Article

Assessment of Operational Performance for an Integrated ‘Power to Synthetic Natural Gas’ System

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Abstract: This article presents a power to SNG (synthetic natural gas) system that converts hydrogen into SNG via a methanation process. In our analysis, detailed models for all the elements of the system are built. We assume a direct connection between a wind farm and a hydrogen generator. For the purposes of our calculations, we also assume that the hydrogen generator is powered by the renewable source over a nine-hour period per day (between 21:00 and 06:00), and this corresponds to the off-peak period in energy demand. In addition, a hydrogen tank was introduced to maximize the operating time of the methanation reactor. The cooperation between the main components of the system were simulated using Matlab software. The primary aim of this paper is to assess the influence of various parameters on the operation of the proposed system, and to optimize its yearly operation via a consideration of the most important constraints. The analyses also examine different nominal power values of renewables from 8 to 12 MW and hydrogen generators from 3 to 6 MW. Implementing the proposed configuration, taking into account the direct connection of the hydrogen generator and the methanation reactor, showed that it had a positive effect on the dynamics and the operating times of the individual subsystems within the tested configuration.

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1. Introduction

Nowadays, alternative opportunities are sought to enable efficient and environmentally-friendly electricity generation due to the need to improve the quality of the natural environment by limiting the emission of harmful substances into the atmosphere, water and soil [1]. Any new developments in the energy sector usually strongly support the gradual reduction of electricity generation that relies on fossil fuels in favor of installations that use renewable energy sources (RES). In recent years, this requirement has led to the continuous increase in energy systems with the capacity of RES installed [2–4]. Renewable systems, such as wind farms or solar panels, are typically characterized by a variation in the amount of electricity produced due to their dependence on the current weather conditions [5]. The latter, combined with the variable electricity demands of consumers throughout the day, rarely coincide with the production needs, and thus may lead to a suboptimal operation of energy systems [6]. Moreover, any major increase in electricity generation due to renewable energy installations may, without ensuring the appropriate energy buffers within the power grids, adversely affect the operational stability of the power systems [7]. The role of such protections in the power grid can be performed by use of energy storage installations. Their main task is to store surplus electricity during its excess production and feed it back into the grid when current demand exceeds the viable production capacity in the electricity network. Currently, the most common solution is pumped hydro-storage installations that enable large-scale energy storage [8]. However, intensive research has also been performed on other technologies, including systems that use hydrogen to store energy; these are known as power to gas (P2G) technologies [9–11]. The main task of power to gas installations is to convert any surplus electricity in the power grid into hydrogen. Another solution is known

as power to gas to power (P2G2P), which allows the generated hydrogen to be reconverted into electricity during a period of energy shortage in the electricity grid [12]. An appropriate potential use of these installations, i.e., those based on power to gas or power to gas to power, in cooperation with other power supply equalizing systems, will enable the effective employment of centralized electricity generating units and the increasing number of RES installations connected to the power grid.

At present, due to its high demand, especially in the industrial sector, hydrogen is obtained using various separation technologies. The foremost solutions rely on processes that use fossil fuels, such as hard coal, oil or natural gas. About 99% of hydrogen production involves the conversion of non-renewable fuels or electricity that is generated using fossil fuels [13]. Currently, hydrogen use mainly is focused on the chemical industry, since its widespread adoption as a store of electrical energy remains far from broadly implemented. This results from the relatively high cost of creating electrolysis installations alongside the expense of H₂ production compared to other available technological solutions, and also the problems that arise when operating high-power hydrogen generator systems. Moreover, H₂ is considered a hazardous gas, which means a high social resistance to their use as a store of energy at an industrial scale. Therefore, many problems relating to the production, storage, transport and the use of hydrogen in the energy sector need to be resolved. This is due to the fact that in the near future, the water electrolysis process may become a key solution to the storage of electricity that emerges from renewable energy sources or any surplus energy within the power grid [14]. Installations that use hydrogen as a carrier of chemical energy, which can be reconverted into electricity, are currently considered as potentially important systems for storing energy from wind farms or other renewable sources that produce variable amounts of electricity over time.

