

Power-to-Gas: Synthetic Natural Gas (SNG) from Renewable Energies

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Abstract: The Power-to-gas (PtG) is an auxiliary solution for long-term and large-scale storing renewable electrical energy in a chemical energy carrier. PtG concept not a solution for storage but it also reduces the CO₂ emission by using it in process and produce CO₂ neutral gas as synthetic natural gas (SNG) for transportation, industry, and households. PtG involves electrolysis as the production of H₂ and CO₂ methanation as the main process for the production of SNG from renewable sources. The interconnected multi-energy system is considered the solution for an efficient and environment-friendly energy system in the future. However, before the implementation of this technology, some key aspects need in-depth analysis. This paper discusses a technical overview as well as an economic overview of the interconnected multi-energy system.

Keywords: CO₂ methanation, electrolysis, power-to-gas, renewable energy, synthetic natural gas.

1. Introduction

Energy generation from renewable energy sources (RES) showed unexpected growth during the last several decades. Renewable sources are the second most contributor to electricity production and it was about 24.5% of the total global generation of electricity in 2017. Electricity production from wind and photovoltaic (PV) presented a significant increase in the last several years. Even solar energy showed robust growth [1].

In the upcoming future, efficient and huge-capacity storage technologies are required to manage intermittent energy production for a long period from renewable sources such as solar and wind. There are numerous ways exists for transforming renewable energy into gaseous or liquid fuels. From these storage technologies, the power-to-gas (PtG) concept represents an efficient and interesting choice for long-term storage for large quantities of energy [1], [2]. The PtG concept has two options based on the final product gas, the first one is hydrogen (PtH₂ configuration) and the second one is synthetic natural gas (PtSNG configuration) [3]. The whole concept is shown in Fig. 1.

In this paper, the various technologies of power-to-gas are described especially for synthetic natural gas. Based on this, a technological and economic overview is presented.

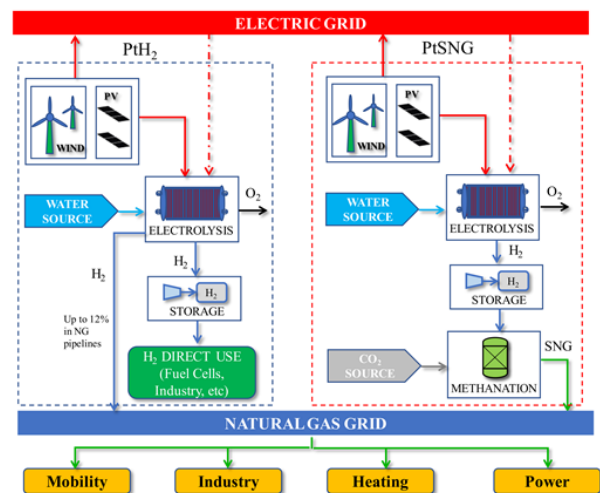


Fig. 1. Principle of power-to-gas concept [6]

2. Technological Overview

As shown in Figure 1, renewable electrolytic hydrogen can be used directly as a fuel or in the chemical industry for the production of natural gas. However, the storage of hydrogen is not so easy, and to maintain their properties (e.g., concentration in the gas grid must be controlled within a limited percentage up to 12% vol. depending on national standards). Therefore, this renewable electrolyte hydrogen is used with CO₂ as a reactant in the methanation process. The final gas mixture is known as synthetic natural gas (SNG) [3]. The techniques of SNG production are described below.

A. Water Electrolysis

The conversion of electric energy into chemical energy is an essential part of the power-to-gas concept. Renewable electrical energy came from solar, wind, or hydro which is used as an electric potential to split water into its component's oxygen and hydrogen which are formed at the anode and cathode respectively, and that is called water electrolysis [4], [5].

There are three main electrolysis technology that can be used for the PtG plant [6]:

- Alkaline electrolyzers
- Proton exchange membrane (PEM)
- Solid oxide electrolysis cell (SOEC)

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1) Alkaline Electrolyzers

This process is most well-known and has been available for industrial purposes for several decades. The electrolyte consists of an aqueous alkaline solution (potassium hydroxide) with a concentration of 20-40wt.% KOH. The electrodes are designed of perforated steel with cobalt, iron, or nickel as a catalyst and separated by an insulating diaphragm (see Fig. 2.). The operating temperature lies about 80 °C with a very low current density range of 0.2-0.4 A/cm². The efficiency of these electrolyzers is up to 67% based on the LHV of the H₂ produced and the purity of hydrogen lies between 99.8-99.99% (with additional purification) [4], [6].

