Opportunities of Power-to-Gas technology in different energy systems architectures

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Abstract

This paper presents an overview of power-to-gas opportunities. Power-to-gas technology is gaining more and more popularity. It can provide large and long-term storage for increasing share of renewable sources in the energy system. In this paper, we would like to review the role of the power-to-gas system in different energy system architectures. Authors have analyzed the literature in the context of the problems, which could be solved by power-to-gas technology. Additionally, different assessment such as techno-economic, Life Cycle Assessment and Multi-criteria Decision analysis for power-to-gas were revised.

Keywords: Power-to-gas; Electric grids; Renewable energy, Sustainable energy system

Acronyms:

AEC - alkaline electrolysis cell
CAPEX - capital expenditures
CCU - Carbon Capture and Utilization
COP - Conference of the Parties
EU – European Union
GDP – Gross Domestic Product
GHG – Greenhouse Gases
HTSE – High-Temperature Steam Electrolysis
LCA – Life Cycle Assessment
LNG – Liquefied Natural Gas
MCDA – Multiple-criteria decision analysis
MCFC – Molten Carbonate Fuel Cell
PEM – Proton Exchange Membrane
PtG – Power-to-Gas
PtM – Power-to-Methane
RES – Renewable Energy Sources
SNG - Substitute Natural Gas
SOEC – Solid Oxide Electrochemical Cell

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VRE – Variable Renewable Energy

1. Introduction

In order to face the challenges caused by climate change, the depletion of resources and the growing population, energy systems are being transformed all over the world to be more sustainable and to reduce the environmental impact. The future sustainable energy system is expected to based on clean and renewable energy sources, which should be able to provide constant and affordable access to electricity. The decision to transform the energy systems in the direction to increase the renewable energy share is due to some specific issues. The first one is the problem of greenhouse gases (GHG) emissions. The power sector is responsible for 25% of world GHG emissions [1]. Two more issues, which are also connected, are the population growth and the increase in electrical energy consumption. Nowadays, the 7.5 billion people living on the Earth [2], consume 20,000 TWh [3]. Recent studies estimate that the Earth's population can reach even 11.2 billion people in 2100 [4]. In this worst-case scenario, assuming constant energy consumption and considering that almost 2 billion people do not have access to a safe and secure supply of electricity, the worldwide electricity supply should double in the next 60 years. Of course, the amount of fossil fuels on the Earth is limited, so they should not be considered as an energy source at the end of this century. For these reasons, most countries are investing in renewable energy sources and energy-saving technologies.

In the EU the biggest push RES was provided by the Kyoto protocol, which was enforced in 2005 by imposing all old and new members to decrease the greenhouse gasses emissions. In 2007, the European Union leaders set the climate and energy package [5]. The key targets to be reached in 2020 in the EU aimed at 20% cut in greenhouse gas emissions (from 1990 level), 20% renewable energy production and 20% improvement in energy efficiency. The protocol was not considered sufficient and in 2015 new targets for lowering the emissions were set at the COP in Paris. The European decarbonization strategy set the target of 75% gross final energy consumption from renewable sources in 2050. This strategy also assumes decarbonization of transport and thermal energy for industry, services and buildings. The same document also states that natural gas will be critical for the transformation of energy systems [6]. All the above measures were not taken worldwide, and other regions and countries set different targets with different timing.

However, the time is showing that increasing the share of renewable energy production creates problems of electric grid operation and stability. The difficulty to predict accurately the energy supply causes challenges in electric grid management and electricity price volatility. Due to RES supporting policy, fossil-fired power plants are being switched-off and decommissioned and there is a strong need for novel solutions and technologies, which provide grid balancing and allow energy storage.

In this paper, we would like to discuss the opportunities offered by power-to-gas technology in balancing the grid and provision of energy storage. We believe that PtG technologies can solve the problems arising with the transformation of energy systems since it is possible to store the surplus between the supply and demand of electricity by transforming electric energy into a suitable carrier which can be later used as fuel in power plants to balance the surplus between the demand and renewable supply of electricity. Alternatively, since electric grids with 75% or more renewable energy production will need to have a large overcapacity of production. In such a case, it may be necessary to convert the surplus power to gas and not vice-versa, and the produced fuel should be used for other energy uses such as in mobility and directly as thermal energy. In this paper, the role of power-to-gas in different system arrangements is also considered.

2. Power-to-x technology

General notation of systems, which convert electric power into another energy vector is denoted as power-to-x, where x is the final product of power conversion. Power-to-x, due to its modular structure, can be arranged in different pathways. The notation power-to-gas describes a variety of systems in which final product is a gaseous fuel. Figure 1 shows the variety of pathways in the power-to-x sector, which represent the processes of obtaining different energy carriers. Naturally, they can be further proceeded to reproduce electric energy.

The primary step of a power-to-gas technology is thus the conversion of excess electric energy into hydrogen via water electrolysis process. This mechanism differs from conventional energy storage systems, in which electric energy is absorbed and released. Gas is a very good energy carrier for storage as it can be easily stored for a long period of time, without losing its energy content [3] and it has more applications than other energy vectors.

