

Water Electrolysis in the Power-to-Gas Process

Tianshu Feng*

Changwang School of Honors, Nanjing University of Information Science & Technology, Nanjing, China

*Corresponding author: 202083310014@nuist.edu.cn

Abstract: As the world moves towards a carbon-neutral energy society, electricity networks will also have to undergo some innovation. As a revolutionary technology that can produce a range of gases to promote industrial development while maximizing environmental protection, power-to-gas (PtG) technology has been the subject of extensive discussion in recent years and will have a huge impact on the electricity grid of the future. In this review, three ways of producing hydrogen by electrolysis in the PtG process are comprehensively highlighted and discussed: alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis. Along with some of the limitations in practical implementations, the guiding concepts for the three approaches are presented. Their advantages and disadvantages are also summarized and compared. Some latest progress and breakthroughs are also collected and discussed in this review. Moreover, analysis about the economics and industrial applications as well as the present limitations and future outlook are also involved in the discussion part. It is hoped that this review study would increase interest in bridging technological gaps to realize scalable hydrogen production in the PtG method.

Keywords: PtG, Electrolysis, Hydrogen, Renewable Energy.

1. Introduction

Although a sizable portion of the world's energy needs are currently satisfied by fossil fuels, it is impossible to ignore the negative consequences of their burning, which harm both humans and the environment. To this goal, the fast growth of renewable energy sources is accelerating the global energy transition. Hydrogen has been investigated as an alternative energy carrier to build on this momentum and minimize carbon emissions, and as the only result of employing fuel cells to generate power from hydrogen is clean water, the local ecology is not harmed. Another benefit is that hydrogen. Compared to gasoline combustion, the amount of energy produced per mass unit might increase by three times. Additionally, the ability to create hydrogen domestically lessens a nation's reliance on foreign energy sources. In particular, it is possible to produce hydrogen in a method that is mostly sustainable as a result of the Earth's abundant water supply. At present, the gas industry generally believes that Power-to-gas technology can solve many challenges in the process of "decarbonization" of the industry: because of the excellent quality of fuel generated by the technology, it cannot only facilitate transportation and long-term storage, but also ensure the high temperature required in the industrial production process. Meanwhile, the technology can retain existing industrial equipment without expensive upgrades, which means lower technology conversion costs.

Power-to-gas (PtG) is an idea that was sparked by the growth of renewable energy imports in Germany. PtG is a technology that transforms electric energy into natural gas or hydrogen, stores the obtained gas in a system of natural gas pipes or in natural gas storage equipment, converts and stores the gas during the peak period of the output of renewable power, and supplies energy in the event of a power outage, increasing the system's capacity to absorb renewable energy. The whole process can be decomposed step by step. Firstly, electricity is got from an environmentally friendly way of generating electricity, and then the electricity is applied to the electrolyte to break it down into hydrogen. The hydrogen can be burned as fuel for energy or made into hydrogen fuel cells as a power source. The hydrogen can also be further processed and converted into methane for storage, burning to generate energy and electricity. Therefore, PtG includes two types in practical applications: electron-to-hydrogen and electron-to-natural gas, among which electron-to-hydrogen is the pre-reaction of electron-to-natural gas.

A well-known method for transforming water into molecular hydrogen and oxygen at very moderate temperatures is water electrolysis. Interest in effective and adaptable ways to obtain high-quality hydrogen has been sparked by the rising demand for sustainable energy carriers [1]. The production of hydrogen can be used to create power through hydrogen fuel cells or methane through the methanation process. However, due to the relative low conversion efficiency that is only 40-60% [2] and the potential safety hazards of the hydrogen fuel cells, methanation is preferred in production.

The methanation process then converts hydrogen into methane. Both biological and catalytic methanation reactors can produce methane. Methanation is a small volume, intense exothermic and eco-friendly process, the highest efficiency of which can reach more than 95% (development stage) [3]. The working principle of gas turbine is that a gas turbine mixes methane with air, compresses it, and ignites it with a spark plug. The shock of the detonation drives the rotor of the motor and generates an electric current, thus turning the gas to electricity back to implement the storage function.

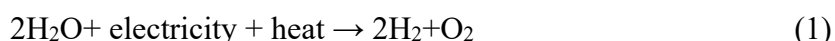
This article focuses on the electrolysis of PtG by introducing three electrolysis approaches and discussing their limitations and future outlook.

2. Electrolysis

2.1. Overview

Because water is an electrolyte, when a current is provided, the binding attraction between the electrolyte atoms starts to wane, causing the electrolyte to separate into hydrogen and oxygen ions with a cathode and ions with an anode.

