Research on Technical Characteristics and Development Trend of P2G Technology

Lujia Xue[1,*] and Pengxiang Pei[2]
[1]*University of Rochester/Department of Earth and Environmental Science, 500 Joseph C. Wilson Blvd., Rochester, NY, 14694, U.S.A.*
[2]*North Carolina State University/Department of Exploratory Studies, 2710 Wolf Village Way 407, Mackenzie, Wolf Village Raleigh, NC, 27067, U.S.A.*

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Abstract: The technical details, performance indicators, and developmental trends of Power-to-Gas (P2G) technology-a crucial advancement for integrating renewable energy sources into the energy framework-are examined in this study. As renewable energy usage grows, the inconsistent nature of sources like solar and wind introduces challenges in maintaining grid stability and ensuring reliable energy supplies. P2G technology, which transforms excess renewable electricity into hydrogen or methane, emerges as a viable solution to these issues. It facilitates long-term energy storage, bolsters grid stability, and aids the decarbonization of the energy sector. This study delves into various electrolysis methods-Alkaline (AEL), Polymer Electrolyte Membrane (PEM), and Solid Oxide (SOEC)-essential to the P2G process, evaluating their efficiency, operational challenges, and potential for scalability. Despite existing constraints such as high costs and low overall efficiency, the paper highlights continuous improvements in electrolysis and methanation processes that are likely to mitigate these issues. Additionally, it discusses the strategic importance of P2G in future energy systems, emphasizing its role in enhancing energy security and sustainability through technical innovations and international cooperation. This research not only highlights the technological promise of P2G but also delineates the steps necessary for its broader implementation, which is vital for progressing towards a sustainable, low-carbon energy future.

1 INTRODUCTION

The need to slow down climate change and lessen dependency on fossil fuels is causing a major shift in the world's energy system. Although renewable energy sources, including wind and solar electricity, are becoming more widely used, their intermittent nature makes grid stability and the dependability of the energy supply difficult. Due to the imperative to diminish carbon emissions and the increase in the capacity of renewable energy sources, researchers were encouraged to exploit the production of renewable energy sources to supply the energy system (Mazza, Bompard and Chicco, 2018). Power to gas (P2G), which produces gaseous chemical energy carriers by using renewable or excess electricity is a solution tackling the objective and requirement (Wulf, Linßen and Zapp, 2018). This study looks at the performance metrics, developmental trends, and technical specifications of Power-to-Gas (P2G) technology, an important development for incorporating renewable energy sources into the energy framework (Mazza, Bompard and Chicco, 2018). Ranging from small pilot projects to large industrial installations, power to gas technology has been demonstrated across various scales. Electrolysis stands as a cornerstone technology within the P2G system. AEL, PEM and SOEC are the three distinct electrolysis technologies that are relevant for power to gas process chains. Solid oxide electrolysis technology is still in the laboratory, while polymer electrolyte membrane electrolysis (PEME) is a relatively recent technique (Götz et al., 2016). In several countries, including Germany, Japan, and the United States, considerable emphasis has been placed on research, development, and application of P2G technology. However, P2G technology is currently facing several challenges. Its

* Corresponding author

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high costs, coupled with low efficiency during the process, poses economic and technical burdens. Scaling up from small-scale demonstrations is difficult, and infrastructure modifications are required. This paper will focus on discussing power to gas's major technology features, overall performance, facing challenges, storage capabilities, and outlook the future of this technology.

2 TECHNICAL PRINCIPLE OF P2G

The conversion of electricity to gas is the fundamental component of power to gas technology. The two-step process of producing H_2 through water electrolysis (electrolyze) and then converting the H_2 with an external CO or CO_2 sources to CH_4 (methanation) is how this conversion process connects the power grid with the gas grid, as illustrated in figure 1 (Götz et al., 2016).

