POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2018 ✦ Volume 21 ✦ Issue 4 ✦ 43–64

DOI: 10.24425/124511

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Management of surplus electricity production from unstable renewable energy sources using Power to Gas technology

Abstract: Increasing the share of energy production from renewable sources (RES) plays a key role in the sustainable and more competitive development of the energy sector. Among the renewable energy sources, the greatest increase can be observed in the case of solar and wind power generation. It should be noted that RES are an increasingly important elements of the power systems and that their share in energy production will continue to rise. On the other hand the development of variable generation sources (wind and solar energy) poses a serious challenge for power systems as operators of unconventional power plants are unable to provide information about the forecasted production level and the energy generated in a given period is sometimes higher than the demand for energy in all of the power systems. Therefore, with the development of RES, a considerable amount of the generated energy is wasted. The solution is energy storage, which makes it possible to improve the management of power systems. The objective of this article is to present the concept of electricity storage in the form of the chemical energy of hydrogen (Power to Gas) in order to improve the functioning of the power system in Poland.

The expected growth in the installed capacity of wind power plants will result in more periods in which excess energy will be produced. In order to avoid wasting large amounts of energy, the introduction of storage systems is necessary. An analysis of the development of wind power plants demonstrates that the Power to Gas concept can be developed in Poland, as indicated by the estimated installed capacity and the potential amount of energy to be generated. In view of the above, the excess electricity will be available for storage in the form of chemical energy of hydrogen, which

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in turn can be used to supply gas distribution networks, generate electricity during periods of increased electricity demand, or to refuel vehicles.

KEYWORDS: wind energy, Power to Gas technology, energy storage

Introduction

The changes taking place over the past few years indicate that the transformation of the energy sector is inevitable. Renewable energy sources (RES), which allow to implement climate protection measures and to develop a sustainable and low carbon economy, play a key role in these changes. In addition, many countries have developed mechanisms to support renewable energy, making investments in this field more profitable than conventional energy investments. The government support, technological improvements and lowering investment costs all affect the dynamics of renewable energy sources development. The global share of RES in the total primary energy production is increasing every year – in 2016 it amounted to 1,882 Mtoe, constituting 13.7% of the world Total Primary Energy Supply (TPES). Among the unconventional energy sources, the greatest increase can be observed in the case of solar and wind power generation. Between 1990 and 2016 the average annual growth rates were 37.3% for solar photovoltaic and 23.3% for wind power (IEA 2018). In view of the above, it should be noted that RES are increasingly relevant elements of power systems. These generation sources, and especially solar and wind energy, are characterized by variability of generation, and as such they pose a serious challenge for power systems as unconventional power plant operators are often unable to provide information about the forecasted production. Moreover, the energy demand is usually not equal to the amount of energy generated by renewable power plants. The stochastic nature of electricity production from variable sources is a challenge for the existing transmission and distribution networks as well (Jiang et al. 2012). If the variable renewable energy sources are connected to the power system, the problems with power quality, voltage stability, and network reliability can be observed (Akinyele and Rayudu 2014). As a consequence, the development of renewable power plants causes an increased risk of interruptions in the operation of power systems.

It is believed that energy storage, that would allow for increasing the flexibility of the power system, the efficiency of the management of energy production and distribution systems, and improving the energy quality and efficient use of renewable energy sources is the solution. The key parameters of the energy storage system include: the storage capacity, energy and power density, efficiency, charging and discharging time, reaction time, service life and cost of the system (Castillo and Gayme 2014). Currently, the most commonly used electricity storage technologies include pumped storage and compressed air energy storage (CAES). However, the mentioned technologies are limited due to their production capacity, which creates opportunities for the development of competing technologies for large capacity storage (Ancona et al. 2016).

The Power to Gas (P2G) technology, which uses electricity to generate hydrogen by means of an electrolyzer, is one of the competing technologies. Hydrogen, being the electolyzer product, can be used in many ways. By applying fuel cells it can be converted into electricity again. Compressed hydrogen can be stored and then used, for example, to power dedicated vehicles. Combined with carbon dioxide, it is subjected to methanation (the so-called Sabatier reaction: $CO_2 + 4H_2 = CH_4 + 2H_2O$) and can be injected into the gas network. Hydrogen can also be injected directly into a gas pipeline; although in small quantities that would not change the network performance. Until now, however, an economic and technical analysis of hydrogen injection into gas networks has not been carried out, so it is not obvious whether these investments would be profitable in Poland (Grueger et al. 2017).

The efficiency of the conversion of electricity into hydrogen in the P2G process is in the range of 54–77% (Leonzio 2017). This value mainly depends on the efficiency of the electrolyzer used. Alkaline and polymer electrolyzers have an efficiency of 55 to 84% (Gahleitner 2013), while the efficiency of solid oxide-based electrolyzers is in the range between 90–95% (Ahern et al. 2015).