By passing direct current through an electrolytic cell containing electrolyte and allowing the water molecules to react electrochemically on the electrode to break down into hydrogen and oxygen, hydrogen can be produced. Cell, anode, and cathode are the basic components of an electrolytic cell. When a direct current flows through an electrolytic cell, an oxidation reaction takes place at the anode's interface with the solution, producing oxygen. At the point where the cathode and solution meet, a reduction process happens, resulting in hydrogen gas. Electrolytes are added to boost the water's conductivity, which makes it easier for current to flow continuously. Different ions, including H^+ , OH^- , O_2 , etc., are utilized as charge carriers in acid and solid polymer electrolytes, which are frequently used for hydrolysis. There may be differences in the hydrolysis reaction on the electrodes of various charge carriers, but the overall reaction is always the same, namely:



Based on the kind of electrolyte and diaphragm materials, contemporary water electrolysis systems can be classified as alkaline electrolysis, proton exchange membrane (PEM) electrolysis and solid oxide electrolysis (SOE) systems.

2.2. Alkaline electrolyser (AEL)

Compared with several other electrolytic water technologies, alkaline electrolytic cell is the only electrolytic water hydrogen production equipment that applies for large-scale engineering applications. It has the advantages of mature technology, stable efficiency and the relative low cost. At present, it has come into service in many large-scale projects around the world and the actual efficiency is considerable.

Alkaline electrolysis uses an electrolyte containing 30–40% KOH, a diaphragm, and two electrodes made of non-platinum group metals (Ni and Fe). Up to the megawatt scale, alkaline electrolysis is recognized as a dependable process for creating hydrogen.

The revolving KOH electrolytes supply the necessary alkalinity. The anode and cathode are separated using the porous diaphragm. Additionally, it performs the crucial task of transporting hydroxide ions, avoiding potential gas crossings, and assuring efficiency and safety. The diaphragm is comprised of organic polymers like polypropylene or ceramic oxide materials like asbestos and

potassium titanate [4]. Alkaline electrolysis has a number of benefits, including the ability to utilize non-precious metal catalysts and easy handling due to its comparatively low temperature operating conditions [4].

The main drawback of AEL is that it uses very corrosive electrolytes, such as 20-30% potassium hydroxide solution, which results in high maintenance expenses. Every 7 to 12 years, the system requires a comprehensive upgrade [4]. Alkaline electrolyzers are currently predicted to last around 30 years [5], which is definitely a long time compared to other forms of electrolyser that have been taken into consideration. Alkaline electrolysis does, however, have some drawbacks, including low working pressure, limited current densities and a generally inefficient use of energy. AEL has improved recently, particularly in terms of efficiency and overall investment.

2.3. Proton exchange membrane electrolyser (PEM)

In comparison to AEL, PEM is a more recent technology. In PEM electrolysis, a proton conductive membrane is used to transport these protons to the cathode side. The external power supply circuit provides the driving force for the reaction, allowing the electrons to escape the anode (battery voltage). The combination of protons and electrons produces hydrogen on the cathode side. PEM uses a polysulfonic acid membrane [6] along with water to improve the electrical conductivity of protons, causing hydrogen ions and oxygen ions to separate and generate larger quantities of hydrogen and oxygen. This method is comparable to fuel cell technology in this regard.

AEL features relative higher current densities than other electrolysis techniques, quick response times, increased hydrogen production rates, and compact system designs with excellent gas purity (99.99%)[7]. PEM electrolysis facilities may also be balanced extremely easily, making them more desirable for commercial use. Due to the membrane cost and the need for a noble metal catalyst, this method is currently more expensive than AEL systems and has a shorter lifespan [8].

2.4. Solid oxide electrolyser (SOE)

Solid oxide electrolysis (also called high temperature electrolysis) is a novel technology that is now being tested in laboratories. The conditions applicable to this method involve heating(500-850 Celsius) [5] and pressurizing water with an estimated oxidant with oxygen ions so that the cation in the water reacts with the solid, leaving hydrogen behind. Because it has excellent conductivity to oxygen ions (charge carriers) and chemical stability at high temperatures, ZrO₂ doped with 8 mol% Y₂O₃ is used as the electrolyte in SOEC [9]. Power demand is decreased by high temperatures because they lower the equilibrium cell voltage, but the rise of temperature also leads to the need for heat. The SOEC system's low power consumption is its key advantage. Theoretically, endothermic mode, which maximizes electrical efficiency, is possible [10]. The PtG process chains in particular have improved overall efficiency when exothermic processes are combined with them.

As a result of operating at high temperatures, materials in SOEC systems rapidly degrade and have a short-term stability [5]. Due to the high temperatures used in the electrolyzer, the product stream mixes the hydrogen and steam, requiring additional processing and increasing the cost of capital. Additionally, SOEC systems are unstable under varying and sporadic power conditions [10,11].

