Power to Gas – an innovative energy conversion and storage solution

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Abstract. Over the past decade the share of renewable energy sources (RES) in electricity production has been increasing exponentially. The influence of aforementioned trend is already clearly visible in the energy mixes worldwide, including Poland. The development of the technology, support from domestic government along with rising awareness of society cause the alternative sources to become increasingly popular. As a result, the amount of the energy generated from variable sources like wind and solar is rising and becoming more widespread. The above mentioned phenomenon creates new challenges. One of the most difficult is the grid balancing and management, due to the fact that the power production is highly depending on the atmospheric conditions. The energy industry urges the innovative solutions and the energy storage has the potential to become one of them. The purpose of this article is to propose Power to Gas (PtG) concept as innovative solution for energy sector. Through this technology the surplus of the electricity can be accumulated in hydrogen via electrolysis. The main objective of the article is to identify the potential markets in the European Union (EU) with the best perspectives for the development of the Power to Gas technology. The authors reviewed the newest research and developments projects of PtG technology, with a special focus on conversion and an energy storage carried out in different countries in Europe.

1. Introduction
The importance of renewable energy sources (RES) in the power sector is constantly increasing. New environmentally friendly power units are installed worldwide every year. In 2016, the total installed capacity of renewable energy sources amounted to 2006 GW; this represents an increase of more than 100% compared to the year 2007, when the installed capacity was 989 GW [1]. Figure 1 shows the global changes in the installed capacity of wind power plants, solar power plants, geothermal power plants, marine power plants, hydroelectric power plants and bioenergy plants. When analyzing the data presented, it should be noted that hydroelectric power plants have played a significant role since 2007. However, their share in the total installed capacity is decreasing every year. In 2007, the share of hydroelectric power plants accounted for 93%, while in 2016 it amounted to 62%.

By analyzing the changes taking place between 2007 and 2016, the largest increase in the total installed capacity in the world was recorded for wind and solar power plants. By the end of 2016, the share of wind power plants, with the installed capacity of 467 GW, amounted to 23%. Whereas for solar power plants, the share amounted to 15%, with the installed capacity of 296 GW [1].
The total installed capacity of renewable energy in Europe was 486.7 GW in 2016, equivalent to 24% of the installed capacity worldwide. Compared to 2007, when this value amounted to 258.5 GW, the installed capacity in Europe has increased by 88%. The contribution of individual renewable energy sources in the total installed capacity in Europe is shown in Figure 2. This graph presents patterns similar to that observed in the total installed capacity worldwide. Hydroelectric power plants have the highest installed capacity in the years 2007–2016. However, over the years analyzed, this value remains almost at the same level, oscillating around 200 GW. The fact indicates that there are no investments in hydropower in Europe. The largest investments in the analyzed years have been made in the case of wind and solar power plants. In 2016, the total installed capacity of wind power plants in Europe amounted to 155 GW, showing a 175% increase compared to 2007. Whereas for solar power plants this value amounted to 104 GW in 2016, which was almost two thousand times more than in 2007 [1].

In Europe, an increase in the installed capacity of renewable energy sources is linked to incentives to promote investments aimed at achieving the objectives set out in “2020 Climate and Energy Package”. The mentioned document sets a 20% increase in the share of renewable energy sources by 2020 [2]. For many Member States, meeting these objectives is only possible through support systems for the development of renewable energy installations.

Figure 1. The total installed capacity of renewable energy in the World in the years 2007–2016, GW.
Source: own work based on [1].
Among power plants investments, solar and wind power have the largest share, both in Europe and worldwide. It should be noted that the volume of electricity produced in the above mentioned types of power plants is not dependent on demand but the prevailing weather conditions. Therefore, the wind speed and the intensity of solar radiation affect the stochastic nature of electricity production, making wind and solar power plants variable sources of energy. Consequently, the actual production capacity is much lower than the power installed in these power plants. In view of the above, energy storage has become increasingly important in recent years and may be an answer to the current problems and challenges faced by power system operators.

