - a gas whose potential scope of application is far larger than that of pure hydrogen. Furthermore, the oxygen produced in the electrolysis installation may be partially used directly in the hybrid system.

The analyses showed that in the case of the operation of the hybrid system focused on use of the entirety of the hydrogen formed in the electrolysis installation with a capacity of 10 MW, the required power of the gasification system (in the supplied biomass) is 1.65 MW. This allows for the production of SNG, whose chemical energy flux is higher than 2.5 MW. The assumption that the gas turbine will operate for 4 h a day during peak demand leads to the choice of a machine with power of 4.4 MW, which can serve as an emergency source of energy in the power system.

The proposed system is a system in which it is possible to use a wide variety of gas turbines proposed by manufacturers, due to the fact that the composition of the obtained SNG is similar to natural gas (in contrast to pure hydrogen). In addition, the heat generated in the process can be usefully employed, e.g. for the production of hot water for heating purposes.

A a full evaluation of the analyzed solution requires an economic analysis. The key issue here will be the adoption of appropriate assumptions for calculations, which can prejudge the profitability of the project in consideration. Such analysis will be conducted by the authors in the future.

Acknowledgements

This research was financed within the project commissioned by the National Center for Research and Development under the GEKON program: "Energy storage in the form of hydrogen in salt caverns", implemented in 2015–2016.

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