Hydrogen generators are a key element for installations that use hydrogen as energy carriers, such as P2G systems. The hydrogen generator, in addition to the electrolyzers themselves, includes a water tank that supplies the electrolyzers, a pump that forces water to circulate through the electrolyzer and the cooling system, a cooler that maintains the optimal operating temperature, and a hydrogen purification system. The electrolyzers are responsible for the electrolysis process itself. Due to the specificity of the structure, operating parameters and the chemical reactions that occur, several forms of distinguishable electrolyzers are available. One type of which are known as alkaline electrolyzers (AEL), which have a rated efficiency and specific energy consumption in the range 63–71% and 4.2–4.8 kWh/Nm³ H₂, respectively, for stack calculations performed for the lower heat value (LHV) [12]. Proton exchange membrane (PEM) electrolyzers are another possibility; the rated efficiency and specific energy consumption for this type of electrolyzer stack are within the range 60–68% and 4.4–5.0 kWh/Nm³ H₂, respectively [15]. A third type involves anion exchange membrane (AEM) electrolyzer technology, which is a relatively new solution compared to the more mature systems based on AEL and PEM electrolyzers. AEM electrolyzers are characterized by relatively less corrosive electrolyte solution, dynamic operation, lower costs (non-precious metal catalysts used). [16]. In the case of SOE (solid oxide) high-temperature electrolyzers, the feed-in system involves steam, and the whole process occurs at a temperature of up to 1000 °C. The main advantage of high-temperature electrolyzers is the lower electricity demands compared to low-temperature electrolyzers. This is due to the use of heat as the main energy source, which is necessary for the relevant reaction to occur. This can lead to much higher efficiencies, as high as 90%, but solid oxide electrolyzers are still on at an early stage of development and only several demonstration systems have been built [17,18]. In case of SOE using high-temperature energy resources, nuclear power plants or concentrated solar power may be required [19].

When considering hydrogen as an energy carrier in power to gas, power to gas to power or power to SNG installations, the possibilities for storing the produced hydrogen should also be analyzed. Due to its low density, i.e., 0.0899 kg/m³ under normal conditions [20,21], hydrogen storage has some difficulties. Hence, numerous studies have been conducted to improve the gas storage technologies that are currently available and to

expand the range of solutions available in this area [22,23]. In the literature, the topic of hydrogen as an energy carrier in P2G and P2G2P installations is often discussed. In the paper [24], the authors present a possible case for the direct cooperation of a hydrogen generator, equipped with AEM electrolyzers, with a wind farm. This analysis makes use of measurements applied to a laboratory stand, employs a variety of ratios for the rated power of the wind farm compared to the hydrogen generator, and examines different operating modes of the analyzed system during a day. Calculations determined the average annual efficiency of the tested systems, the efficiency of the hydrogen generators operating at different powers, and the variation in hydrogen production at nominal operation points. The authors showed that the proper selection of the nominal power of the hydrogen generator compared to the wind farm ensures a higher efficiency for the tested system.

Power to SNG (synthetic natural gas) is a promising technology to store intermittent renewable electricity in the form of synthetic fuels. Power surplus on the electric grid is converted to hydrogen via water electrolysis and then to synthetic natural gas (SNG) [25].

The methanation process produces synthetic natural gas from CO₂ and CO using hydrogen. It is a catalytic, exothermic process, typically conducted in the temperature range of 200–550 °C and under increased pressure (up to 30 bar). The efficiency of methanation increases with increasing pressure. Maintaining the process temperature below 300 °C and the pressure above 5 bar allows a process efficiency of well above 96% [26].