The paper focuses on volatility of electricity production in Polish wind power plants. A comparison with energy production in conventional power plants leads to the conclusion that under Polish conditions the concept of electricity storage in the form of chemical energy of hydrogen (Power to Gas) would improve the functioning of the power system. The work discusses the P2G projects that have been undertaken in Europe. It presents the advantages of such a solution and the barriers and challenges facing the hydrogen economy in Poland.

1. The impact of electricity production in wind farms on the stability of conventional units production

The growth in the share of renewable energy sources and the reduction of greenhouse gas emissions into the atmosphere are among the proposals of the Polish government for the energy sector. The implementation of European Union (EU) regulations into the Polish law, the applied incentives and technological development are the reasons for a significant increase in the share of renewable energy sources in the total energy production. Figure 1 indicates that wind energy is the most developing renewable energy nowadays, in spite of recent obstacles of wind farm location, which caused a visible decline in the growth rate of capacity of onshore wind farms. In 2017, 5.8 GW of the installed wind farms capacity constituted 69% of the total installed capacity of renewable sources in Poland (URE 2017). The share of renewable energy capacity in 2016 in the total installed capacity in the polish power system was 14.0% and it rose to 14.6% in 2017 (PSE 2017b).

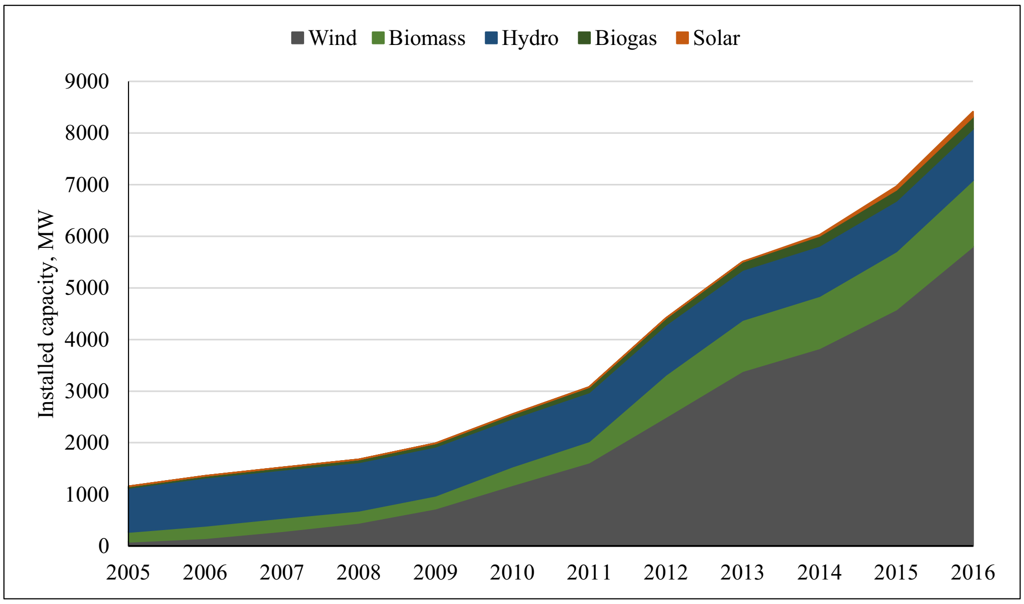

Fig. 1. Installed production capacity of renewable energy sources in the years 2005–2017 in Poland [MW]
Source: own work based on (URE 2017)

Rys. 1. Moc zainstalowana odnawialnych źródeł energii w Polsce w latach 2005–2017 [MW]

The total installed capacity in wind power plants will gradually increase to: 7.2 GW in 2018, and to 8.5 GW in 2019 (PSE 2017a). In addition, according to the forecasts of the operator of the national grid, the share of the installed capacity in wind power plants in the total installed capacity of the national power system will be increasing. The projected increase is presented in Table 1.

Table 1. Forecast of the installed capacity in the Polish power system

Tabela 1. Prognozy wielkości mocy zainstalowanej w polskim systemie elektroenergetycznym

Specification	2016	2017	2018	2019
The installed capacity in the national power system [GW]	41.4	42.7	44.1	47.2
The installed capacity of wind power plants [GW]	5.8	6.4	7.2	8.5
The share of wind power plants in the total installed capacity [%]	14.0	15.1	16.4	18.0

Source: (PSE 2017a).