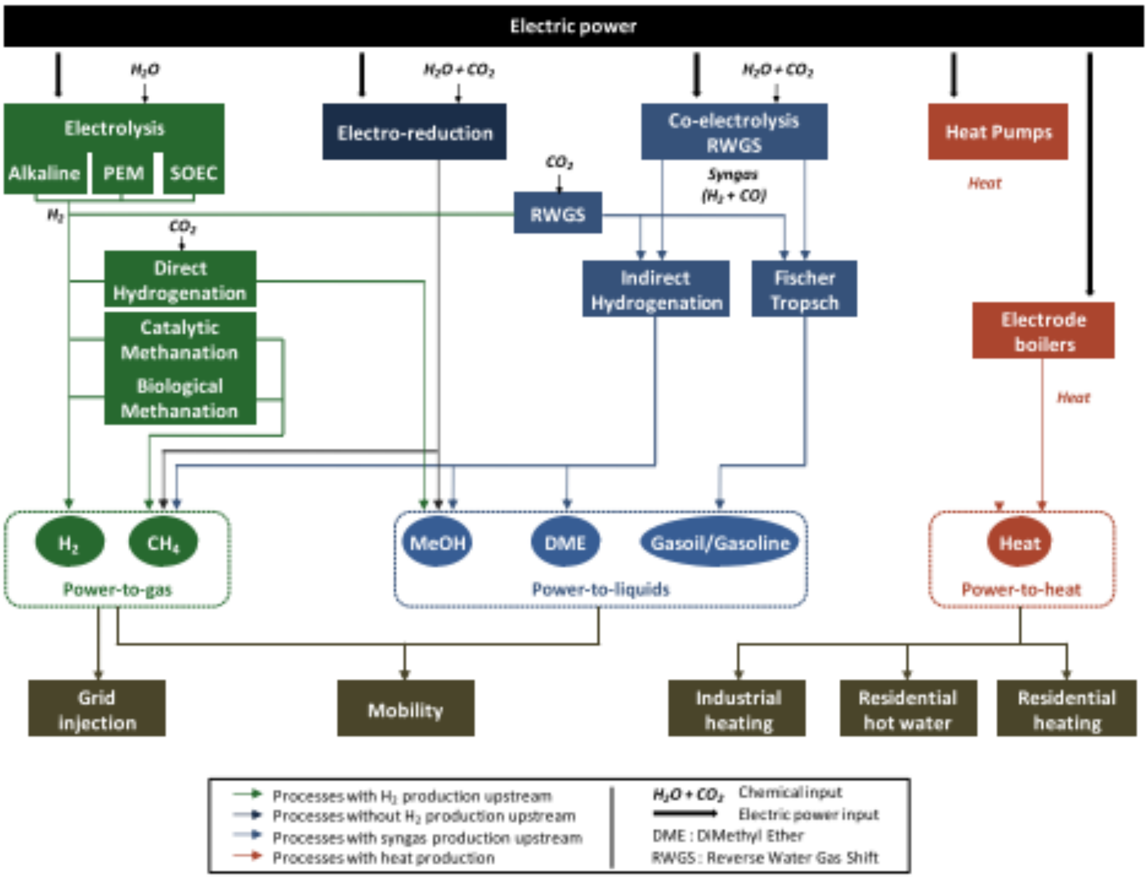

Fig. 1 Different power-to-x pathways; sources: [7]

The process of hydrogen production is carried out by water electrolysis with a conversion efficiency of RES into hydrogen ranging from 54 to 77%. There are three main types of electrolyzers: alkaline, proton exchange membrane (PEM) and high-temperature electrolyzer.

It is important to note that hydrogen is important in this scenario not only as a gaseous fuel by itself but also as a chemical compound necessary for methanation or synthetic methane production and for all liquid fuels in the so-called power-to-liquid technologies.

2.1. Type of fuels

2.1.1. Hydrogen

Hydrogen is the lightest element in the periodic table. At atmospheric conditions, it is a colourless, odourless, tasteless, non-toxic, nonmetallic, highly combustible diatomic gas. It provides much more energy per unit weight than any other fuel. It also has a high energy-to-weight ratio (three times more than gasoline or diesel), ignites easily and burns with a wide range of oxidant/fuel mixtures [8]. It is used in a variety of industrial applications such as ammonia synthesis, fertilizer production, Ni and Fe production, glass and fibre production and in nuclear reactors [9].

The International Energy Agency defines hydrogen as a flexible energy carrier with potential application across all energy sectors [10]. Hydrogen can be produced by using various primary or secondary energy sources. The industrial production of hydrogen is mainly based on steam reforming. The process can be described as:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \qquad (1)$$

Another process of obtaining hydrogen is water electrolysis. In this process, water particle is decomposed due to an electric current. The process is described by equation (2).

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (2)$$

Currently, steam reforming is the cheapest, technically and commercially well-established technology for hydrogen production. The utilization of water electrolysis in power-to-gas systems can contribute to the development and improvements of this technology. The possibility of using renewable energy sources to produce hydrogen can increase the profitability of clean hydrogen. Clean hydrogen can be used as a fuel for mobility [11], or for heating [12] and is also a chemical compound that can be further transformed into many others.

Hydrogen is considered to replace hydrocarbons in the mobility-fuel sector. In Germany, the forecast of car market assumes that in 2050 the 75% of car stock will be hydrogen vehicles. This means that the demand for hydrogen will reach around 2.93 million tons in 2052 [13].

2.1.2. Methane

Methane is a most popular hydrocarbon, used as a fuel. It is an important carrier for electricity generation and heat production. In comparison with hydrogen has higher volumetric energy content and most important is much safer [14].

There are two ways used in power-to-gas for methane production.

2.1.2.1. Biological

In this process, methane is produced from organic matter. The process is carried by hydrogenotrophic methanogens in process of methanogenesis at 35-70°C at atmospheric pressure.

$$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O \qquad \Delta H = -131 kJ/mol \qquad (3)$$

Another example of is anaerobic digestion, which is conducted according to the equation (4).

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \qquad (4)$$

As a result, methane and carbon dioxide is obtained. From power-to-gas context, anaerobic digestion can be a source of CO_2 for methanation process. Biological methanation has low costs as the reactor has a simple design, low pressure and low temperature. The microbial power-to-gas plant utilizes microorganisms, such as hydrogenotrophic methanogenic arches to catalyze the Sabatier reaction. This process can be achieved at lower temperatures and pressures than in chemical, catalytic reaction. Such approach has a higher tolerance to contaminations, such as organic acids and H_2S [15], [16].

2.1.2.2. Catalytic

This method is a most popular choice in the power-to-methane system. The conversion efficiency of the process is 49-65%, and the overall efficiency of power-to-methane-to-power is 30-38%. The reaction takes place at a temperature of 300°C and at 50-200 bar pressure.

Methanation reaction $$CO_2 + 3H_2 \rightarrow CH_4 + H_2O \qquad (5)$$

Methanation rector is most commonly composed of the adiabatic fixed-bed reactor. For small scale or intermittent reaction such as power-to-gas, the isothermal reactor is sufficient.