2.5. Comparison of the technologies

The summary of the key operational parameters for Alkaline, PEM, and SOE is shown in Table 1. Working temperature, cell voltage, efficiency, longevity, etc. are some of the variables that have been considered.

Table 1. Summary of Alkaline, PEM, and SOE.

	Alkaline electrolysis	PEM electrolysis	Solid oxide electrolysis
State of development	Commercial	Commercial	Laboratory
Electrolyte	Alkaline solution	Solid polymer membrane	ZrO ₂ ceramic doped with Y ₂ O ₃
Cell temperature in °C	40-90[6]	20-200[6]	80-1000[6]
Cell voltage in V	1.8-2.4[5]	1.8-2.2[5]	0.91-1.7[5]
Efficiency	63-73%[3]	60%[3]	100%[3]
Cold start time	Minutes-hours	Seconds-minutes	—
Lifespan	Up to 30 a[12]	5 a, shorter lifetime than AEL[12]	—
Advantages	Available for large plant sizes, cost, lifespan	Integration of waste heat possible, high electrical efficiency	high power, high electrical efficiency
Disadvantages	Maintenance costs (system is highly corrosive), low current density	Fast degradation, expensive	Not suited to fluctuating systems, limited long term stability of the cells, expensive

3. Discussion

3.1. Economics of “Power-to-Gas”

The performance of PtG in energy systems for the foreseeable future is covered in a number of papers and studies. Particularly, a great deal of study has been done on the statistics of the German energy transition (Energiewende). The total costs, climate-related difficulties, and integral and geographical PtG capacities along with the anticipated shares of variable renewable energy sources are analyzed in addition to the overall quantity of storage required. Combinations of various storage systems are taken into consideration in this regard. For instance, if Germany were to produce 85% of its energy from renewable sources, both Power-to-Heat and PtG might be pertinent[13]. The conclusions of the investigations can vary greatly depending on the underlying assumptions.

According to study results by Thema et al.[14], the average cost of alkaline electrolyzers will decrease from around 1300 €/kW_{el} in 2017 to less than 500 €/kW_{el} in 2050. Based on the current situation of the market, the price evolution in this paper predicts the fulfillment of PtG technology in the upcoming years [14,15].

The particular prices of PEM are anticipated to decrease from roughly 1900 euros per kW_{el} in 2017 to 500 euros per kW_{el} in 2050. Values below 500 €/kW_{el} are obtained by exponentially fitting the data, similar to what is done in alkaline electrolysis. As a result, both technologies will experience a cost reduction of almost 75% throughout the allotted time.

It is most definitely feasible to reduce the cost of high-temperature electrolysis by 85%, from around 3570 euros per kW_{el} in 2017 to 535 euros per kW_{el} in 2050. By 2030, alkaline electrolysis costs are projected to be 700 euros per kW_{el} and PEM costs will be approximately 600 euros per kW_{el} [14]. In the long term, the exponential approximation's prediction, which has substantial uncertainties as previously mentioned, results in about identical costs. Annual estimations of all relevant electrolysis methods are compared in order to show that the current cost disparity will narrow over time [15].

3.2. Present limitations

Alkaline electrolysis has drawbacks such low operating pressure, low operating current densities (below 400 mA/cm²), and relatively low energy efficiency. Because the membrane expenses are higher and a noble metal catalyst is used, PEM electrolyser systems are presently more costly than

AEL systems. Their short lifespan is another drawback. As a result of operating at high temperatures, materials in SOEC systems rapidly degrade and have a limited long-term stability [16].

The temporary hydrogen storage needed by the variable power source and the electrolyser's resulting intermittent operation present another difficulty for PtG systems. The size and additional hardware required for hydrogen storage varies greatly depending on the system's setup and operational parameters. The two greatest solutions for short-term hydrogen storage are metallic hydride tanks or high pressure gas tanks (350–700 bar). Gahleitner [16] claims that the preferred method for the now and the future is to store hydrogen in PtG systems using high pressure gas cylinders (both planned and realized in 2012) [17].

3.3. Future outlook—future development trend

(1) Efficiency promotion:

Based on data in 2021, the present efficiency of the electrolysis is fairly close to the final aim [2]. AEL systems have an electrical efficiency of roughly 63%–73%, whereas the ideal level is 70%–80% [14]. The efficiency of a PEMEL system is currently only about 60%, but it is anticipated that this will increase to 67%–74% in the future [14]. Because the electrolyser can operate more efficiently with partial loads instead of full loads in actual production. In order to help electrolysers operate at their optimal load, optimization and control procedures may be developed, which could help to increase operational efficiency [18].