In order to determine the nature of the operation of wind power plants in Poland, this article investigates changes in electricity production over a one year period. The data on electricity production in wind farms for each hour of the year, provided by the operator of the national power system, was analyzed. It can be assumed that the analysis carried out for one year may form the basis for future forecasts of electricity production in wind sources due to the fact that the weather conditions in Poland in individual months of the year and over the years are similar.

Data on electricity production in particular hours (8,784) of the 2016 year is presented in Figure 2.

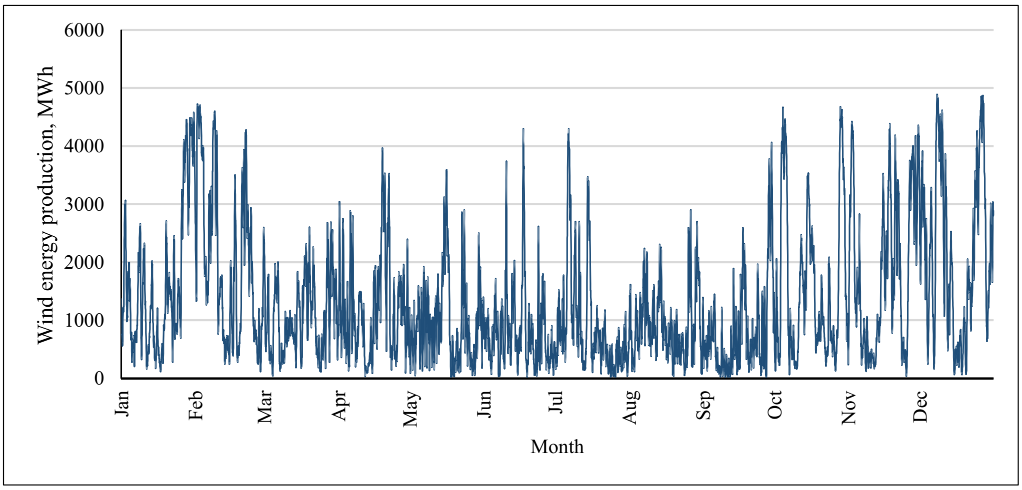

Fig. 2. Wind energy production in Poland in 2016 [MWh]
Source: own work based on (PSE 2016a)

Rys. 2. Produkcja energii elektrycznej ze źródeł wiatrowych w Polsce w 2016 roku [MWh]

The analysis proves that the greatest amount of energy is produced in the winter months, which is related to the weather conditions prevailing in this geographical area. In 2016 the windiest months were February, November, and December. In February, the average amount of electricity produced in one hour from wind sources was 2,024 MWh, in November it amounted to 1,847 MWh, while in December to 2,157 MWh.

The total electricity production from wind energy sources in December was 1,604.8 GWh, which accounted for 14% of the total wind power generation in 2016.

The volatility of electricity production from wind farms affects the power system of the country. This is a difficult issue for the transmission network operator, whose task is to balance the demand for energy with its production. The existing regulations require the transmission system operator to purchase any amount of electricity from renewable sources. To avoid excess energy in the grid in the periods of increased energy production from the wind, ancillary services for balancing power were introduced. These regulations consist in a temporary reduction of production in Centrally Dispatched Generating Units (CDGUs). These are conventional power plants that have signed contracts for ancillary services. As a result, maintaining the balance of the national power system is done by managing the volume of production in conventional units.

The amount of power generated in wind farms to the amount generated in conventional power plants was compared to assess how the production of wind energy affects the stability of electricity production in conventional sources. The objective of the analysis was the indication hours, when wind energy production resulted in the reduction of the electricity production in conventional units.

The comparison was carried out for the production data in December 2016 (on an hourly basis) with the aim to check if priority in purchasing electricity from wind sources restricts the production of conventional power plants.

This month was chosen for further analysis, not only because of the significant production of energy from wind sources, but also because the hourly production in wind farms and Centrally Dispatched Generating Units in this month showed the highest correlation.

The highest production from wind farms was recorded on December 8, 2016, at 9 in the morning and amounted to 4892 MWh. In total, the number of hours in which the generation reached over 4,000 MWh amounted to 105 compared to a total of 380 hours during the entire year. During the periods of increased energy production in wind power plants, the share of energy produced in Centrally Dispatched Generating Units in the structure of the national power system decreased. Figure 3 presents electricity production in wind farms and CDGUs as well as the load of the Polish power system.