However, some issues still have to be overcome when applied in PtG concerning the minimum part-load capability of 10-40%P_n range [6]. This is limited by the gas conductivity of the diaphragm, where it causes critical H₂ concentrations for low gas flows in the O₂ stream, which means the electrolyzers have to be shut down and its modular design is also allowed to do it for single modules [4]. Moreover, the restarting time takes 30-60 min after shutdown due to purging operation [6]. The system costs of large-scale are about 1000 €/kW and have a lifetime of 15 to 30 years [6].

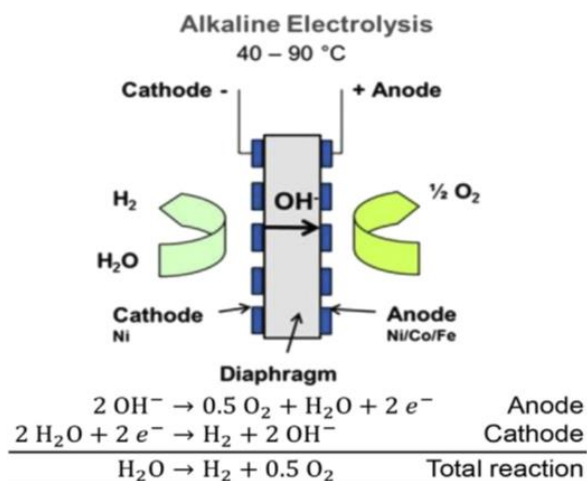


Fig. 2. Schematic working principle of alkaline electrolyzers [4]

2) Proton Exchange Membrane (PEM)

This process technology was developed by General electric in 1966 and was introduced in the market in 1978. In this technology, a polymer membrane is used as an electrolyte. Due to the acidic regime, noble material (platinum group metals) was adopted as a catalyst. The operating temperature lies between 20-100 °C [6] with a high current density range of 0.2-2 A/cm². The PEM is shown below Fig. 3.

Due to the impermeability for gases, load capacity is very low about 0-5% P_n. The efficiency of these electrolyzers is the same magnitude as that of alkaline electrolyzers, but the stack efficiency is lower [4]. The purity of hydrogen is higher and it is more than 99.99% without further purification [6].

The requirement of noble catalyst and titanium-based bipolar plates leads to a higher investment cost of about 2000 €/kW and has a lifetime of 5-20 years. Moreover, alternative materials such as nickel could be valid materials but it needs to be improved efficiency and the reduced estimated cost is about 500

€/kW [4]. A comparison of the main characteristics of alkaline and PEM electrolysis is shown in Table 1.

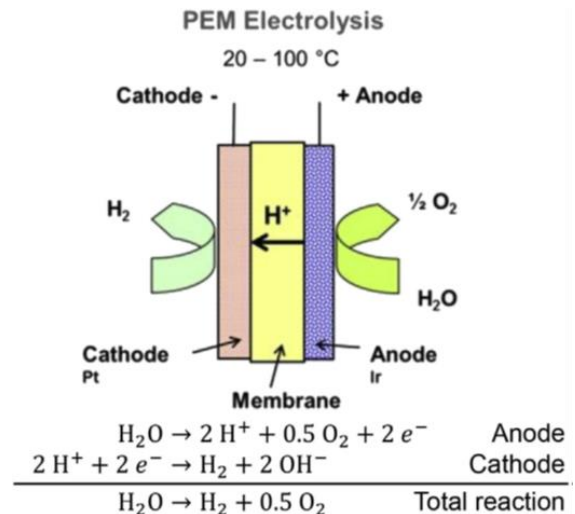


Fig. 3. Schematic working principle of PEM electrolysis [4]

Table 1
Comparison of different electrolyzer technologies [4]

	Alkaline electrolysis		PEM electrolysis	
	Today	Potential	Today	Potential
System efficiency [% (LHV)]	<67%	<70%	<67%	<74%
Minimum part load [%PN]	20–40%	10–20%	5–10%	0–5%
Load change [%PN/s]	<10%/s	<25%/s	10–100%/s	10-100 %/s
Operating pressure [bar]	<30	<60	<30	<100
Stack lifetime [h]	~75,000	~95,000	~30,000	~80,000
Investment costs [€/kW _{el}]	~1000	~500	~2000	~500

3) Solid oxide electrolysis cell (SOEC)