Substitute Natural Gas (SNG) is another product, which can be obtained in the power-to-gas process. SNG gas is composed mainly of methane, produced from fossil fuels, biofuels or from renewable electric energy in the power-to-SNG process. The main advantage of SNG is its unlimited possibility of storage in the gas network.

SNG production – Sabatier reaction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta H = -165\ kJ/mol \tag{6}$$

The choice of proper methane technology depends on the system requirements. Catalytic methanation is more flexible than a biological one. It also enables faster achievements of production rates and has lower power requirement per unit of gas produced. In contrary biological reactor is much more tolerant of impurities such as H_2S [17].

2.2. The technology inside the power-to-gas system

As mentioned earlier power-to-gas is a technological chain, which converts electric energy into gas. The first step of the process is water electrolysis. Water electrolysis is an electrochemical process of water decomposition into oxygen and hydrogen. The process takes place in electrolyze cell. The cells differ by the type of electrolyte and temperature of operation

An additional process, which can take place in the power-to-gas chain is methanation. The most popular electrolysers and methanation reactors are briefly described in this section. The comparison of electrolyzer technologies is sum-up in **Table *1***.

2.2.1. Alkaline electrolysis cells (AEC)

The alkaline electrolysis cell is the most mature technology. For this reason, it is suitable for the large-scale power-to-gas system. It uses an aqueous alkaline solution to transfer the electrons. It operates at atmospheric or elevated pressure. ACE efficiency varies from 66 to 74%. The system can operate at loads of 10-150% for limited times and has a restart time of 10-60 min [17].

2.2.2. Proton exchange membrane (PEM)

Proton exchange membrane technology is composed of proton transfer polymer membrane. PEM technology is being recently developed technology which is gaining popularity. It is used in small-scale applications in the industrial market. Its advantage in case of PtG is its fast start up and shut down time from the cold and transient operation and part load range of 5-100% [17]. The challenge of this technology is long-term degradation of the cell. PEM currently have higher CAPEX than AEC due to lower technology readiness level (TRL). It is expected to significantly reduce investment costs and dominate power-to-gas electrolysers market.

2.2.3. Solid oxide electrolysis cells (SOEC)

Solid oxide electrolyzer is a high-temperature cell. Nowadays it's early stage technology what is responsible for its high investment cost, but high-temperature electrolysis is considered as the technology of the future. It operates at 700-800ºC due to use of ceramic materials. High temperate enables achievement of high efficiencies – typically 80-90%. The disadvantages of high-temperature use are limitations of system flexibility and fast temperature degradation [17].

Use of high-temperature cells can increase the overall power-to-gas efficiency up to 75.8% [14]. Luo et al. in [18] have made exergy analysis of an integrated solid oxide electrolysis cell-methanation reactor. They found out that the use of SOEC over low-temperature electrolyzers can increase exergy analysis by 11% at current densities higher than 8000 Am/m^2, owing to lower electricity consumption.

Table 1

Characteristic of alkaline, PEM and high-temperature electrolyzer, source based on: *[19]*, *[20]*, *[21]*

	Alkaline electrolyzer	PEM electrolyzer	High -Temperature electrolyzer

Electrolyte	Aqueous alkaline solution (KOH or NaOH)	solid polymer	yttria-stabilized zirconium oxide
Operation temperature	60-80°C	50-80°C	700-1000°C
Operating pressure range	1-200 bar	1-350	1-5 bar
Efficiency	65-75%	50-70%	70%
Part-load range	20-40%	0-10%	
Capacity	1-700 Nm^3/h	1-100 Nm^3/h	1-10 Nm^3/h
Durability	100 000 h	10 000–50 000 h	500–2000 h
Cost	800-1300 €/kW	1200-2000 €/kW	
Advantages	• Most mature technology • Simple and robust • Low cost • High reliability and durability • Possibility to operate at elevated pressure	• Ability to operate in part-load and overload conditions • Flexible • Can sustain on/off cycles • more efficient at a high current density	• Can be used with high-temperature heat sources like nuclear or geothermal power
Disadvantages	• Relatively low current density • Short lifetime • High maintenance costs • Not totally appropriate for operation using transient power sources	• Expensive due to platinum-based family catalysts and proton exchange membrane	• The need for constant operation • Laboratory stage • No dependable cost information

2.2.4. Methanation reactor

Methanation reactor is generally a fixed bed reactor with Ni-based catalyst operating in the range of 200-550°C and at 20-25 bar. The reaction present in methanation reactor is:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad \Delta H_{623K} = -218.53\ kJ/mol \tag{7}$$

2.2.5. Sabatier reactor

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \Delta H_{623K} = -179.90\ kJ/mol \tag{8}$$

3. Power-to-gas in on-grid system

On-grid systems are large energy systems, where renewable sources are part of energy system diversity. As mentioned in the introduction, the transformation of the energy system towards sustainability requires the change in energy supply from conventional sources to renewable intermittent sources, such as solar and wind power. Such action requires a technology, which will facilitate the changes and provide the flexibility to the system. Power-to-gas, due to its multitasking role in the system, can provide some solutions:

3.1. Integration of renewable energy sources in the existing system

Integration of renewable energy sources with the existing system requires storage of excess electricity, which without storage or use would be curtailed. For intermittent energy source, storage system needs to have fast charge and recharge time of response to answer the needs of the system, based on unpredictable and variable power source.

Power-to-gas could be an option for storing excess electricity produced by RES and prevent the RES curtailment. In this approach, electric power is stored in form of a gas in a storage tank or in gas grid, which enables large, storage capacity. Another advantage of PtG is fast time or response of electrolyzer and fuel cells. PtG can also be integrated with existing gas-fired power plants, which could use renewable methane.

3.1.1. RES storage

Due to its unpredictability, not all potential of renewable power is used. The main advantage of PtG in case of storing RES energy is its long-timescale and the stabilization of the system [22], [23]. Energy stored via power-to-gas system can be stored in various forms like hydrogen, methane or SNG. Modularity of PtG handicap the general cost of stored electricity. Nevertheless, some research has been done in this field.