This article presents Power to Gas technology (PtG) as an innovative way to store energy from unconventional sources. According to the authors, PtG could play a significant role in stabilizing the power system and make renewable energy to be available for users at the moment of the greatest demand.

2. The Power to Gas technology

The concept of Power to Gas technology is based on the use of electricity derived from variable generation sources in order to carry out the electrolysis process. During the electrolysis cycle, the supplied electricity decomposes water into two components, namely hydrogen (H₂) and oxygen (O₂). It should be noted that the water used for this process must be demineralized and deionized. Achieving a high degree of purity of the liquid is possible by carrying out reverse osmosis process in which water is passed through a membrane with microscopic holes separating liquid from minerals. On the other hand, the process of deionizing water occurs as a result of interaction of water and ion exchanger; as a consequence, positive ions are replaced by hydrogen ions while negative ions with hydroxide ions [3].

It has hitherto used three types of cells in the electrolysis process: alkaline, polymer, and solid oxide electrolyzer. The distinctive parameter of the mentioned electrolyzers is the efficiency of the electrolysis process. In the case of alkaline and polymer electrolyzers, this parameter is in the range of 55–84%, while in the case of solid oxide electrolyzer the efficiency is in the range 90–95% [4].

The PtG technology can be used in both the energy and gas sector. The PtG enables the combination of electricity and gas infrastructures by converting the excess electricity in the water electrolysis process and injecting the resulting hydrogen into the gas network. There are two methods of introducing H₂ into the gas network: (1) a direct method (called Power to Gas Hydrogen) allowing hydrogen injections in amounts not negatively affecting the system and (2) an indirect method (the so-called Power to Gas
SNG) involving the methanation with carbon monoxide (CO) or carbon dioxide (CO₂), the product of which is the so-called substitute natural gas (abbreviated as SNG). The technical conditions of the existing gas infrastructure, the safety of hydrogen transmission to end users, and legal regulations are the reasons why restrictions on the introduction of hydrogen into the gas network are imposed worldwide. Each country, in which the Power to Gas Hydrogen technology is being studied and developed, has its own legal regulations concerning the amount of hydrogen that can be injected into the gas network without affecting the existing infrastructure. Currently, eight European countries have established legal regulations in this area. The values are summarized in Table 1. In the United Kingdom and Belgium, the practice of injecting hydrogen directly into the gas network is prohibited. The most liberal in this regard is the Netherlands, where hydrogen can be introduced into the gas infrastructure in the amount of almost 2% of the mixture.

| Country           | Volume/molar [%] | Mass [%] |
|-------------------|------------------|----------|
| The United Kingdom| 0                | 0        |
| Belgium           | 0                | 0        |
| Sweden            | 0.5              | 0.1      |
| Switzerland       | 4                | 0.6      |
| Austria           | 4                | 0.6      |
| France            | 6                | 1        |
| Germany           | 10               | 1.6      |
| The Netherlands   | 12               | 1.9      |

As shown in the table above, the possibilities of use of hydrogen in Power to Gas Hydrogen technology are limited. This results from differences in quality parameters of transmitted gases. Moreover, the storage capacity and total discharge time for Power to Gas Hydrogen are lower than for Power to Gas SNG, and that is shown in Table 2. It should also be noted that the two discussed technologies are currently characterized by the highest values of the storage and discharge time parameters. When compared to other energy storage technologies, they are characterized by much better parameters than flywheels, accumulators, compressed air and hydropower [5].

| Storage         | Power to Gas SNG | Power to Gas Hydrogen |
|-----------------|------------------|-----------------------|
| Discharge Time  | 1 hour–1 month   | 1 hour–1 year         |

In view of the above, the most common solution is the methanation of hydrogen and the use of the produced methane (CH₄). Therefore, the presented article is primarily focused on technological possibilities of the concept of indirect injection of hydrogen into the gas network, and thus subjecting it to the methanation process. Methanation of hydrogen is a process in which the so-called synthetic methane (SNG) is formed by reacting hydrogen with carbon dioxide or carbon monoxide. It has parameters similar to natural gas parameters, so its share in the mixture with natural gas can be considerably higher than in the case of pure hydrogen. The chemical reactions that can take place in the methanation reactor are presented below:

\[
(1) \ CO + 3 \ H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H_r^0 = -206.3 \text{ kJ/mol} \\
(2) \ CO_2 + 4 \ H_2 \leftrightarrow CH_4 + 2 \ H_2O \quad \Delta H_r^0 = -167 \text{ kJ/mol}
\]