SOEC was first developed in Germany between 1975 and 1987 and it is still under research. This is also called High-temperature water electrolysis (see Fig. 4.). It operates at a very high temperature of about 700-1000 °C with steam instead of liquid water. Here, one part of the energy is provided in the form of electric energy, and the rest can be provided with a high-temperature heat source. The electric efficiency (ratio of chemical energy output to electric input) can even exceed 100%. Because of the high temperatures, SOEC can also bring into the co-electrolysis, where CO₂ to CO and H₂O to H₂ reactions occur simultaneously and it is resultant in syngas production. This process may be used for CO₂-neutral production of all products in the chemical industry. However, for this technology, many characteristics need to be improved. For use in Power-to-gas, requires several times start-up and shut-down because it is necessary to flexible modes of operation [4].

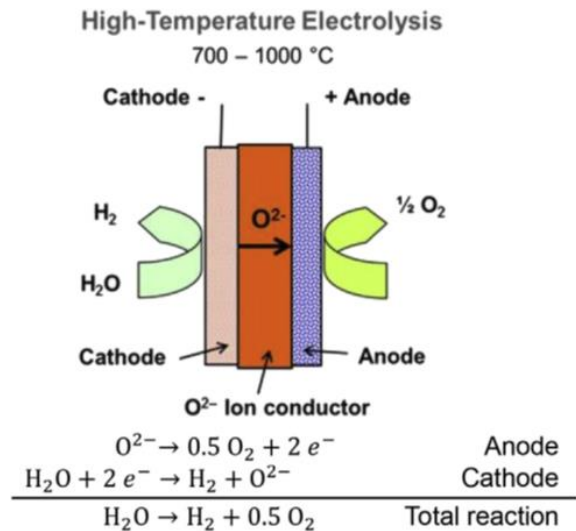


Fig. 4. Schematic working principle of SOEC electrolysis [4]

B. Methanation

For the production of renewable synthetic natural gas (renewable power methane), hydrogen from the electrolysis process and CO₂ is a key component of the whole process and it is further proceeded via Sabatier reaction (see Fig. 5.).

Apart from H₂, carbon dioxide is the second most important reactant of SNG production. It must be energy-efficient and economically affordable. For the carbon dioxide, high purity and strict parameter have to be verified [4], [6]. The main sources of CO₂ are,

- Carbon dioxide from Carbon Capture (CC);
- Carbon dioxide from biomass;
- Carbon dioxide from industrial processes;
- Carbon dioxide from the air;

The energy consumption and cost are shown in Table 2.

Table 2
Cost and energy consumption for CO₂ capturing [6]

Source	Cost [€/tCO ₂]	Energy consumption [kWh/tCO ₂]
CC	20-60	100-350
biomass	35-80	-
industrial processes	45-150	-
air	1000	3000-5000

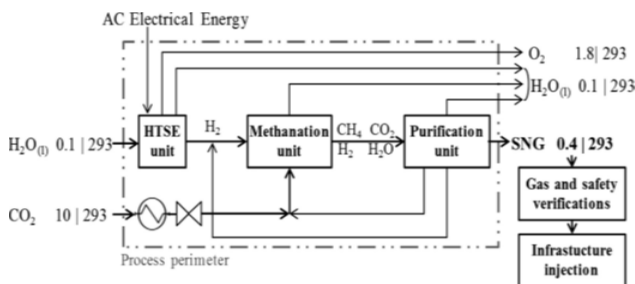


Fig. 5. Schematic diagram of methanation process [4]

Methanation is a highly exothermic and catalytic reaction and it is based on the catalytic hydrogenation of carbon dioxide to methane. The operating condition is at 250-400 °C

temperature and 1-80 bar pressure with the nickel and ruthenium-based catalyst [4], [7].