Analysis of renewable market in Spain in [24] has shown that in 2050 the renewable energy production can exceed 63% with the 1.4 TWh - 13.5 TWh of surplus electricity. The capacity of power-to-gas required to store such amount of energy was evaluated on 7.0-19.5 GW. Authors point out that the location of PtG near renewable plants can help to avoid ohmic losses and transmission congestion since energy can be easily transmitted through the natural gas network as methane.

In Germany, the potential of surplus electricity from the renewable market is estimated to reach 167 TWh in 2050. To fulfil the future requirement for the hydrogen-mobility sector, electrolysis capacity in Germany should reach 28 GW [13].

In Italy, the extension of RES can reach up to 19.1 GW in wind power and 97.6 GW in solar power, which can yield in about 51 TWh/y of excess energy [25].

Ferrero et al. in [26] have estimated the costs stored electricity in form of hydrogen injected to the gas grid. They estimated that in 2030 the costs of hydrogen will be as follows: 0.04 €/kWh for alkaline electrolysis, 0.03 €/kWh for PEM electrolysis and 0.04 €/kWh for SOEC electrolysis [26]. In the same paper, authors have investigated the costs of power-to-power pathway. Their results are presented in **Table *2***. Kötter et al. in [27] had analyzed the role of power-to-gas as long-term storage for 100% renewable energy system in German region. The utilization of PtG as energy storage facility could reduce the levelized cost of energy from the system.

Table 2

Final costs of stored electricity from the power-to-power system for 2030 scenario, source: *[26]*

		Fuel cell type		
		Alkaline	PEM	SOFC
	Alkaline	117 €/MWh_{el}	84 €/MWh_{el}	106 €/MWh_{el}
Electrolysis type	PEM	103 €/MWh_{el}	56 €/MWh_{el}	91€/MWh_{el}
	SOEC	116 €/MWh_{el}	84 €/MWh_{el}	78 €/MWh_{el}

3.1.2. Curtailment prevention

Application of PtG system can prevent the frequent curtailment of renewable energy. Due to the low flexibility of the existing systems, this solution is widely used to keep grid balance. PtG not only provides the storage capacity, which is always limited by space or volume but, due to the production of clean hydrogen or methane, significantly increase the opportunity of use RES power. The possibility of curtailment prevention was investigated by various researchers.

Qadrdan et al. in [28] analyzed how the production of hydrogen from wind farm electricity would influence the curtailment in Great Britain They found out that the operation of the power-to-gas system can reduce wind curtailment during high wind periods up to 62% (during low demand day). Another research on solar systems done in Bavaria (Germany) shows that 370 MWe of PtG capacity can capture 30% of excess solar power. The authors predict that the utilization of power-to-gas systems will increase in time as the installed solar power capacity will increase [29]. Analysis of Irish system done by Ahern et al. in [30] has shown that Ireland may obtain reduce the level of wind curtailed by 5% compared to the base case.

3.2. Provision of flexibility to the system

A flexible energy system is one, which is able to maintain continuous operation even during large and rapid changes in supply and demand. So far, balancing the energy system relies on the supply side. There are actions taken for increasing the resilience of demand side by implementing smart technologies, like smart meters or changeable pricing, but even despite all these actions production side must be able to react to changes [31]. The European strategy of increasing renewable share entails the decentralization of energy and heat systems [6]. In such arrangement, small systems will have to cooperate with large, centralized structures. Another dimension of interconnections will be created between energy markets. Such approach requires an easily transportable with low shipment losses, storable and affordable energy carrier. Electrical energy is not the best match. Fuel gas seems to be a better solution for these requirements, thereby we can introduce power-to-gas systems to the network. Zeng et al. in [32] have analyzed the role of power-to-gas in the integration of natural gas and the electric power grid. The result of their simulation has shown that use of the power-to-gas system can reduce power and total energy loss of the integrated system.

Power-to-gas is able to convert electrical energy into much more flexible gaseous fuel. Of course, the process can be reversed and we can easily obtain electrical energy from the gas. The advantage of power-to-gas systems in case of flexibility is its fast time of response, which takes from seconds to minutes, depending on the electrolysis technology. Grueger et al. in [33] have proven that power-to-gas system composed of electrolyzer cell and the fuel cell is able to significantly reduce forecast errors of wind farms.

Power-to-gas systems integrate all energy sectors: electricity, gas, heat and even CO_2 market in one synergic system. In such configurations, the balance would not only lie between the supply and demand side but also among different networks. Such approach will allow to better utilize resources. The role of power-to-gas in the integration of different grids was pointed out in [34].

3.3. Contribution to emission reduction target

3.3.1. The increase of RES power utilization in the system

Power-to-gas can contribute to emission reduction in two ways. Firstly, it enables the proper grid maintenance by providing flexibility in energy grid with a high share of renewables. Secondly, it can facilitate the development of clean fuel markets. Burkhardt at al. in [11] claims that power-to-hydrogen has strong potential to lower GHG emissions in comparison with hydrogen obtained by conventional fuels. The same conclusion was drawn Walker et al. in [35] by comparing fuel cell vehicles fueled by clean hydrogen with an internal combustion engine vehicle running on gasoline.

Ahern et al. in [30] point out that the reduction in curtailment could result in an avoided cost of 3.7 million €/a for wind farm Irish operators.

3.3.2. CO_2 Utilization

The problem of captured carbon dioxide utilization is one of the major concerns of CCU since CO_2 storage is still controversial. There are efficient CO_2 captured technologies present in the market, but there is no efficient idea what to do with captures CO_2. One of the possibilities is to store the gas in deep, geological structures. Unfortunately, this solution has three disadvantages. First, there is limited storage space underground and it will cover only small part of captured CO_2. Another problem is that the underground storage is very expensive. Finally, we are not able to predict the consequences of underground CO_2 storage. There are some concerns that in a long-time period such action can influence the geological structures [36].