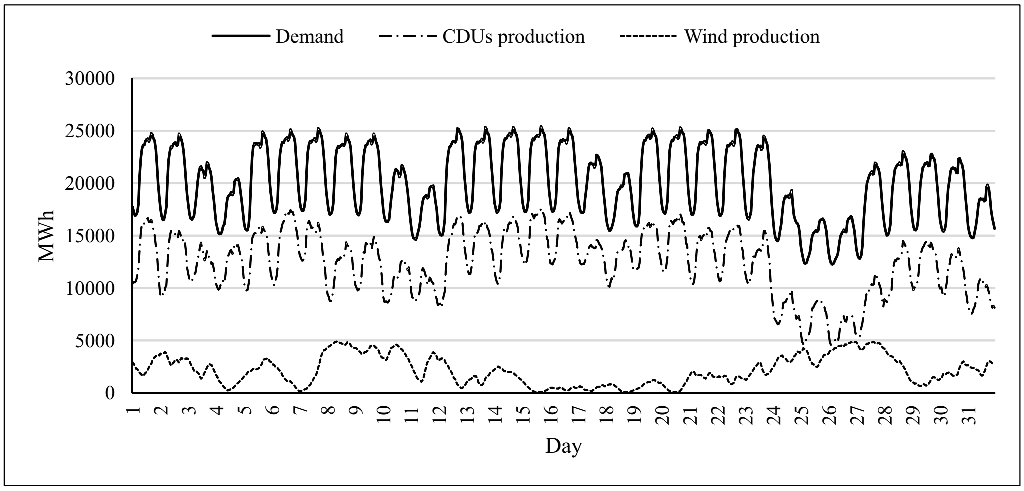

Fig. 3. Load of the Polish power system, electricity production in Centrally Dispatched Generating Units and in wind farms in December 2016 [MWh]
Source: own work based on (PSE 2016a, b)

Rys. 3. Zapotrzebowanie polskiego systemu elektroenergetycznego, produkcja energii elektrycznej w jednostkach wytwórczych centralnie dysponowanych i w elektrowniach wiatrowych w grudniu 2016 roku [MWh]

The load of the system is changeable. In addition to changes in individual hours of the day, the differences in energy demand on working days and holidays can be observed. Changes in the production of CDGU units in the analyzed month have a different shape than the load curve of the system. It can be seen that changes in the production of the CDGU in the analyzed month do not depend on the power demand. In the periods of high production of electricity in wind farms the reduction of CGDU's production is noticed.

The analysis of available data on the load of Polish power system and the amount of electricity production in the Centrally Dispatched Generating Units and wind farms has indicated that, during some days in December, there were days when ancillary services were provided by the Centrally Dispatched Generating Units. In December, there were two periods during which the amount of energy produced in the CDGUs was less than 10,000 MWh. The first one was reported on December 8–12, while the second one on December 24–31. On these days, the wind also reached the highest speeds and wind turbines generated the highest amounts of capacity.

On the basis of the above results, it can be stated that in some days the surplus electricity produced by wind turbines occurs, forcing load control in the CDGUs.

Reducing electricity production from CDGUs in favor of wind power generation leads to problems with the stability of power systems and increases the costs of starting up CDGUs (Lewandowska-Bernat and Desideri 2017). Wasting the potential of the existing capacity of conventional power plants leads to lower effectiveness of electricity production.

The solution to this problem would be to store the surplus of electricity and use it when the demand is higher. The energy storage problem is not solved in the global scale yet, although many efforts have been undertaken worldwide. One of the conceptual (up to now) ways is the use of Power to Gas technology, in which excess of electricity could be stored in the form of hydrogen.

2. Overview of Power to Gas technology

Power to Gas technology is a concept to produce hydrogen using the surplus of electricity. This technology is based on conversion electricity for chemical energy that occurs in the water electrolysis process. The electrolysis products are hydrogen and oxygen in gas form, in the following formula:

$$H_2O + \text{electricity} = H_2 + O_2$$

The concept lies in using the generated surplus electricity in this process from renewable energy sources working under uncertainty conditions.

The efficiency of the water electrolysis process and the purity of the resulting hydrogen largely depend on the effectiveness and properties of the electrolyzer. The most popular are: alkaline (AEL), polymer (PEL), and solid oxide-based (SOE) electrolyzers. The characteristics of the mentioned electrolyzers are presented in Table 2. It should be noted that with the improvement of the electrolyzer parameters, the price of the electrolyzer has also increased. Therefore, when choosing the appropriate unit, it is crucial to conduct a quality and cost optimization.

TABLE 2. Characteristics of selected electrolyzers

TABELA 2. Charakterystyka wybranych elektrolizerów

Parameters	Unit	Electrolyzer type		
		Alkaline (AEL)	Polymer (PEM)	Solid Oxide (SOE)
Electrolyte		Aqueous alkaline solution: KOH, NaOH, or NaCl	Solid polymer	Yttria–stabilized zirconium oxide
Operation temperature	°C	60–80	50–80	700–1000
Operation pressure	bar	<30	<30	<30
Efficiency	%	55–84	55–84	90–95
Energy consumption	kWh/Nm^3	4.5–7	4.5–7.5	2.5–3.5
Cell capacity	Nm^3/h	<760	<450	no data
Hydrogen purity	%	>99.5	>99.99	no data
Cost	EUR/kW	1,000–1,200	1,900–2,300	no data

Source: (Ursua et al. 2012; Gahleitner 2013; Ahern et al. 2015; Lewandowska-Bernat and Desideri 2017).