In the article [27], the authors present an analysis of the influences on the system that are responsible for the hydrogen production processes and the storage operations of the power to SNG (P2SNG) installation. For this purpose, the authors created a mathematical model that enables a study of the dynamic states and the operating time of the individual elements of the system, which is then extended to the entire discussed energy storage installation. Analyses show that the highest average annual efficiency of the hydrogen generator installation are not associated with the most effective use of energy from the renewable energy source. However, in line with the thesis, it is worthy of note that the efficiency of the installations intended for energy storage within the power grid is of secondary importance, since, without these kind of installations, the surplus energy would be completely dispersed from the power grid. The main purpose of these types of systems is the managing of the surplus energy present in the grid at any given moment; they return electricity back into the grid when demand is higher than viable production in the electricity network. However, in this paper, the analysis of the power to SNG installation did not consider a variant that enables direct transfer of the hydrogen produced in the electrolysis process to the methanation reactor, which omits the need for a buffer tank.

Installations designed for hydrogen production based on the electrolysis of water are also often used in energy storage systems that cooperate with solar installations [28,29]. The article [30] presents a system for the storage of the energy generated from PV (photovoltaic) panels. This scheme is based on the cooperation of a hydrogen generator, equipped with electrolyzers of the PEM (proton exchange membrane) type, with a lead-acid battery acting as an electrical energy buffer. The use of an additional accumulator, in the form of a battery, allowed for an increased energy storage capacity during the period of time under study; it also ensured the operation of a hydrogen generator using its nominal parameters, despite being solely supplied by a photovoltaic installation. A comparison of systems that operate using a similar principle, with and without an installation dedicated to the production of hydrogen via the water electrolysis process, is presented in [31]. However, in order to fully realize the potential of hydrogen as an energy carrier, the size of the devices selected for the installation, in particular the hydrogen generator and the gas buffer tank, must be properly optimized. The appropriate selection of these types of devices enables improvements to the time indicators and the efficiency of the tested installation.

The main novelty of this paper lays in its comprehensive analysis of an integrated P2SNG energy system, which considers various hydrogen flow directions alongside a regulation of the hydrogen generator load. The hydrogen that is generated can be supplied either into the buffer tank or directly into the methanation reactor. The proposed

plant configuration enables a reduction in the capacity of the hydrogen buffer tank, while maintaining a continuous operation of the methanation reactor. In the analyzed case, the charging and discharging states of the tank, which are used for storing the hydrogen produced from the electrolysis process, were considered alongside the varying efficiency of the hydrogen generator that results from the variation in the power that supplies the device. Assuming the off-peak period for electricity demand occurs over nine hours a day (21:00–6:00), a number of characteristics are analyzed to enable a qualitative assessment. This includes an account of the efficiency of the power to SNG system, the amount of hydrogen produced and the operating time of the installation.

2. Method

The integrated power to synthetic natural gas system that is analyzed in this paper (depicted in Figure 1) consists of a hydrogen generator (which is supplied with electricity from renewable energy in the form of a wind farm), a methanation reactor and a compression section. The plant is also equipped with a water treatment station, a water separator and two buffer tanks for either the hydrogen or water. The general concept behind this system is also described, in detail in article [27].

Figure 1. Scheme of the power to SNG system.

The models of the individual elements of the power to SNG system were developed using Aspen Plus software. The system cooperates with a renewable energy source, a wind farm in this case. The hydrogen generator, which is a vital component of the installations, is prepared so that it operates with a variable power supply, which derives from the wind farm. The characteristics of both elements, i.e., the wind farm and generator efficiency, are described in detail in the paper [27]. For the purposes of our calculations, it was assumed that the hydrogen generator is powered by the renewable source over a nine-hour period per day (between 21:00 and 06:00); this corresponds to the off-peak period in energy demand. This enables the use of excess energy that is sold at much lower prices compared to periods of high demand. The important part of the calculations focused on the temporary buffering of the hydrogen, and its impact on the system operation. While the general concept of cooperation with hydrogen tanks has been presented in the paper [27], the bypass (line 4a in Figure 1) is added in this manuscript. This has a strong impact on the behavior of the installation. When the hydrogen generator cooperates solely with the buffer, the only determinant of its load is the renewable supply power. However, in the variant presented here, the generator can operate even if the tank is full. This is because, when the hydrogen tank is filled, the hydrogen generator load is reduced to directly match the demand of the methanation reactor, and the hydrogen stream is directed through the bypass (4a).