Based on the obtained enthalpy values of the reaction ($\Delta H_r^0$) it can be stated that reactions taking place in the methanation reactor are exothermic. This means that heat is generated when the reaction
products are formed. Methanation is another process in the PtG technology, right after electrolysis process. The hydrogen produced by the electrolysis process reacts with carbon dioxide or carbon monoxide. Energy and economic efficiency of methanation affect the effectiveness of PtG technology. The scale of its impact depends primarily on the source from which carbon dioxide or carbon monoxide can be captured and the difficulty of carrying out this process.

The methanation process can be divided into chemical and biological methanation. The main division criterion is the type of catalyst used. In chemical methanation, the catalyst is usually nickel. It is preferred than other metals with similar properties mainly due to economic considerations. The low price of this raw material and the relatively high reactivity are the reasons why it is more often chosen than such metals as cobalt, ruthenium, or rhodium [6]. Due to the fact that the methanation reaction is highly exothermic, it is important to control the temperature of the process. The chemical methanation process takes place according to the reaction (1) at 250–550°C and at a pressure of 1–100 bar [7]. Therefore, several reactor concepts, adapted to the above conditions, have been developed. Depending on the type of deposit and substrates, chemical reactors are divided into fixed and fluidized bed reactors.

Another type of methanation is biological methanation. In this case, methanogenic microorganisms act as catalysts of the process. Methane is produced directly from carbon dioxide and hydrogen particles by Archaea microorganisms. These microorganisms obtain energy for their growth during the transfer of electrons from hydrogen to carbon dioxide according to the chemical reaction expressed by the equation (2) [8]. Biological methanation takes place under anaerobic conditions at a temperature of 20–70°C and at a pressure of 1–10 bar [6]. The efficiency of the process depends primarily on the type of microorganisms, the concentration of their cells, reactor type, and the temperature and pressure during the process. Microorganisms acting as catalyst are present in the fermentation medium; as a result, the methanation reaction takes place in aqueous solution at natural or slightly alkaline pH.

In view of the above, the efficiency of the conversion cycle of electricity into gas is the sum of the efficiencies of the following processes: the production of electricity from renewable energy sources, hydrogen production from water electrolysis, and the production of synthetic methane. In order to estimate the potential benefits of the integration of the power system with the gas system, technical and economic analyzes of the PtG technology are carried out in many research and industrial centers.

3. Overview of the demonstration projects

The dynamic development of electricity generation from renewable sources is a reason for difficulties in the operation of the power system. The volume of energy produced does not always meet the demand from end users. Energy storage seems to be a key solution to eliminate the mentioned differences between the demand and supply in the electricity market.

Injection of hydrogen into the gas network is not the only one solution in the Power to Gas technology. On the contrary, it is believed that hydrogen economy is only beginning to develop [9]. Hydrogen produced in PtG process can be stored, inter alia, in compressed gas or in liquid form and then used in industry or transport [10]. Hydrogen can also be used in fuel cell systems to be re-converted into electricity or heat.

When we will analyze the world situation, the Tohoku University and Hitachi Zosen which initiated their research in PtG systems in 1996 appears as pioneer in this field.

The PtG technology is more and more popular in Europe [11]. The Figure 3 shows the Power to Gas demonstration projects that are operational or planned at this moment in Europe. First pilot projects were launched between 2004 and 2009 and the tests of technologies took place in subsequent years, that is 2007 and 2012.
Figure 3. Power to gas demonstration projects in Europe [12].

The pilot projects of Power to Gas hydrogen production for mobility were launched in the United Kingdom in 2005 and in the Netherlands in 2006. The first pilot project of PtG SNG with methanation was launched later in Germany in 2009.