(2) Technology development:

The least expensive and most dependable water electrolysis method available right now is alkaline electrolysis. Due to its improved performance in transient operation, PEM electrolysis might soon be the preferred option for PtG facilities. Although solid oxide electrolysis technology is still in its infancy, there is a good likelihood that it will pair with exothermic reactions when it is operating at steady state [8].

4. Conclusions

Only electrolysis in the PtG process is examined in this investigation. The decarbonization of numerous industries, including transportation, electricity generation, and industry, is being supported in large part by hydrogen. There have been initiatives taken to hasten the process of making this possibility a reality. The key electrolysis methods were examined in this essay, and it was determined that hydrogen has the ability to store and transport energy. Large-scale deployments of renewable hydrogen electrolysers will be possible in the coming years thanks to improved technological preparedness. The capital cost of the system and the expense of producing hydrogen in its current stage are still prohibitive for the broad use of hydrogen in industrial deployments, and the progress has been constrained from a sustainable point of view by the use of water and rare materials.

According to a review of the literature across time, many advancements are required in the near future. It is necessary to do research and develop methods for cost reduction while enhancing the effectiveness and stability of the system. In addition, policymakers should encourage the creation of integrated hydrogen energy systems and strengthen the initiatives that can bring hydrogen to the markets of today.

References

- [1] Li, C., & Baek, J. B. (2021). The promise of hydrogen production from alkaline anion exchange membrane electrolysers. *Nano Energy*, 87, 106162.
- [2] Cheng, X., Shi, Z., et al. (2007). A review of PEM hydrogen fuel cell contamination: Impacts, mechanisms, and mitigation. *Journal of Power Sources*, 165(2), 739-756.
- [3] RUSMANIS, Davis, et al. Biological hydrogen methanation systems—an overview of design and efficiency. *Bioengineered*, 2019, 10.1: 604-634.

- [4] Yue, M., Lambert, H., et al. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews*, 146, 111180.
- [5] A. Ursua, L.M. Gandia, P. Sanchis, hydrogen production from water electrolysis: current status and future trends, *Proc. IEEE* 100 (2012) 410-426.
- [6] Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis—A review. *Materials Science for Energy Technologies*, 2(3), 442-454.
- [7] M. Carmo, D.L. Fritz, J. Mergel, D. Stolten, A comprehensive review on PEM water electrolysis, *Int. J. Hydrogen Energy* 38 (2013) -4934.
- [8] Götz, M., Lefebvre, J., et al. (2016). Renewable Power-to-Gas: A technological and economic review. *Renewable energy*, 85, 1371-1390.
- [9] M. Reytier, S. Di Iorio, A. Chatroux, M. Petitjean, J. Cren, J. Mougín, Stack Performances in High Temperature Steam Electrolysis and Co-electrolysis 20th World Hydrogen Energy Conference, 2014. Grenoble 2014.
- [10] M.A. Laguna-Bercero, Recent advances in high temperature electrolysis using solid oxide fuel cells: a review, *J. Power Sources* 203 (2012) 4e16.
- [11] AN, Li, et al. Recent development of oxygen evolution electrocatalysts in acidic environment. *Advanced Materials*, 2021, 33.20: 2006328.
- [12] A. Ursua, L.M. Gandia, P. Sanchis, hydrogen production from water electrolysis: current status and future trends, *Proc. IEEE* 100 (2012) 410e426.
- [13] Gondal, I. A. (2019). Hydrogen integration in power-to-gas networks. *International journal of hydrogen energy*, 44(3), 1803-1815.
- [14] Thema, M., Bauer, F., & Sterner, M. (2019). Power-to-Gas: Electrolysis and methanation status review. *Renewable and Sustainable Energy Reviews*, 112, 775-787.
- [15] Lim, D., Lee, B., et al. (2021). Projected cost analysis of hybrid methanol production from tri-reforming of methane integrated with various water electrolysis systems: Technical and economic assessment. *Renewable and Sustainable Energy Reviews*, 111876.
- [16] G. Gahleitner, Hydrogen from renewable electricity: an international review of Power-to-Gas pilot plants for stationary applications, *Int. J. Hydrogen Energy* 38 (2013) 2039-2061,
- [17] Moçoteguy, P., & Brisse, A. (2013). A review and comprehensive analysis of degradation mechanisms of solid oxide electrolysis cells. *International journal of hydrogen energy*, 38(36), 15887-15902.
- [18] Inkeri, E., Tynjälä, T., & Karjunen, H. (2021). Significance of methanation reactor dynamics on the annual efficiency of power-to-gas-system. *Renewable Energy*, 163, 1113-1126.