Mathematical models of the individual elements of the system, alongside the thermodynamic analysis of the integrated system, were conducted using a model of the P2SNG system that was simulated using the process simulation software, Aspen Plus. A built-in Aspen Plus procedure, i.e., the Peng-Robinson, was used to calculate the energy parameters.

A detailed analysis of the P2SNG system is presented in previous works of the authors, e.g., ref. [32]. The efficiency of the methanation process is defined here as the degree of CO₂ conversion, i.e., the ratio of the CO₂ stream in the gas after the methanation process (mCO₂, out) to the CO₂ stream in the gas before this process (mCO₂, in).

The cooperation between the main components of the system, especially the wind farm, hydrogen generator and a hydrogen tank, were simulated using Matlab software. Several characteristics were modeled that represent the operational parameters of the installation over five days and all year round. The analyzes considered various nominal power values for the renewables (8–12 MW) and hydrogen generators (3–6 MW).

3. Results and Discussion

Calculations were made for several variants of the nominal power of the wind farm and hydrogen generator, for different capacities of the buffer tank, and for various operating times of the system.

3.1. Nominal Power of the Wind Farm—10 MW, Nominal Power of the Hydrogen Generator—5 MW, Capacity of Hydrogen Buffer—3 MWh and Operating Time—5 Days

Figure 2 presents the operation characteristics based on the analysis of cooperation of a wind farm with a P2SNG installation for a five-day operating time (120 h). It is assumed for the calculations that the nominal power of the wind farm and the hydrogen generator are 10 MW and 5 MW, respectively; the capacity of the hydrogen buffer is equal to 3 MWh. During this time period, the power generated by the RES (symbolized by P_{RES}), the power supplied to the hydrogen generator (P_{HG_supply}), the amount of hydrogen produced in the electrolysis process (P_{H2gen}), and the amount of hydrogen used in the methanation process ($P_{H2usage}$) were analyzed.

Figure 2. Graphs depicting the computational results for a P2SNG system with a 15 MW wind farm and a 5 MW hydrogen generator integrated with a hydrogen buffer tank (3 MWh for 120 h time operation). (a) Power-time series and (b) state of charge of the buffer (TF).

The hydrogen generator is powered with a maximum power of 5 MW, the value of the accumulated power in the form of hydrogen (P_{H2gen}) is lower than the value of the power that supplies the generator. This is due to the efficiency of converting electricity

into chemical energy of the hydrogen. The latter, often called the efficiency of a hydrogen generator, can be expressed by the following equation:

$$\eta_{HG} = \frac{\dot{m}_{H_2} \cdot HHV_{H_2}}{P_{HG_supply}}, \quad (1)$$

where $\dot{m}_{H_2}$ is the hydrogen flow rate, kg/s, P_{HG} is the power supplied to the hydrogen generator (kW) and HHV_{H_2} is the hydrogen higher heating value (141.8×10^3 kJ/kg). The efficiency of the hydrogen generator depends on its rated power (size) and the type of electrolyzers used within the device [24]. The efficiency curve used in the calculations is adopted from the paper [27].

The model of the analyzed P2SNG system was designed so that, when the tank (which acts as a hydrogen buffer in the system) is completely filled, the hydrogen for the methanation process is supplied via the bypass used in the installation. This enables the constant operation of the hydrogen generator-methanation reactor system, due to a bypass of the buffer tank in the installation. The power received by the hydrogen generator is reduced when the hydrogen storage is completely filled and, simultaneously, the efficiency of the system relies on the direct supply of the hydrogen produced in the electrolysis process to the methanation reactor. Such a procedure does not extend the operating time of the hydrogen generator at the nominal operating point, as the methanation installation in the presented case is characterized by a lower value for the rated power compared to the water electrolysis installation. However, it ensures an extension of the continuous operation between the hydrogen production and the other relevant systems (Figure 2). Moreover, improving the operating time indicators of the individual subsystems of the installation not only positively affects the efficiency of the power to SNG system, but may also improve the service life of the devices within it, due to the elimination of the numerous “on-off” sequences.