Massive development of renewable electricity production in Europe from intermittent sources could be seen especially in Germany and it is expected in a larger extent the future decades [13]. This country is the spearhead nation in developing PtG systems, mainly focused on CO₂ catalytic methanation (Power to Gas SNG). In hydrogen mobility several initiatives and projects are planned or ongoing in Europe with the most ambitious being the Clean Energy Partnership in Germany targeting a network of 100 stations by 2019 and of 200 to 400 stations by 2023 [14]. We could expected that the clean mobility could play a predominant role in the development of this market.

3.1. Germany

The German energy policy is strongly concentrated on the development of renewable energy sources investments. According to government documents, renewable energy sources are expected to account for 60% of gross final energy consumption and 80% of electricity consumption by 2050 [15]. The biggest potential in achievement this goals is visible in wind energy and in photovoltaics system.

Germany’s interest for PtG technology is directly linked with its Energiewende (government policy of the transition to a low carbon, environmentally sound, reliable, and affordable energy supply) and high targets of renewable electricity production. Germany, from all European countries, has the most extensive number of PtG projects.

They have carried out processes with CO₂ methanation, for example projects like:
- Audi e-gas,
- Power to Gas 250,
- Alpha-plant,
- Biological methanation of pure streams.

They have also carried processes with biogas upgrading, for example projects like:
- Alpha-plant,
- BioPower2Gas,
- Mikrobielle Methanisierung,
- Power-to-Gas im Eucolino.

The project named Audi e-gas is realized in Wertle. In this plant they use three electrolyzers with total power input of 6.3 MW to produce hydrogen from intermittent wind power. The hydrogen is reacted with carbon dioxide in a chemical-catalytic process under high pressure and temperature. The CO₂ is extracted from a nearby biogas plant. The end product is synthetic methane which is injected to the natural gas transmission network. The conversion efficiency from electricity to gas is around 54%,
but the total efficiency of the plant is higher since the waste heat is recycled in the processes and utilized also in the adjoining biogas plant [16]. Figure 4 shows a diagram outlining the energy production process at Audi’s e-gas plant.

The first wind power electrolysis plant went live in Herten. In this project they used two hydrogen production facilities on the site which produce hydrogen electrolytically from wind power. The electrolyzers with maximum load of 160 kW are applied. Afterwards the hydrogen is compressed to a pressure of up to 45 bar. Therefore with this pressure, a total amount of 470 kg of hydrogen can be stored in a storage tank. A separate battery bank can be used for short term load balancing. It has an overall capacity of 28 kWh and can be charged with up to 40 kW [18].

The next Germany project is BioPower2Gas. This projects combines a biogas plant with a PEM electrolyzer, the end product being biomethane. The biomethane is injected into the natural gas grid. The electrolyzer has an input capacity of 400 kW and its maximum hydrogen production is 400 m³/h [16]. The surplus power from renewable sources is used in this process. The use of PEM electrolyzer and biological methanation enables to stabilize variations of electricity production.

3.2. Denmark

Renewable energy sources represent an important fraction of the power mix in Denmark (e.g. wind represents almost 40% of the electricity consumed) [19]. Denmark also has tested several installations of PtG production. 1 MW facility will use excess wind energy to produce pipeline-grade renewable gas for storage in the Danish natural gas grid [20]. Denmark is aiming at procuring 50% of its total power consumption from domestic wind energy by 2020 and 80% by 2050. These ambitious renewables targets put the country at the global forefront of the energy transition [21].

The Biocat Project aims at testing the technology with a 1 MW electrolyzer to be provided by hydrogenics and a biological methanation reactor. The end product, methane, is injected in a local gas grid. On the other hand, the end products like a heat and oxygen are recycled in the associated wastewater treatment processes. The CO₂ for the methanation comes from two sources: a raw biogas from a biogas production process, and a pure CO₂ from an on-site biogas upgrading system.