Hydrogen obtained in the electrolysis process in Power to Gas installations is characterized by high purity and can be used in various ways, e.g. for the production of electricity in fuel cells, internal combustion engines and cogeneration installations, as fuel for hydrogen powered vehicles, energy carriers in a gas system, a substrate for the synthesis of methane (or other hydrocarbon fuel) (Piskowska-Wasiak 2017).

In Europe, and especially in Germany, Power to Gas technology projects are developing very intensely. In Tables 3 and 4 an overview of selected Power to Gas projects in Europe is given. Hydrogen is the final product in the largest number of projects. The others are methane, hydrogen/methane and methanol. Most of all the projects are implemented in Germany (Table 3). Many projects both operational and planned are also present in other European countries (Table 4), although some of them are already finished – after the accomplishment of the research. The resulting products are used in a wide range of applications. Above all, they are used in the gas grid (28 projects), mobility (22 projects) and power generation (22 projects). They are applied in power storage (14), heat (5) and CHP (2). Other application are flexible load, industry and chemical.

TABLE 3. Overview of selected Power to Gas projects in Germany

TABELA 3. Przegląd wybranych projektów Power to Gas w Niemczech

Output product	Project	Current status	Installed power [kW]	Electrolysis technique	Application	Output product production [Nm^3/h]	Source
1	2	3	4	5	6	7	8
Hydrogen	Dresden	F	10	solid oxide	mobility	50	(European Power to Gas)
	Leverkusen – CO2R-RECT Project	F	300	PEM	power generation power storage	50	(LTT)
	Ibbenburen – RWE	O	150	PEM	gas grid heat	30	(RWE Deutschland AG)
	Hamburg – Schnackenburgallee	O	185	PEM	mobility	30	(Shell)
	Hamburg – Hafencity – Vattenfall	O	630	alkaline	mobility	120	(Clean Energy Partnership)
	Hamburg – Reitbrook – WindGas Hamburg	O	1,000	PEM	gas grid	290	(HenseWerk)
	Grapzow – RH2 WIND	O	1,000	alkaline	CHP gas grid	210	(Wind–Wasserstoff–Projekt GmbH & Co. KG)
	Prenzlau – ENERTRAG AG	O	600	alkaline	mobility power generation power storage	120	(Vattenfall Europe Innovation GmbH)
	Berlin Airport – H2BER	O	500	alkaline	CHP mobility power eneration power storage	90	(Total Deutschland GmbH)
	Cottbus	O	150	alkaline	power generation	30	(Vartainen; Wassertoff–Forschungszentrum Brandenburgische Technische Universität Cottbus)
	Freiburg – H2Move	O	40	PEM	mobility	6	(Fraunhofer ISE)

TABLE 3 cont.

TABELA 3 cd.

1	2	3	4	5	6	7	8
Hydrogen	Hanau	O	35	PEM	power generation	4	(European Power to Gas)
	Frankfurt am Main – Thuga	O	315	PEM	flexible load	60	(ITM Power Thüga)
	Mainz	O	3,900	PEM	industry mobility power generation power storage	1000	(Stadtwerke Mainz AG and Linde AG)
	Etzel	P	6,000	no data	hydrogen storage in salt cavern	no data	(European Power to Gas)
	Wind to gas Südermarsch	P	2,400	PEM	gas grid	no data	(Market Watch)
	Reussenköge	P	1,000	PEM	chemical heat power generation	no data	(European Power to Gas)
	Leipzig – HYPOS Project	P	1,000	alkaline & PEM	gas grid	no data	(Geschäftsstelle Hypos)
	Hassfurt	P	1,250	PEM	gas grid	110	(Städtische Betriebe Haßfurt – Greenpeace Energy; Paulus)
	Wyhlen	P	1000	alkaline	mobility	no data	(European Power to Gas)
Methane	Niederaussem	F	300	PEM	gas grid	360	(Energy Storage Journal)
	Schwandorf – Eucolino: Schmack & Viessmann	F	250	alkaline & PEM	gas grid power generation power storage	30	(Erdgas-Schwa-ben)
	Werlte – Audi AG	O	6,300	alkaline	gas grid mobility	1,300	(European Power to Gas)
	Rostock – EXYTRON Demonstrationsanlage	O	21	alkaline	gas grid power generation	4	(Exytron GmbH; Carbon Commentary)
	Falkenhagen – DVGW	O	1,000	alkaline	gas grid	no data	(DVGW For-schungsstelle am EBI)
	Schwandorf – MicrobEnergy GmbH	O	275	PEM	heat power generation	30	(European Power to Gas)

TABLE 3 cont.