Figure 3 provides the characteristics of the hydrogen stream for the process of charging and discharging the tank, and the hydrogen stream produced in the electrolysis process for two variants of the hydrogen generator power supply. In this graph, the green line represents a powering of the device with all the available power from the wind farm, which corresponds to line 4 of Figure 1, and the blue line is the reduced power supplied to the generator when the produced hydrogen is directed through the bypass to the methanation reactor, which relates to line 4a in Figure 1.

For the mathematical assumptions regarding the power of individual installations, the process of filling the buffer tank requires a concise time because, after a few minutes, the presumed capacity of the tank is filled with the gas produced from the electrolysis process. The assumed nominal power of the hydrogen generator, amounting to 5 MW, corresponds to the nominal stream of produced hydrogen that equals to 0.021 kg/s. The discharge of the stored hydrogen may (depending on the power supplied to the hydrogen generator system) require additional time because the methanation installation, in order to operate at the nominal operating point, requires a constant flow of substrate in the form of H_2 , which amounts to a stream value of 0.0095 kg/s. In line with the adopted concept, if an additional connection is used between the H_2 generator and the methanation reactor, which allows the filled gas buffer tank to be omitted and the reactor to be continually fed, the value of the produced hydrogen stream is reduced and is stabilized at the level required by the methanation reactor.

Figure 3. Graphical representations of the results for the hydrogen stream in the plant operation, simulated for 120 h: (a) charging and discharging the buffer; (b) the two operating states of the hydrogen generator that results from an adopted concept of the P2SNG system.

3.2. Nominal Power of the Wind Farm—10 MW, Nominal Power of the Hydrogen Generator—3 MW and Operating Time—365 Days

The analyzes performed over the five-day period included the charging and discharging cycles of the buffer tank, alongside the phases of the direct feeding of the methanation reactor with the hydrogen produced in the electrolysis process. They showed that the introduction of an additional bypass, which connects the H₂ generator with the methanation reactor, may significantly affect the operating parameters of the tested system. Therefore, the next step was to perform year-round calculations that cover the basic parameters of the power to SNG installation. The mathematical model uses the variant for the nominal power of the wind farm and the hydrogen generator with 10 MW and 3 MW, respectively. The stream of hydrogen, at the nominal operating point, to the methanation reactor was kept at 0.0095 kg/s. As determined previously, it is concluded that the capacity of the hydrogen tank is a key component in the two analyzed variants, especially in relation to the installation operation time. Figure 4 shows the characteristics of the system operation times for the two operating states, that depend on the filling state of the buffer tank as a function of its capacity.

The curves presented in Figure 4 illustrate that the capacity of the hydrogen buffer tank has a significant effect on the operating time of the installation. Hence, the operating time of the hydrogen generator in a given mode is modified with an increase in the capacity of the buffer tank. The use the bypass is not needed above a 5 MWh capacity for the buffer tank, and thus a reduction in the load extends the operating time of the generator. Tank capacities at these levels are able to accumulate the produced hydrogen (of course, it is discharged simultaneously for use in the methanation process). An increase in the gas buffer capacity reduces the operation time of the SNG system at a reduced load (blue line in Figure 4).