Another possibility of utilization of captured CO_2 is its use in chemical industry. Although demand for CO_2 in the chemical industry it's very limited, it gives the idea how useful CO_2 can be. Carbon dioxide is a chemical compound used in many chemical reactions to produce different kinds of fuels. This application can be used in the power-to-gas system. Captured carbon dioxide can be a very useful source of the gas needed in methanation (7) and Sabatier reaction (8) used in power-to-methane and in power-to-SNG.

Implementation of power-to-methane technology could influence the market of CCU. The research on possibilities of utilization of captured CO_2 to produce methane via power-to-gas processes was investigated by Reiter [37].

De Saint Jean et al. in [14] have modelled the power-to-SNG system, composed of High-

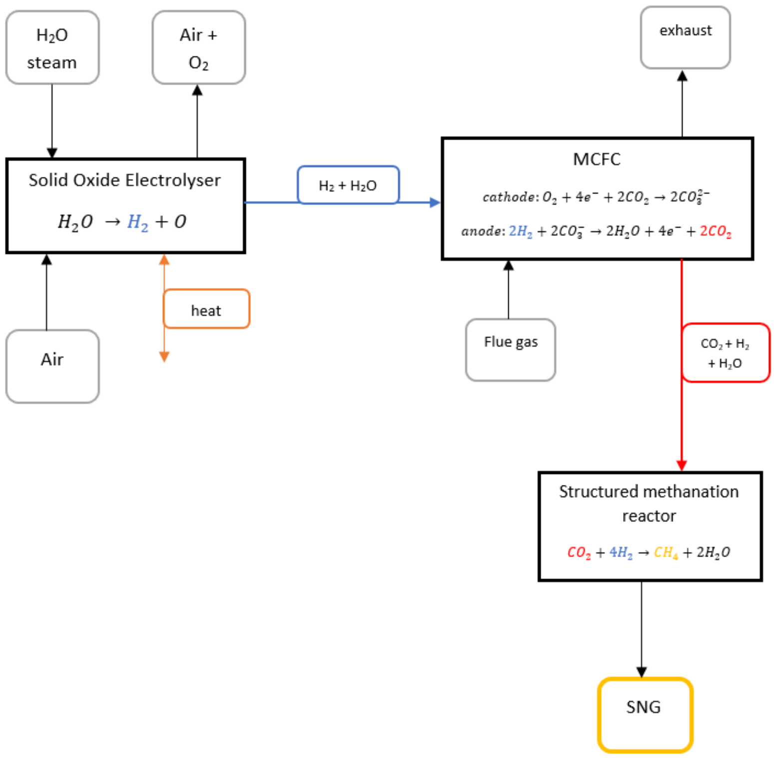

Fig. 2 The scheme of power-to-SNG for CO_2 from coal-fired power plant

Temperature Steam Electrolysis (HTSE) unit, methanation unit and purification unit. They obtained 75.8% efficiency and a cost of SNG between 300-570 €/MWh_{HHV}. The sensitive analysis made by authors has shown that there is a possibility to lower the cost of SNG even up to 211 €/MWh_{HHV}, by increasing plant annual availability.

In Figure 2 we present the scheme of power-to-SNG installation for the coal-fired power plant. Such system utilizes on side Molten Carbonate Fuel Cell to capture CO_2 from exhausted gases and uses them directly in Sabatier reactor to produce SNG. The source of hydrogen is Solid Oxide Fuel Cell, which produces hydrogen from excess electricity.

3.4. Contribution to increase sustainability in sectors like the industry and the mobility sector

Power-to-gas can become a source of clean gases. It enables the production of renewable hydrogen and renewable methane. Hydrogen can be used as a clean transportation fuel or as a raw material in chemical industry. Renewable methane is basically used as a transportation fuel. In this case, the power-to-gas can contribute to increasing the sustainability in the transport sector by becoming an important source of clean fuel.

3.4.1. Hydrogen fuel

Schiebahn et al. in [38] claim that renewable hydrogen has the potential to become an economical fuel, since fuel cell vehicles have a very high efficiency, what makes hydrogen competitive to gasoline. The costs of hydrogen produced from photovoltaic technology are estimated at 5.78 $/kg to 23.27$/kg, whereas from wind energy it ranges from 2.27 $/kg to 6.77 $/kg. Still, a cheaper option is the production of hydrogen from fossil fuels. The price of hydrogen from coal is 0.36-1.83 $/kg and from natural gas 2.48-3.17 $/kg [39]. The prices of hydrogen from renewables varies depending on weather conditions. The infrastructure needed for hydrogen mobility is at an early stage of development, which also increases the costs of operation of hydrogen-powered vehicles.

3.4.2. Renewable methane

McDonagh et al. in [17] have modelled the power-to-gas system to predict the levelized cost of energy gaseous transport fuel. Authors have analyzed different case scenarios for different years. The results of their work are presented in

Table *3*. Authors point out that the most important variables in LCOE of power-to-gas are electricity cost, run hours per annum and the total CAPEX. Their work has shown that increase in run hours to a certain level can reduce the LCOE. Authors claim that assuming electricity available at zero cost for the same number of hours, the LCOE would drop to 55 €/MWh.

Earlier mentioned research of Ahern et al. [30] have shown the potential of biomethane produced from anaerobic digestion in PtG system can contribute to 10.2% of energy in transport. The utilization of CO_2 from anaerobic digestion can allow obtaining further 8.9% of energy in transport.

Table 3
Levelized costs of energy (LCOE) of renewable methane fuel *[17].*

	2020 scenario	2030 scenario	2040 scenario
LCOE	107-103 €/MWh	89-121 €/MWh	81-103 €/MWh

3.4.3. Renewable SNG

De Saint Jean et al. in [14] have estimated the price of SNG produced by high-temperature steam electrolysis on 300-570 €/MWh_{HHV}. The high cost is linked to the cost of electrolyzer stack and high stack degradation. Further sensitive analysis has shown that it is possible to decrease the cost of SNG by 26%-60% obtaining the lowest cost of 211 €/MWh_{HHV}.

3.5. Pilot projects

At present, there are only a few existing pilot plants. The European power-to-gas pilot plants are monitored on a web platform [40]. The average size of pilot projects is in the range between few kW to 6 MW.