TABELA 3 cd.

1	2	3	4	5	6	7	8
Methane	Straubing	O	no data	PEM	mobility	no data	(MicroPyros GmbH)
	Stuttgart – ZSW II	O	250	alkaline	no data	50	(European Power to Gas)
	Stralsund	P	20	alkaline	gas grid mobility	no data	(EERE Energy)
	Alzey – Exytron Null – Emission – Wohnanlage	P	63	alkaline	heat power generation	10	(Speicher-bar)
Hydrogen / Methane	Allendorf, Eder – BioPower2Gas	O	1,100	PEM	gas grid	60–220	(IdE Institut dezentrale Energietechnologien GmbH)
	Kirchheimbolanden – RegEnKibo	O	no data	no data	gas grid	no data	(E-rp GmbH)
	Emden – I	P	312	alkaline	gas grid mobility power generation power storage	no data	(Stadwerke Emden GmbH)
Metha-nol	Lünen – MEFCO2	P	1,000	PEM	industry mobility	200	(Mitsubishi Hitachi Power Systems)

Current status: F – finished; O – operational; P – Planned.

TABLE 4. Overview of selected Power to Gas projects in other European countries

TABELA 4. Przegląd wybranych projektów Power to Gas w innych krajach europejskich

Output product	Project	Current status	Installed power [kW]	Electrolysis technique	Application	Output product production [Nm^3/h]	Source
1	2	3	4	5	6	7	8
Denmark							
Hydrogen	SamsØ	O	20	alkaline	mobility	no data	(European Power to Gas)
	Hobro – HyBalance	P	1,200	PEM	industry mobility	230	(HyBalance)
	Vestenskov	F	0	PEM	gas grid power generation power storage	16	(Grahl-Madsen)

TABLE 4 cont.

TABELA 4 cd.

1	2	3	4	5	6	7	8
Methane	Avedøre – BioCatProject	O	1,000	alkaline	gas grid	200	(Hydrogenics and Audi)
Methane	Foulum – Electrochaea	F	250	PEM	gas grid	50	(Götz et al. 2016; Electrochaea)
the United Kingdom							
Hydrogen	Aberdeen – Hydrogen Bus Project	O	1,000	alkaline	mobility	180	(Scottish & Southern Energy Power)
Hydrogen	Fife – Levenmouth Community Energy Project	O	370	alkaline & PEM	mobility	no data	(Bright Green Hydrogen)
Hydrogen	Rotherham – hydrogen mini-grid Project	O	30	PEM	power generation power storage	no data	(ITM Power Rotherham; Fuel Cell Systems)
Hydrogen	Leicestershire – Hari Project	O	36	alkaline	power generation power storage	8	(Gammon et al. 2006)
Hydrogen	HyDeploy	P	500	PEM	gas grid	no data	(ITM Power 2016)
France							
Hydrogen	Abalone Energie Nantes	O	0	no data	power generation power storage	no data	(Abalone Energie)
Hydrogen	Corsica – MYRTE	O	150	PEM	power generation power storage	23	(AREVA)
Hydrogen / Methane	Dunkerque – GRHYD Project	O	0	PEM	gas grid mobility	10–15	(ENGIE)
Hydrogen / Methane	Fos-sur-Mer – Jupiter 1000	P	1,000	alkaline & PEM	gas grid	200	(CRTGas)
the Netherlands							
Hydrogen	Nes	F	5	PEM	gas grid heat	1.05	(European Power to Gas)
Methane	Rozenburg	O	10	PEM	gas grid	1	(DNV GL; HyWays)

TABLE 4 cont.

TABELA 4 cd.

1	2	3	4	5	6	7	8
Hydrogen / Methane	Delfzijl	P	12,000	PEM	gas grid industry	no data	(HyWays)
Spain							
Hydrogen	Aragon – ITHER	O	4,070	alkaline & PEM	mobility	no data	(Aragon Hydrogen Foundation)
	Xermade – Sotaven-to Project	F	200	alkaline	power generation power storage	60	(Gas Natura lfenosa and Hydrogenics)
Austria							
Hydrogen	Auersthal – Wind2Hydrogen	O	100	PEM	gas grid mobility	no data	(European Power to Gas)
	Linz – H2FUTURE	P	600	PEM	gas grid	no data	(European Power to Gas)
Hydrogen / Methane	Vienna – Undergro-und Sun Storage	O	600	alkaline	storage	120	(Rohöl-Aufsuchungs Aktiengesell-schaft)
Belgium							
Hydro-gen	Don Quichote – Colruyt	O	150	PEM	mobility	30	(Colruyt and Waterstofnet)
Italy							
Hydrogen / Methane	Puglia region – INGRID Project	O	1,152	alkaline	gas grid	no data	(Engineering Ingegneria Informatica)
Hungary							
Metha-ne	PtG Hungary Ltd.	P	10,000	biological	gas grid	no data	(Electrochaea and MVM)
Norway							
Hydrogen	Utsira	F	48	alkaline	power generation power storage	10	(Ulleberg et al. 2010)

Current status: F – finished, O – operational, P – planned.