For the calculated subsystems powers in this analysis, the hydrogen bypass is not used at all with a 5 MWh tank. This occurs because the additional H₂ generator-methanation reactor connection is only applied when the hydrogen buffer tank is completely full. Another analyzed operating parameter of the power to SNG installation was the average filling of the gas tank over an annual operation time. It is defined according to the following equation [27]:

$$\eta_{\text{avg_HG}} = \frac{E_{\text{H}_2\text{gen}}}{E_{\text{HG_supply}}}, \quad (2)$$

where $E_{\text{HG_supply}}$ is the amount of energy supplied to the hydrogen generator and $E_{\text{H}_2\text{gen}}$ is the amount of chemical energy in the generated hydrogen, respectively. The characteristics of the average filling of the gas buffer tank, as a function of its capacity, is shown in Figure 5. For the smallest analyzed H_2 tank capacity, corresponding to 1 MWh, its average filling in one year was 0.150. As the buffer capacity increased, its average filling decreased (for example, it is 0.112 for 5 MWh). For the largest analyzed tank capacity, equal to 10 MWh, the obtained filling value was 0.083.

Figure 4. Graph showing the operating time for the two variants of the hydrogen generator working as a function of the hydrogen buffer capacity.

Figure 5. Graph showing the average fill of the hydrogen buffer over an annual operation.

In addition to the operating-time indicators of the individual subsystems used in the analyzed power to SNG installation, the parameters that enable a determination of the effectiveness of a given system also play a key role. One such parameter is the stored energy share factor, which can be described as follows [27]:

$$\gamma = \frac{E_{\text{GenLoad}}}{E_{\text{RES}}} , \quad (3)$$

where E_{GenLoad} is the amount of energy supplied to the hydrogen generator and E_{RES} is the amount of energy generated in the wind farm. This indicator, defined as the ratio of the amount of energy supplied to a hydrogen generator in relation to the amount of electricity generated in a renewable source (e.g., a wind farm), is also used to assess the selection of the power range and the capacity of the subsystems of the energy storage installations. The characteristics of the stored energy share factor defined according to Equation (3) as a function of the capacity of the used buffer tank is shown in Figure 6.

Figure 6. Graph showing the stored energy share factor as a function of hydrogen tank capacity.

According to Figure 6, a significant increase in the γ factor is observed from a value of 0.205 (obtained for a 1 MWh H₂ tank) to 0.227, which was found for a 5 MWh buffer tank. When the value of 5 MWh is exceeded, which represents the capacity of the tank, the value of the stored energy share stabilizes at a constant level. The shape of the presented plot is influenced by the operation method of the power to SNG installation used in the computational model. With small reservoir capacities, its filling persisted for a short period of time and the electrolysis installation operates at a constant reduced power, which adapted to the needs of the methanation reactor. In the case of a larger capacity gas buffer, it is possible to operate the hydrogen generator over a longer period of time at its nominal power; when the appropriate power generated by the wind farm is ensured, the simultaneous reduction of the bypass operation time of the electrolysis installation occurs.

As can be seen in Figure 6, for a capacity greater than or equal to 5 MWh for the H₂ buffer, the γ coefficient assumes a constant value. When this arises the water electrolysis installation constantly cooperates with the H₂ storage, meaning that the available bypass is not used. Therefore, the hydrogen generator is able to operate constantly at its nominal power, when it is provided by RES. In the analyzed energy storage installation, the direct connection between the H₂ generator and the methanation reactor enables an improved stored energy share factor for hydrogen storage tanks with a small capacity. This procedure

enabled further deployment of the power from the RES in the electrolysis process, despite a full hydrogen reservoir. For larger buffer reservoirs, the use of the bypass has no effect on the value of the γ coefficient. This is because the additional circulation is not used, and the produced hydrogen is completely injected into the reservoir.

3.3. Nominal Power of the Wind Farm—8–12 MW, Nominal Power of the Hydrogen Generator 3–6 MW, Capacity of Hydrogen Buffer—5 MWh and Operating Time—365 Days

The previously presented characteristics have been used in preparation of an analysis for a specific configuration, which is given in this subsection. In order to perform a wide spectrum of efficiency analyses of the proposed configuration, a simulation of the year-round operation of the power-to-SNG system was performed using different nominal power values from the RES and the hydrogen generator. The performed calculations have the nominal power of the wind farm and the hydrogen generator ranging between 8–12 MW and 3–6 MW, respectively, and the capacity of the H_2 buffer was set at a constant level of 5 MWh. The stream of hydrogen, at the nominal operating point, to the methanation reactor was kept at 0.0095 kg/s. Figure 7 shows the quantity of H_2 produced in the water electrolysis installation as a function of the rated power of the hydrogen generator and the RES. This is provided for two cases: the cooperation of the generator with a gas buffer (stream 4) and the direct cooperation of the water electrolysis system with the methanation reactor (stream 4a).