In the Sabatier process, one mole of carbon dioxide reacts with four moles of hydrogen over a catalyst as described below by equation:

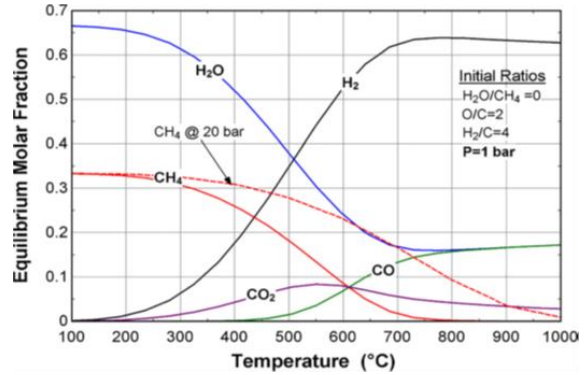


Fig. 6. Temperature dependency for equilibrium molar composition at 1 bar and H₂:CO₂ feed ratio of 4:1 [5]

When the reaction proceeds further to the right (forward reaction), the reaction is favored at low temperature due to high pressure and exothermicity based on its molar stoichiometry. The equilibrium concentration of carbon dioxide is very small at low temperatures, which leads to a high degree of forwarding reaction (see Fig. 6.). With the temperature increase, the concentration of methane is decreasing; it is due to the formation of carbon monoxide (CO forms at a temperature higher than 450 °C). This happens due to the reverse water gas shift, shown as below: [5], [7].



The maximum concentration of carbon dioxide at 550 °C is indicated the thermodynamics preference for both the reverse methanation and reverse water gas shift reaction. After achieving 600 °C, steam reaction dominates, it produces CO and H₂O in equal amounts as shown in Fig. 6. Results of methane concentration at 20 bar are also illustrated and depicted that the concentration is increasing at higher pressure. Since this effect is not significant at 300 °C. The highest equilibrium concentration of methane is at the stoichiometric ratio for H₂:CO₂ of 4:1, the unreacted hydrogen molecule dilutes the mixture and causes the lowers the concentration of methane [5].

To reach a high concentration of methane around 95-98% in the final gas stream, it is necessary to connect several methanation reactors with intermediate cooling in series. This architecture converts hydrogen and carbon dioxide to more than 95%. The final gas stream (methane-rich gas stream) contains residual H₂, CO₂, and H₂O which needs to be removed to meet the requirements [7], [8].

The purification unit needs to be purified the methane gas as a final product. This unit has mainly three units: amine scrubber for CO₂ capture, condenser for H₂O removal, and membrane process for separation of H₂ [7].

C. Power-to-gas: synthetic natural gas from biomass (Biological process route)

Flexible sorption enhances gasification (SEG), where calcium oxide (CaO) based raw material circulating between combustor and gasifier for producing syngas to further production of SNG (see Fig. 7.).

In Fig. 7., part (a) is an exclusive PtG technology discussed in detail above and (b) is the assessed PtG plant wherein SNG is produced from biomass and hydrogen (water electrolysis) instead of direct introducing carbon dioxide. In this technology, the gasifier operates at 600-700 °C (feedstock: steam and biomass) to produce syngas, and the combustor operates at 800-900 °C (feedstock: limestone, biomass, and air) to produce flue gas. The rest of the intermediate products circulate in between both reactors [9].

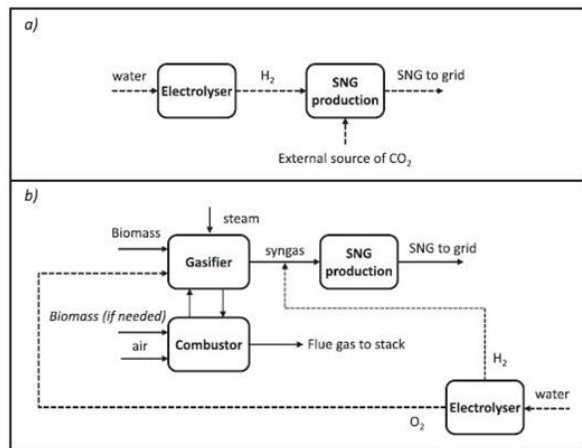


Fig. 7. Block diagram of (a) an exclusive Power-to-gas for SNG production (b) the assessed SNG production plant coupled with a power-to-gas technology [9]

From this concept, SNG production efficiency is about 62% (LHV based) with methane content (purity) of 98% [9].

3. Economic Overview

The economic factor is as important as technological. As per Fig. 8., there was a great difference in the gas price due to the high production of shale gas in the United States. While in Japan and Europe, the price range of 25-40 €/MWh over the past few years and the price in the United States was dropped to about 5-15 €/MWh. Due to this reason, Europe is a major player in the renewable SNG sector [10].