3. Possible application of P2G technology in Poland

In light of the analysis of electricity production from wind sources and from conventional power plants shown above, it can be stated that there are periods in which the Power to Gas technology can provide a solution to the problems related to the stochastic nature of wind farms. Hydrogen as a possible solution to the negative phenomenon of grid destabilization due to the increased share of renewable energy sources in the Polish power system. This choice is dictated by many factors. First and foremost, the storage of electricity in Power to Gas technology does not require water or underground reservoirs in the proximity. The electrolysis process can therefore be carried out around the wind farms. Another advantage is that the hydrogen fuel is a zero-emission fuel, both during the production (if the electrolysis process uses renewable energy) and combustion processes ($H_2 + 1/2O_2 = H_2O$). The hydrogen economy is developing dynamically in the world, and the question of energy storage using the Power to Gas technology has been discussed in many papers (Balan et al. 2016; Guandalini et al. 2017; Kötter et al. 2016; Schneider and Kötter 2015). Thus, Poland can also rely on examples from abroad and develop the discussed concept of energy storage drawing from the experience of other countries. Furthermore, by analyzing European Union legislation, it should be borne in mind that the discussed technology will be further supported (EC 2006–2007; HyWays 2007).

In this context, the hydrogen economy seems to be a promising solution for the Polish power sector, which will have to face the challenges of wind energy development. Technology has not been implemented in Poland so far, although companies associated with energy production and gas companies are thinking about launching such projects.

The possibilities of using hydrogen generated from the electrolysis of water (the supplied electricity is produced in wind farms) are shown in Figure 4. The gas fuel can be stored directly and re-converted to electricity, used in the power and transport industries, or injected into the gas network (directly or after the methanation process).

Figure 4 presents that hydrogen is a very flexible energy carrier. In addition, the energy contained in this fuel can be stored for a long time. Currently, hydrogen is considered to be one of the most efficient ways of storing energy, dealing with fluctuations in electricity produced in power systems, and optimizing the use of energy from renewable energy sources (Garcia 2017). However, despite the advantages mentioned above, there are still many challenges and obstacles (of both an economic and non-economic nature) for the hydrogen economy. The non-economic barriers are the limited capabilities of the electricity and gas system, which are not technically prepared for the introduction of Power to Gas technology (Garcia 2017; Bai et al. 2014). In many countries, including Poland, there is no legal and regulatory framework for hydrogen storage technology; this results in a lack of interest from investors. Further technical and economic research is needed to be able to conclusively state whether the discussed technology is a beneficial solution for stabilizing the power system under Polish conditions.

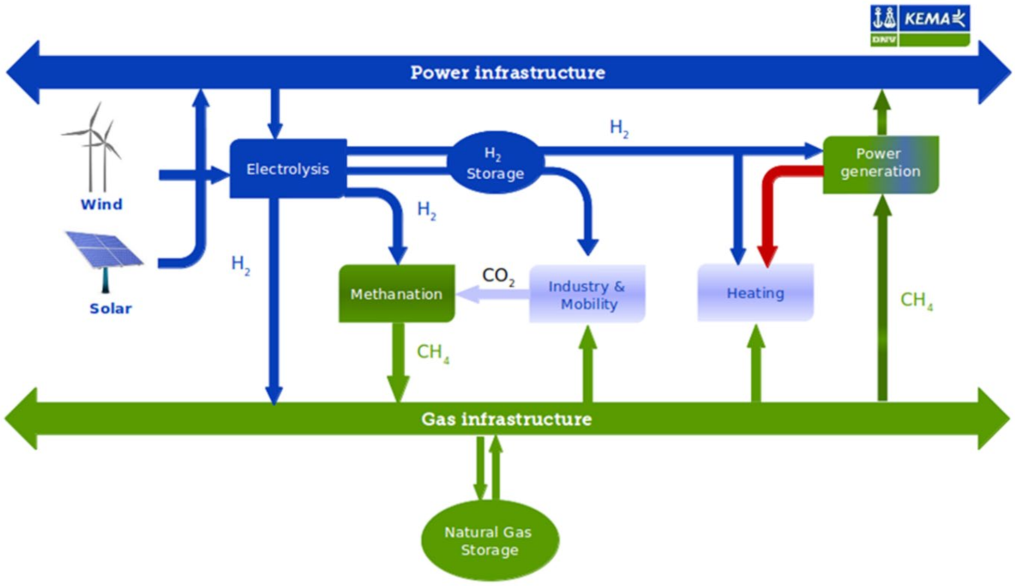

Fig. 4. The scheme of possible application in Power to Gas concept (Risto 2015)