Audi e-gas – WOMBAT project

In June 2013 Audi opened 6 MW power-to-gas plant at Werlte in German region Emsland. The system consists of three electrolyzers. The system used surplus, renewable energy to produce methane, called by the company e-gas. The plant produces around 1000 metric tons of gas per year, using 2800 metric tons of CO_2 [41].

Table 4
Parameters of Audi e-gas plant, source: *[42]*

Parameter	Value
System size	6 MW
Efficiency (power-to-methane)	~ 54%
Life time	>20 years
Discharge time	30 sec.

4. Power-to-gas in an off-grid system

In off-grid systems, the source of electric power is mainly a renewable energy source such as a windmill or PV panels. Such solutions can provide clean and cheap electricity, which however is unpredictable and not constant. It is almost impossible to match the supply and demand of electricity in off-grid systems if energy is not stored in some ways. The off-grid is mainly applied in a remote location, where there are favourable weather conditions and the connection with the larger grid is impossible or unfeasible. Transmission of electrical energy at long distances is expensive and inefficient. Gases, such as hydrogen or methane are better energy carriers for transportation. The possibility of conversion of renewable electrical energy into gas opens new possibilities of building renewable power plants in remote places.

5. Power-to-gas in mini-grid system

Mini-grid is a specific type of off-grid system. Mini-grids are independent energy systems, which provide electricity for people in remote places, mainly in developing countries, where the connection with the national or large grid is not profitable. Such systems provide a prospective potential solution to power poverty. Access to electrical energy is an important issue, which should be provided to everyone. It increases not only the comfort of living but also economic status, education and health levels. Despite technological advancement, there are problems with the provision of constant access to electricity. The role of power-to-gas in the mini-grid system is described below.

5.1. Energy storage

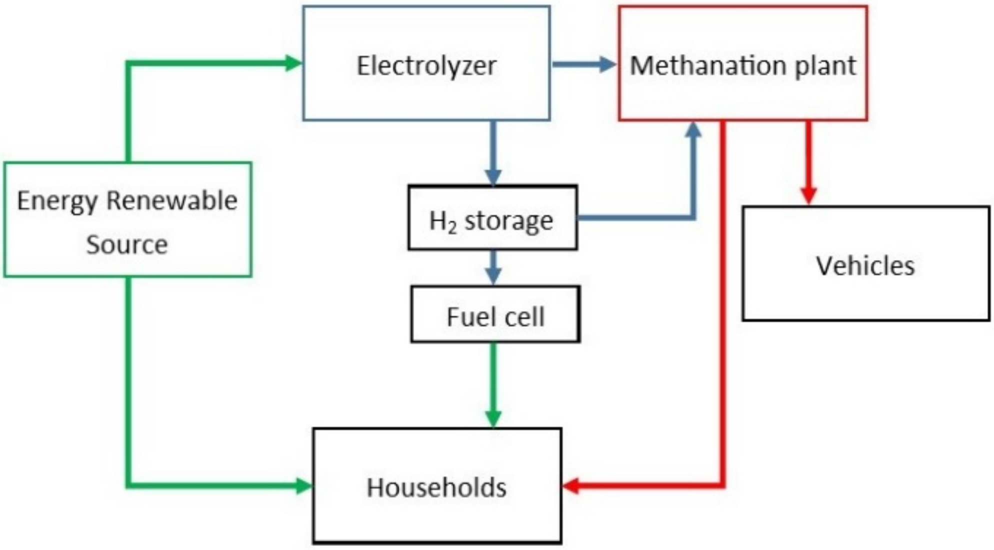

Fig. 3 Proposition of power-to-gas system design for off-grid system

Renewable energy sources can have great potential as a main source of electricity in remote places, where mini-grid is the only option. Such system requires a flexible and reliable energy storage.

As mentioned earlier gas is a better energy storage carrier than other forms of energy. It can also be stored for long periods, what can be an important aspect in case of intermittent energy source. At this point, gas storage exceeds the widely-used batteries. When needed, gas can be converted into electrical energy for example in fuel cells or in a gas turbine. Figure 3 presents a possible configuration of mini-grid with a fuel cell. Such systems can be implemented on islands. Although the conventional systems have lower levelized cost than hybrid systems (mainly power-to-power) the environmental criteria are better performed by RES-fuel cell system [43].

5.2. Clean gas production

Another advantage is the introduction of a second energy carrier for the community. Hydrogen can be used as mobility fuel or for methane production and could also be used for cooking or heating. It could also be used as a fuel for a fuel cell or gas turbine to produce electric energy when the RES power is not available. Local production of a clean gas could contribute to industrial development in the neighbourhood. The excess gas can be stored in the gas grid (if available) or in gas-tanks.

5.3. Emission reduction

For developing countries, where fossil fuels are the main fuel, the CO_2 emission is high and the air is polluted. In countries such as India or China, the air quality index is notoriously high. It means that staying outdoor is unhealthy and can cause health problems. For this reason, investment in clean technologies in those locations is crucial. Renewable sources, with the support of storage technologies, can provide a continuous supply of electricity to the community. In developing countries, which are mainly located in suitable climates for RES, power-to-gas can also significantly influence the clean fuel sector. The role of the power-to-gas system in emission reduction has been already described in section 2.1.

5.4. Grid elasticity

Mini-grid should supply the community with all necessary energy carriers such as electricity, gas and heat. Due to the limitation of space and resources, the good option is to convert one energy carrier into three other. For example, gas can be used to produce electricity and heat. Because often gas needs to be imported, renewable sources which can be built in place are an interesting option. Along with RES, the flexible storage system is needed to provide constant access to electricity. Also, the distribution of the resources between electricity and heat system requires flexible technology.

A specific example of mini-grid is the island energy system. In such system provision of electricity along with heat and gas is necessary. The potential of power-to-gas in the tri-generation system in the remote island was described in [34]. Figure 4 presents the scheme of such system, presented by the authors for Singapore. The modelling has shown that such system can provide all three necessary carriers (energy, gas and heat) but also provides energy savings by 20% and contribute to the reduction of 40% CO_2 emissions.