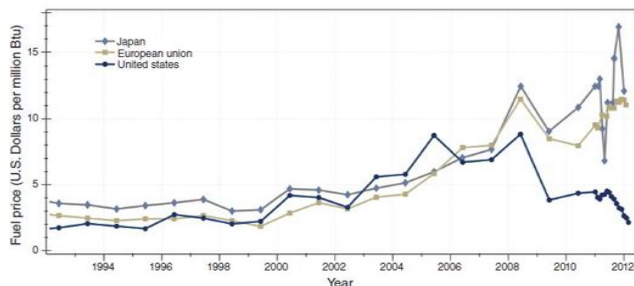


Fig. 8. Natural gas price in Japan, the European Union, and the United States, 1992 to 2012 [10]

Generally, operational cost is determined through the cost of carbon dioxide capture, the possibility of methane utilized and its by-products, plant size, annual operational hours, existing infrastructure. Based on the electrolysis and methanation process with auxiliaries, the evaluated cost is 1000 €/kW (connected duty of 48 MW), of which around 86.3% are allocated to electrolyzers. So, the cost for the methanation process amount to 140 €/kW. Furthermore, nearly 2000 €/kW investment cost for 5-10 MW and it is assumed to reduce to 1000 €/kW for a larger capacity of the plant [11].

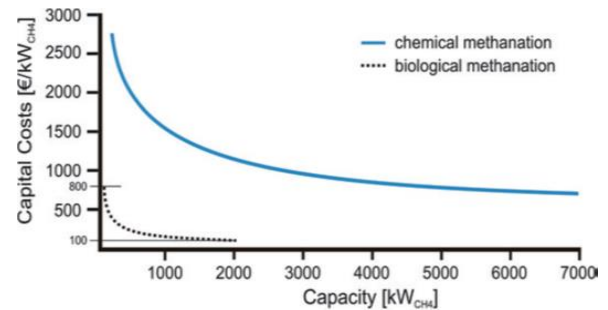


Fig. 9. Investment costs of chemical and biological methanation [11]

As shown in Fig. 9., for both types of methanation plants, the investment costs are lower than 10 MW are depicted. For the smaller than 10 MW plants, cost degradation can be assumed due to standardization of smaller plants and it resultant to 300-500 €/kW_{CH4} for chemical methanation. (by the multiplication of efficiencies of methanation (80%) and electrolysis (70%), the conversion of €/kW to €/kW_{CH4} can be achieved). Thus, 160-280 €/kW are equal to 300-500 €/kW_{CH4}, so it is in the same range [11].

The capital cost of the biological process is very lower than the chemical, it is due to the moderate operational condition such as atmospheric pressure and lower temperature, and also purification of gas is simple or sometimes it is not necessary. On the other side, the plant size of the biological operation is limited to a lower MW range. This cost structure may change in the future as it depends on the development of a methanation reactor [11].

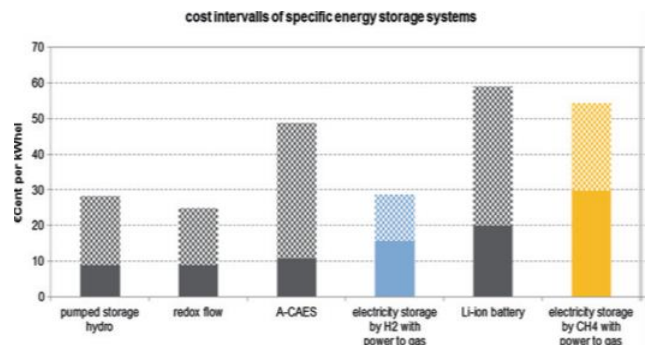


Fig. 10. Comparison of cost intervals of specific energy storage system [11]

Fig. 10. illustrates the characteristics of cost for the power-to-gas system with an exclusive focus on storage for electricity in comparison with the current cost of alternative gas storage for electricity. This integration shows the major difference in

economic as well as by environment friendly as it is a green gas [11].

4. Conclusion

Power-to-gas (PtG) concept might give a significant contribution to the future energy system. But it still needs to be implemented technically as well as economically before it can be commercially successful. In the electrolysis process, efficiency improvement and cost reduction are required. Currently, alkaline electrolysis is the most reliable and cheapest technology; but PEM electrolysis could be the better choice in the near future based on its performance. SOEC is still in its development phase, however, this technology has a high potential for dealing with the exothermic process. In methanation, catalytic methanation requires a smaller reactor size than the biological methanation for the same feed flow and catalytic methanation gives more efficiency. For improving the efficiency of SNG, heat utilization from methanation is required. The biological route is best and viable but only at a lower capacity. Also, the economic analysis would be helpful for cost-reducing as well as for achieving the best results globally.

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