The other project name is The Vestenkov. This project has been realized in three phases, in which Danish micro combined heat and power units were developed, five prototypes were installed in consumers’ houses and finally 32 units were installed. The units installed in households are hydrogen fuel cells of nominal electric power of 1.5 kW and thermal power of 1.5 kW. The combined efficiency is 94%. Electrical input of the electrolyzer is max 104 kW. Continuous hydrogen production is 16 m³/h and continuous oxygen production is 8 m³/h. The volume of H₂ storage is 25m³ with maximum pressure of 6 bar [16]. The installations can be fitted to all houses and are suitable for use throughout the year in homes currently heated by natural gas or crude oil.
The MeGa-stoRE provided successful proof-of-concept of the PtG technology by combining a biogas plant with electrolytic production of hydrogen, and using new cleaning processes of the gas. First, the biogas undergoes a two-step catalytic purification process that removes many contaminants and transforms them into substances that can be added to the digested slurry as useful micronutrients. After that, the biogas is delivered to the methanation plant where the CO₂ and methane contained in the gas, along with the necessary amount of hydrogen is fed into a developed reactor that converts CO₂ and hydrogen to methane [22]. The Danish Government assumed that this plant should demonstrate that this technology could play a significant role in achieving the Danish Energy Agency goals for upgraded biogas in 2035.

3.3. France

France has set the target of meeting 23% of its gross end-user energy consumption from renewable sources by 2020 [23].

The first installation is the Mytre. The objective in this project is to develop a system to manage and stabilize relatively small and isolated power network of Corsica. Electric power from a photovoltaic array is either fed directly into the power grid or used to produce hydrogen, which is later converted to electric power again via fuel cells. Different operating strategies are implemented in the system control. Several aspects are reviewed, such as the sufficiency of the capacity of the system, the handling of the fluctuations of the photovoltaic output, ageing of materials. The power output from the stored hydrogen is 150 kW [14].

The second one is Grhyd project. The pilot program is led by the GDF Suez Centre for Research&Innovation in Gas and New Energy Sources [24]. This project aims to produce hydrogen from renewable electricity surplus. The hydrogen is injected into the natural gas network of a new residential neighbourhood to heat about two hundred houses. Energy from renewable sources (wind power) are to be delivered into the power distribution network. Surplus power will be used to produce hydrogen for storage and subsequent distribution to meet demand.

3.4. Italy

The biggest project in Italy is named INGRID. The project is carried in the Puglia, in the region that has already more than 3,500 MW of installed solar, wind and biomass. The consortium of this project will design, build, deploy and operate a 39 MWh energy storage facility using hydrogen-based solid state storage and hydrogenics electrolysis technology and fuel cell power systems. The main innovation of the project is the modular Hydrogen Solid Storage (HSS), in which the hydrogen is absorbed in magnesium hydride without the need for gas compression. HSS is connected to a 120 kW fuel cell system, which on demand will de-absorb the hydrogen gas and produce electricity. The project is focused on [25]:

- decentralized power generation and energy distribution based on effective rapid and safe hydrogen-based energy storage/deliver solutions capable to accept and manage any RES fluctuation and variability,
- advanced ICT solutions for intelligent Simulation and Energy Management System able to correctly simulate, manage, monitor, dispatch energy in compliance with the power request of the grid, allowing a correct balance between variable energy supply,
- perform a limited demonstrative scaled-down test for assessing the storage system’s balancing capabilities in condition of high variable electricity demand, consisting in a small pilot version of a green urban mobility system.

The hydrogen energy storage installation, with more than 1 ton of safely stored hydrogen, including a novel fast responding 1.2 MW hydrogen generator, will be fully controlled by advanced smart grid solutions and will provide effective and smart balancing support for the local grid. Several potential value streams for the generated carbon-neutral hydrogen will be investigated.
3.5. Spain

The first one of the discussed in Spain is a project located at the Sotavento Experimental Wind Farm. It is the biggest conversion plant from wind power in Spain. The excess electricity of wind turbines is used in an alkaline electrolyzer with the capacity of 60 m³/h. The hydrogen fuel is converted back to electricity by a motor generator. The storage system at 200 bar is composed by 7 blocks of 28 bottles each, with a maximum capacity of 1.725 m³. These blocks are interconnected forming two groups of H₂ storage, with the possibility of isolation of each group. The H₂ stored can be used in a 55 kW engine in case of energy deficit, that is, if the amount of energy produced by wind turbines in the wind farm is less than is expected to generate [26].