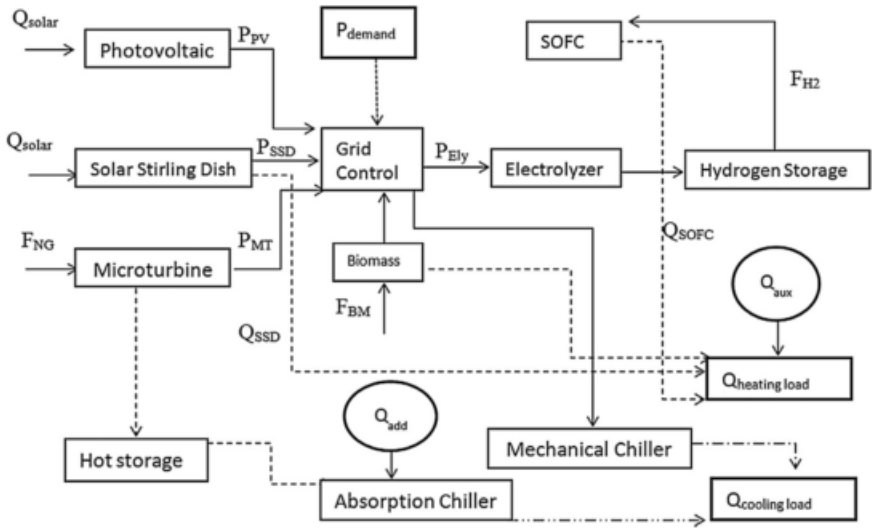

Fig. 4 Tri-generation network with power-to-gas system, source: [34]

Although such systems can operate independently, most of them will be connected to a large grid in future. If along with the mini-grid to the system will be introduced the significant amount of intermittent energy sources, such action can cause the serious fluctuations of the system. Application of power-to-gas system in mini-grids could help to prevent this problem. Even though batteries, which are for now applied as a storage technology, are cheaper, they won't solve the balancing problems in large grids. For this reason, it is worth to take into consideration this problem during the system design stage. The advantages of power-to-gas in the on-grid system have been already described. Investment in PtG technology in the early stage of mini-grid creation will solve future problems arise with the connection of mini-grid to the national grid.

6. Power-to-gas assessment

The economic profitability of the power-to-gas systems can be criticized. The cost of hydrogen produced from steam reforming is low, so for a new technology, it is hard to be competitive. At this point, it is worth to think whether the economic profitability should be the main indicator in the decision-making process. The time has shown that energy and industry investment cannot rely only on money. The problem of air quality in China or India has shown that savings in fuel price can result in tremendous health problems. Health Effects Institute estimated that 2.9 million deaths in 2013 were caused by air pollution [44]. The air pollution-related health care costs are estimated at the level of 21 billion USD in 2015 [45]. This value does not include the influence of reduced labour productivity on

GDP. For this reason, a basic economic analysis is not sufficient and is worth to find another, more universal tools.

6.1. Techno-economic Assessment

Techno-economic assessment is a most popular tool used to analyze the profitability of the technology.

Thomas et al. in [46] have analyzed the potential of power-to-gas in Belgium region, Flanders. It found out that that potential is significant, especially in mobility sector. As main benefits, they list improvement of air quality, the reduction of CO_2 emission, an improved energy security of supply position and the job creation. Authors admit that power-to-gas is expensive technology, which is not economically profitable but underlines its sustainable value. Van Deal et al. in [15] also in Belgium have made a techno-economic assessment of microbial power-to-gas plant.

Bailer et al. in [47] have gathered and classified existing power-to-gas projects. Authors highlight the increase in development of the technology in Europe and point out the problems of the CO_2 source in power-to-methane systems. Götz et al. in [48] have presented a technological and economic review of existing PtG projects where the available electrolysis and methanation technologies are compared with respect to low CAPEX, high efficiency and high flexibility.

Van Deal et al. in [15] have analyzed the potential of the microbial power-to-gas plant in Belgium. They indicated that high-investment costs are influenced by high investment cost of the electrolyzer and a low number of operating hours. Other factors which influence the cost are electricity price in large part composed of grid costs and taxes. Authors have listed some aspects which can improve the business model of PtG:

1) renewable electricity should be used to minimize the environmental impact and reduce the electricity costs
2) operating hours of the electrolyzer should be as high as possible
3) multiple products should be produces

6.2. Life Cycle Assessment (LCA)

Life Cycle Assessment is an analytical tool which assesses the environmental impact at all life stages of the product and its impact on the environment. LCA analysis enables the calculation of economic factors such as CAPEX and OPEX, but also the influence of the technology on human health, ecosystem quality and resources. The advantage of the LCA over economic assessment in case of energy technology is spotting of its impact on the environment, which later becomes an important political issue. In case of technology like power-to-gas, which can play multiple roles in energy system Life Cycle Assessment is an important analytical tool.

Different Life Cycle Assessment has shown that in comparison with other storage technologies power-to-gas can contribute to the reduction of GHG [11], [23].

Parra et al. in [49] have analyzed the crucial factors responsible for PtG and PtM price. In PtG system for 48% of the costs is the cost of electricity purchased for running the plant. In PtM 33% is the price of electricity and 27% price of CO_2 capture. Another important factor is grid charge for being connected to the electricity network, which is responsible for 20% in PtG and 13% in PtM. Authors also underline the fact that power-to-gas is able to provide several products at the same time, what increase its value, but generally, are not taken into account in economic assessments.

Another analytic tool, which can be used to evaluate and compare the environmental and social impact of the technology is nexus-assessment. This approach studies the influence of the technology on energy, food, land and water use. Such assessment would be the best choice to evaluate the design of mini-grids in developing counties. By doing this the future problem will be avoided.

6.3. Multi-criteria decision making an analysis (MCSM or MCDA)

MCDA is the analytical method, which compares multiple conflicting criteria for the decision-making process. This methodology enables comparing quantitative and qualitative criteria. For such reason, this methodology is getting more popular in multi-dimensionality of the sustainability goals in the energy sector [50].