Rys. 4. Schemat możliwych zastosowań w koncepcji *Power to Gas*

Conclusions

The implementation of the Climate and Energy Package leads to changes in the national power system. Within the framework of this document, Poland is obliged to achieve a target of 15% from renewable energy sources in gross final consumption of energy by 2020 (Ahern et al. 2015). The National Action Plan for RES has determined the path to achieve this goal, setting specific targets for various sectors. In the mentioned document, the target for electricity was set at 19% (MG 2010). Further development of the wind power would help to meet the obligations resulting from the Climate and Energy Package.

With the increasing share of wind energy in the national production structure, interruptions in the power system may occur. This is related to the stochastic nature of production, depending on the weather conditions rather than the national power demand. Still, despite these problems, renewable energy sources are of great potential and will continue to be developed.

An analysis of the electricity production in wind farms and Centrally Dispatched Generating Units has confirmed the thesis that there are periods during which Polish wind power plants produce surplus energy. This phenomenon results in the need to provide ancillary services by the Centrally Dispatched Generating Units or to shut-down units in conventional power plants. This creates additional costs for these generating units and leads to lower efficiency of electricity production. To avoid this, the Power to Gas concept is proposed. The authors point out that hydrogen is a potential way to improve the stability of the electricity grid and that this technology can eliminate some problems of the imbalance between supply and demand resulting from the increasing share of renewable energy sources in power systems. The introduction of such solutions under Polish conditions requires the establishment of a dedicated legal framework, which will result in increased interest from investors.

This study was done within the statutory research of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences.

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Zagospodarowanie nadwyżki produkcji energii elektrycznej z niestablinych odnawialnych źródeł energii z wykorzystaniem technologii *Power to Gas*

Streszczenie

Zwiększenie udziału produkcji energii ze źródeł odnawialnych (OZE) odgrywa kluczową rolę w zrównoważonym i bardziej konkurencyjnym rozwoju sektora energii. Wśród odnawialnych źródeł energii największy wzrost można zaobserwować w przypadku wytwarzania energii słonecznej i wiatrowej. Należy zauważyć, że OZE są coraz ważniejszym elementem systemów elektroenergetycznych i że ich udział w produkcji energii będzie nadal wzrastał. Z drugiej strony rozwój niestabilnych źródeł wytwarzania (elektrowni wiatrowych i fotowoltaiki) stanowi poważne wyzwanie dla systemów energetycznych, ponieważ operatorzy niekonwencjonalnych elektrowni nie są w stanie dostarczyć informacji o prognozowanym poziomie produkcji, a zapotrzebowanie na energię elektryczną jest często niższe od ilości energii wytworzonej w danym okresie. Dlatego wraz z rozwojem OZE tracona jest znaczna część wytworzonej energii. Rozwiązaniem jest magazynowanie energii, co pozwoliłoby na usprawnienie zarządzania systemami energetycznymi. Celem niniejszego artykułu jest przedstawienie koncepcji magazynowania energii elektrycznej w postaci energii chemicznej wodoru (*Power to Gas*) w celu poprawy funkcjonowania systemu elektroenergetycznego w Polsce.

W związku z oczekiwanym wzrostem mocy zainstalowanej w elektrowniach wiatrowych należy się spodziewać, że w systemie będzie coraz więcej okresów, w których wytwarzana będzie nadwyżka energii. Aby uniknąć marnowania dużych ilości energii, konieczne jest wprowadzenie systemów magazynowania energii. Analiza rozwoju elektrowni wiatrowych pokazuje, że koncepcja *Power to Gas* może być rozwijana w Polsce, o czym świadczy szacowana moc zainstalowana i potencjalna ilość energii do wygenerowania. W związku z nadwyżką energii elektrycznej będzie dostępna do magazynowania w postaci energii chemicznej wodoru, która z kolei może być wykorzystana do zasilania sieci dystrybucyjnych gazu, wytwarzania energii elektrycznej w okresach zwiększonego zapotrzebowania na energię elektryczną lub do tankowania pojazdów.

SŁOWA KLUCZOWE: energetyka wiatrowa, *Power to Gas*, magazynowanie energii