The second one is the Technology Infrastructure for Hydrogen and Renewable Energies, ITHER, conceived and carried out by the Aragon Hydrogen Foundation. This is an installation consisting of wind farm with three turbines (635 kW), each in different technology, a grid connecting photovoltaic installation with seven different technologies (100 kW), big scale alkaline technology electrolyzer and energy management subsystems, electrical grid interconnection, hydrogen storage, and final use of hydrogen in fuel cells [27]. The installations are experimental test bench facilities for renewable energy and hydrogen, accessible to researchers on the basis of collaboration agreements. They generate hydrogen proceeding from renewable sources for consumption in stationary or mobile applications. The hydrogen is injected in a hydrogen station for hydrogen powered vehicles and buses.

3.6. Norway

A demonstration project in Norway is located at Utsira. An autonomous wind/hydrogen energy demonstration system was officially launched by Norwegian concerns – StatoilHydro and Enercon. The main components in the system installed are: a wind turbine (600 kW), water electrolyzer (10 m³/h), hydrogen gas storage (2400 m³, 200 bar), hydrogen engine (55 kW), and a PEM fuel cell (10 kW) [28]. A separate transformer is connected to a 1.5 km long cable that transmits power from the autonomous system to the customer substation. Ten households are connected to the customer substation. One of the goals of this project is to see if the wind-hydrogen concept could be made commercially feasible. The time frame, to be competitive with conventional remote-site power supplies, diesel or combined wind and diesel generators, has been estimated to about five to ten years.

4. Conclusion

The aim of the article was to present Power to Gas technology as an innovative solution for the integration of the energy system with the gas system. The dynamic development of renewable energy, especially the variable energy sources, forces new energy management decisions. Electricity generation, not dependent on demand but on atmospheric conditions, creates new challenges for transmission system operators. The presented PtG installations indicate that the mentioned technology can eliminate the problems of the imbalance between supply and demand resulting from the increasing share of renewable energy sources in power systems.

This article focuses primarily on the Power Gas SNG technology, that is the use of the generated hydrogen in the methanation process in order to produce synthetic natural gas. The resulting product has similar properties to natural gas, so it does not affect the gas network operation. Pure hydrogen additions to the natural gas systems have been allowed in some countries, while its share in the gas mixture is determined based on the national legal framework. This is due to the fact that the permissible hydrogen concentration should be determined individually for each network, taking into account the network structure, injection site, natural gas composition, and different gas-fired appliances of the consumers.

The article reviews the most popular European projects involving the use of PtG technology. An increasing number of pilot plants in Europe and worldwide shows that the Power to Gas technology is considered by many countries as an innovative approach to integrate separate systems. Based on the experience of countries such as Germany, Denmark, France, Italy, Spain, and Norway, we can see the possibilities and the effectiveness of the solutions associated with the use of hydrogen fuel and methane. The cases described show that a country with a highly developed wind power technology can use the
PtG to mitigate energy supply disruptions. The integration of the power system with the gas system is carried out in almost one third of the projects where the gas product is introduced into the gas network.

The use of hydrogen in the transport sector, mainly in cars, is becoming more and more popular. Carmakers, such as Audi, are interested in introducing hydrogen into their vehicles. Such projects are implemented in cooperation between energy, fuel and gas concerns. Cooperation in this area is required for the widest possible development of this innovative technology.

Power to Gas technology can play a significant role in achieving the objectives of the EU member states set by the requirements of the EU environmental directives. The implementation of PtG technology in order to integrate the power system with the gas system may increase the share of renewable energy sources in national power mixes. The use of hydrogen in transport sector can help to reduce the carbon dioxide emission. In addition, the application of the discussed technology leads to the optimization of electricity consumption, improvement of network efficiency, and the reduction of CO₂ emissions.