Figure 7. 3D graph depicting the quantity of hydrogen directed through either line 4 and 4a, for a one-year operation, as a function of the variable power of the RES and hydrogen generator.

For the operating mode that enables a charge in the gas tank, much greater amounts of hydrogen are produced compared to the case at reduced generator power operations. Working in conjunction, the hydrogen generator-gas storage-methanation reactor enables the hydrogen generator to operate at the nominal point, when sufficient electricity is supplied by the wind farm. However, it is especially noteworthy that the largest amount of

produced hydrogen in the tank operation relates to the largest analyzed wind farm (12 MW) and the smallest hydrogen generator (3 MW). This arises because of the performance characteristics of the hydrogen generator, which can achieve the highest values at the nominal operating points of the device; for lower power values that supply the generator, the efficiency of hydrogen production is lower [27]. Hence, for the cooperation of the hydrogen generator-gas reservoir-methanation reactor, on increasing the rated power of the hydrogen generator relative to the farm power, the amount of produced hydrogen was smaller, because the H₂ generator had a lower likelihood of operating at the rated power. Conversely, the amount of produced hydrogen is provided via operation of the water electrolysis installation at a reduced load. This enables a direct cooperation with the methanation reactor, which is set apart from the fully charged buffer tank. In such a case, the electrolysis plant produced gas that is forced directly into the reactor. The relationship for the tank loading rate depends on the selected power of the individual subsystems, which strongly influences the amount of hydrogen directed (bypassing the H₂ tank) into the methanation installation. Most of the hydrogen passes through the bypass for the highest nominal powered wind farm and hydrogen generator that are analyzed (i.e., 12 MW and 6 MW, respectively). In this configuration, the fixed capacity tank (5 MWh) is filled relatively quickly with the produced gas, and the remaining hydrogen is redirected through the bypass, thus bypassing the filled tank. According to the data presented in Figure 7, the gas buffer filling rate has a stronger effect on the amount of hydrogen produced compared to the hydrogen production plant efficiency. For generators with a lower power, the results showed that a smaller amount of the generated hydrogen passed through the bypass of the power to SNG installation. Devices with a lower power, and thus a lower efficiency, require a longer period of time to charge the gas reservoir. Therefore, despite the fact that H₂ generators (which have a lower nominal power), with a reduced power that is necessary for direct cooperation (i.e., the hydrogen generator- methanation reactor), work closer to the nominal operating point. They also generate less hydrogen compared to higher-power units, which are characterized by greater hydrogen production at the nominal point. The greater amount of hydrogen produced via line (4) is also justified by the characteristics shown in Figure 4, i.e., the mode of this operation continues significantly longer than the operation with a reduced load.

To verify the efficiency of the power to SNG installation, an analysis of the influence of the selected rated power of the renewable energy source and the hydrogen generator, on the stored energy share factor (Figure 8) and the average annual efficiency of the synthetic natural gas production (Figure 9) was performed. The amount of chemical energy stored in the SNG was calculated taking into consideration the annual amount of produced SNG (stream of gas in point 10, Figure 1 multiply by the operation time of the system) and its LHV was determined on the basis of the composition of this mixture. The average annual efficiency of the SNG production was calculated using the following formula:

$$\eta_{SNG}^{avg} = \frac{E_{SNG}}{E_{HGsupply}} \quad (4)$$

where E_{SNG} denotes the amount of chemical energy stored in the synthetic natural gas and $E_{HGsupply}$ is the amount of energy supplied to the hydrogen generator.