Using the analytic hierarchy process (AHP), technical, economic, environmental and social parameters can be compared. Issues analysed in MCSM can be seen in **Table *5***.

Table 5
Example of multi-criteria decision analysis

1. Technical criteria		
1.1 Technology maturity		
1.2 Reliability		
1.3 Energy storage density		
1.4 Power consumption		
1.5 Carrier transportation	1.5.1 Cost of transportation	
	1.5.2 Transportation losses	
2. Economic criteria		
2.1 Investment costs		
2.2 Operation and maintenance		
2.3 Life service		
2.4 Payback		
3. Environmental criteria		
3.1 Potential for greenhouse gasses		
3.2 Impact on the ecosystem:	3.2.1 Land use	m^2/MW
	3.2.2 Water consumption	Gallons/MWh
	3.2.3 Solid wastes	
	3.2.4 Ground contamination	
4. Social criteria		
4.1 Social benefits	4.1.1 Job creation	
	4.1.2 Social welfare	
	4.1.3 Local income	
4.2 Social acceptability		
4.3 Political acceptance	4.3.1 Matching policy framework	
	4.3.2 Improving energy security	
5. Additional criteria		
5.1 System sustainability	5.1.1 Contribution to increase the share of clean energy	
	5.1.2 Integration of gas and electric energy network	

Such criteria analysis could be upbuilded specifically to compare different energy technologies.

7. Challenges

As the power-to-gas is a young technology, a lot of work and research needs to be done to convert it into commonly used and profitable technology. In this section, we would like to present the most important challenges, which need to be considered before the commercial utilization of power-to-gas technologies.

7.1. Electrolyser technology development

Production of water electrolysis is still a much more expensive method of hydrogen production than steam reforming. The main challenges concerning the electrolyzer technology are:

- High investment cost
- Fast material degradation
- Expensive materials for stack production

Godula-Jopek et al. in [19] have summarized the technical difficulties of PEM and alkaline electrolyzers. These are:

• Stack degradation and membrane deterioration.
• Safety problems with the alkaline electrolytes due to leaks.
• Problems with intermittent and fluctuating power sources such as delayed reaction.
• Difficulties with starting the system after shutdown, especially during cold weather.
• Extensive maintenance due to insufficiently mature parts of the system in the conditions of operation.
• Freezing of the membranes in PEM during winter.
• Very rapid stack degradation in some cases and limited warranted lifetime by the supplier.

Carmo et al. in [21] have proposed a list of problems, which should be solved in PEM technology.

Currently, there are no commercially working, large-scale power-to-gas systems. The existing pilot projects do not provide sufficient data for reliable assessment. They also do not give the proper view on the behaviour of PtG in the energy system. Thus, there is still need for bigger and longer pilot projects which will provide necessary data.

7.2. Hydrogen restrictions

Although hydrogen can play an important role as a fuel in the future at present has some limitations. First, is highly combustible, which limits its use as a vehicle fuel. Another challenge concerns the restrictions of hydrogen injection into gas network. The limit of hydrogen in the gas grid is 2-10%. The reasons for this restrains are:

1. Hydrogen gas has a lower energy density, what would reduce the thermal energy of natural gas
2. Higher addition of hydrogen can cause embrittlement of pipe material, what decreases it strengthens
3. Hydrogen has higher leakage rate, what can cause economic and safety concerns
4. High addition of hydrogen can influence the gas appliance in burners, boilers and gas engines.

7.3. Cost-covering

Power-to-gas has a lot of opportunities, which could support the energy system on the way towards sustainability. Altogether like renewable sources, power-to-gas is in the early stage of development, what appears through high investment costs. Unfortunately, most analyses do not consider the indicator of technology maturity. In some years the situation on energy market will change, mainly due to clean energy policies, provide in European countries. The increasing share of RES can contribute to change of electricity prices on the market. Such circumstances can influence the profitability of power-to-gas technology. There are some researchers, which already predict the change in profitability of PtG. McKenna et al. in [51] predict that in German region Baden-Wurttemberg hydrogen production from PtG can be cost-covering operation after 2030. For today the positive business case is challenging [33]. Parra et al. in [49] that business model based only on selling renewable hydrogen and renewable SNG cannot compete with conventionally produced gas.

In case of PtG final product hydrogen and methane for the highly dependent on electricity price [15]. This variable can change in future behalf of PtG technology.

7.4. Establishment of the policy framework

Introducing power-to-gas on the market with its ability to produce clean gases and balancing role, requires proper policy framework. The example of subsidizing renewable sources has shown that misguided promotion of one technology over others can cause serious problems, like unprofitability of this technology after the end of subsidizing period, unprofitability of other technologies and its premature shutdown. On the other hand, without the governmental support clean technologies have reduced chances to come into existence on the economy ruled by the market.

7.5. Management strategies

Power-to-gas can play different roles in energy systems. To fully use its potential, it requires a proper management strategy. PtG will create a synergy between different energy networks and will facilitate an exchange of the resources between them. This approach can lead to more efficient and economic utilization of the resources. To reach this goal PtG technologies must be followed by a smart management system, which will provide an exchange of accurate data between market's participants.

8. Conclusions

Power-to-gas is the technology which can support the necessary transformations of energy sectors towards sustainability. We have presented the most important opportunities of PtG in different energy system architectures. Power-to-gas is very flexible technology, which can play multiple roles in the energy system, these are:

- Large-scale and long-term energy storage for renewable sources [3], [13] [22], [23], [24], [25], [26], [27];
- Balance and flexibility of the integrated gas-electricity network based on the high share of renewable energy sources [6], [31], [32], [33], [34], [52];
- A significant source of clean fuel for heating or transportation [13], [14], [17], [30], [38], [39], [46];
- Contribution to emission reduction target [15], [46], [48], [49];

Although power-to-gas is not yet economical profitable different researchers have shown that with ongoing trends in 10-20 years the situation can change [11], [23], [35], [36], [37], [46]. Considering all opportunities of PtG this technology is worth investing in.

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