It is expected that the results of the pilot studies will show the energy and economic efficiency of the Power to Gas process chain.

References
[1] IRENA (2017), Renewable capacity statistics 2017, International Renewable Energy Agency (IRENA), Abu Dhabi.
[2] Directive 2009/28/EC. Directive 2009/28/EC of The European Parliament and of The Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.
[3] Grond L, Schulze P and Holstein J 2013 Systems Analyses Power to Gas. Deliverable 1: Technology Review (Groningen: DNV KEMA Energy & Sustainability).
[4] Ahern E P, Deane P, Persson T, Gallachoir B O and Murphy J D 2015 A perspective on the potential role of renewable gas in a smart energy island system Renewable Energy 78, 648–656.
[5] Newton J 2014 Power-to-Gas and Methanation e pathways to a 'Hydrogen Economy' http://www.apgtf-uk.com [available: 04.10.2017].
[6] Göetz M, Lefèvre J, Mörs F, Koch A M, Graf F, Bajohr S, Reimert R and Kolb T 2016 Power-to-Gas: A technological and economic review Renewable Energy 85 1371–90.
[7] Müller K, Stadter M, Rachow F, Hoffmannbeck D and Schmeißer D 2013 Sabatierbased CO₂–methanation by catalytic conversion Environmental Earth Sciences 70 771–78.
[8] Burkhardt M, Koschack T and Busch G. 2015 Biocatalytic methanation of hydrogen and carbon dioxide in an anaerobic three-phase system Bioresource Technology 178 330–333.
[9] Zhang F, Zhao P, Niu M and Maddy J 2016 The survey of key technologies in hydrogen energy storage International Journal of Hydrogen Energy 41 14535–52.
[10] Gahleitner G 2013 Hydrogen from renewable electricity: an international review of power-to-gas pilot plants for stationary applications International Journal of Hydrogen Energy 38 2039–61.
[11] Hausen M 2015 Power to Gas - Potential Markets in Europe The IMRE Journal 2 1–12.
[12] Power-to-gas (demonstration) projects in Europe http://www.europeanpowertogas.com [available: 04.10.2017].
[13] Thema M, Sterner M, Lenck T and Götz P 2016 Necessity and Impact of Power-to-gas on Energy Transition in Germany Energy Procedia 99 392–400.
[14] Developing hydrogen mobility -Transport forum Hannover 2015. http://www.h2fc-fair.com [available: 04.10.2017].
[15] Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung http://www.bundesregierung.de [available: 04.10.2017].
[16] Vartiainen V 2016 Screening of power to gas projects (Finland: Lappeenranta University of Technology).
[17] ETOGAS delivers world’s largest methane production plant to Audi https://www.ngva.eu [available: 04.10.2017].
[18] Wind Power Electrolysis / Hydrogen Application Center in Herten http://hyer.eu [available: 04.10.2017].
[19] The potential of Power-to-gas 2016. http://www.enea-consulting.com [available: 04.10.2017].
[20] Commercial-scale power-to-gas ‘demonstration’ project launches in Denmark 2014 http://www.renewableenergyfocus.com [available: 04.10.2017].
[21] P2G in Denmark http://biocat-project.com [available: 04.10.2017].
[22] Final report Mega–Store 2015. http://www.lemvigbiogas.com [available: 04.10.2017].
[23] The GRHYD demonstration project http://www.engie.com [available: 04.10.2017].
[24] National Environment and Energy Conservation Agency 2014 McPhy Energy role in French Power-to-Gas GRHYD programme Fuel Cells Bulletin 2 9–10.
[25] High-capacity hydrogen-based green-energy storage solutions for grid balancing 2016 http://cordis.europa.eu [available: 04.10.2017].
[26] Rey Porto M, Carretero T, Aguado M and Garde R 2010 H2 Production in Sotavento Wind Farm (Essen: WHEC).
[27] Facilities and infrastructures http://hidrogenoaragon.org [available: 04.10.2017].
[28] Ulleberg O, Nakken T and Eté A 2010 The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools International journal of hydrogen energy 35 1841–52.