Figure 8. Plot showing the influence of the selected rated power of the renewable energy source and the hydrogen generator on the stored energy share factor, γ .

Figure 9. Plot showing the influence of the selected rated power of the renewable energy source and the hydrogen generator on the average annual efficiency of SNG production, η_{SNG}^{avg} .

For the case of the stored energy share factor, which is defined in Equation (3), the most advantageous configuration for obtaining the highest γ values and, simultaneously, storing the most amount of energy, is to connect a hydrogen generator and a wind farm that contain a rated power of 4 MW and 8 MW, respectively. For such a combination, the γ factor was determined to be 0.2532. The least favorable value for the stored energy share factor (i.e., $\gamma = 0.2074$) was obtained for a 12 MW wind farm and a 3 MW generator. This

results from the adopted definition of the γ coefficient, which is defined as the ratio of the amount of electricity supplied to the hydrogen generator compared to the amount of electricity generated by the wind farm. Using this definition, the largest part of the energy from a renewable energy source will be used in the electrolysis process of the RES systems with a low rated power. However, as mentioned earlier, the selection of the low-capacity renewable energy installations may also have negative factors. It should be noted here that the presented calculations are based on specific assumptions in relation to the characteristics of the adopted wind farm. The latter are based on operations that depend on the wind conditions that prevail in a given area at a given time. Hence, despite the very favorable determined characteristics in terms of the stored energy share factor, there may be situations that occur that involve unfavorable wind conditions, which translates into low electricity production from the RES and hydrogen generators that cannot operate at their nominal levels; thus, the efficiency of the power-to-SNG operation can be significantly comprised. Moreover, in the case of cyclically repeated drops in the energy supplied to the water electrolysis installation, a situation may arise in which the hydrogen generator is continually forced to operate in an “on-off” mode, which may adversely affect the lifetime of such devices.

Hence, in order to verify the functionality of the analyzed power to SNG system, other operating indicators are required for a full analysis of the tested range of nominal powers for the wind farms and the hydrogen generators. One of which is the average annual efficiency of the SNG production. From Figure 9, the highest value of η_{SNG}^{avg} was found to be 49.59%, which corresponds to the largest wind farm (12 MW) cooperating with the smallest hydrogen generator (3 MW). While the lowest value of the annual average efficiency of SNG production was obtained for a hydrogen generator with a nominal power of 6 MW cooperating with an 8 MW wind farm. For such a set of installations, the average annual efficiency was found to be 48.78%.

4. Conclusions

This article proposed a power to SNG system that converts electricity from a renewable energy source into chemical energy that is stored in synthetic natural gas. To the standard configuration of the H₂ generator-gas buffer-methanation reactor, an additional connection was included that acts between the water electrolysis installation and the methanation reactor in the form of a bypass, which operates when the H₂ tank is at full capacity. From the analysis of the results presented in the article (Figures 8 and 9), it can be seen that the most favorable results for the analyzed indicators of the power-to-SNG installation operation, stored energy share factor and the average annual efficiency of the synthetic natural gas production were obtained at different configurations of its subsystems, i.e., hydrogen generator and RES installation. Therefore, at the design stage of this type of installation, all available options and solutions should be considered, including the principal indicators for determining the optimal efficiency and operations time. This will enable efficiency improvements to the electricity grid via pertinent adjustments to the operation of the energy storage installation and to the configuration of the power system as a whole.

Implementing the proposed configuration, by use of a computational model of the power to SNG installation, showed that it had a positive effect on the dynamics and the operating times of the individual subsystems within the tested configuration. The use of the additional hydrogen route to the methanation reactor enables the suitable regulation of the hydrogen generator in relation to the hydrogen demands throughout the installation, whenever the electricity from the RES is appropriately availability. The use of a bypass also minimizes the operation of the hydrogen generator in an “on-off” mode. This allows for device operations over a longer period of time, which in the long term could positively affect the lifetime of the water electrolysis installation that operates within the proposed system.

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