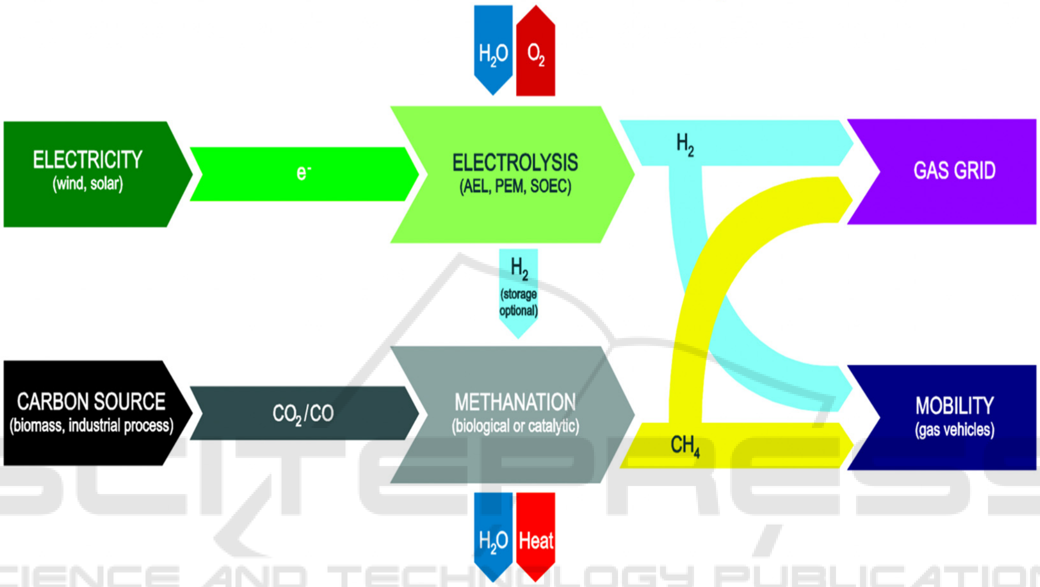

Figure 1: Exemplary Power-to-Gas process chain

2.1 Electrolysis

By using an electric current, water can be electrolyzed to produce hydrogen (H^+) and hydroxide (OH^-) ions. Water electrolysis is one method of producing hydrogen with surplus electrical energy. The P2G technology relies on electricity derived from renewable sources, including solar, wind, hydro, and geothermal power, to supply the electrons required for hydrogen generation. Three different electrolysis methods are now being used by AEL, PEM, and SOEC; these technologies are pertinent to P2G process chains (Götz et al., 2016).

Alkaline electrolysis employs aqueous alkaline solution (KOH or NaOH) as electrolyte, functioning effectively under both atmospherically and elevated pressure (Götz et al., 2016). AEL is the most developed and understood technology that has been for many years on the market and it can operate within a flexible range of 20 to 100% of its design capacity, and it can operate at up to 150% overload (Kreuter and Hofmann, 1988). This operation versatility makes alkaline electrolysis suitable for power to gas system, which is coupled with fluctuating and intermittent power sources. It is applicable for large-scale plant demonstrations (Ursua, Gandia and Sanchis, 2012). Moreover, the cost of alkaline electrolysis is relatively low, and the operational lifespan typically extends between 8 to 10 years, signifying durability. Nevertheless, the electrolytes are highly corrosive, the current density tends to be low, and the maintenance costs are considerable (Götz et al., 2016).

PEM relies on solid polymer membranes. The primary benefit of PEM technology offers several advantages, including faster cold starts, higher flexibility, improved integration with dynamic and intermittent systems, and higher purity of the produced hydrogen (Götz et al., 2016). Therefore, it demonstrates a better transient operation than alkaline electrolysis (AEL) and boasts better dynamic adjustment capabilities (Gahleitner, 2013). However, the current drawback of this technology is a higher cost relative to AEL systems, which is attributed to expenses related to the membrane and the utilization of noble metal catalysts (Götz et al., 2016). Moreover, PEM technology is characterized by a limited lifespan, compared to the alkaline electrolysis (Ursua, Gandia and Sanchis, 2012).

SOEC uses zirconium oxide doped with 8% Yttrium oxide as the electrolyte. This technology represents the most recent advancement in electrolysis and is currently in the laboratory development phase (Carmo et al., 2013). The electrolyte has strong thermal and chemical stability and is highly conductive for oxygen ions at high temperatures. This technology shows high electrical efficiencies, with the potential possibility to achieve electrical efficiencies exceeding 100% (Brisse, Schefold and Zahid, 2008). It also presents a low electricity demand. However, challenges arise due to rapid material degradation and limited long-term stability, which require further attention (Gőtz et al., 2016).

2.2 Methanation

Methanation is the hydrogen conversion with an external carbon monoxide or carbon dioxide to methane through hydrogenation, and it can be realized through two distinct reactor types: biological and catalytic reactors (Götz et al., 2016).

Reactors for biological methanation are normally run between 20 ° C and 70 ° C with pressures ranging from 1 to 10 bar (Götz et al., 2016). In these systems, microbial communities catalyze the conversion process, typically within anaerobic environments. These reactors offer advantages such as ambient operation conditions and the potential for utilizing waste biomass as feedstock. In contrast, catalytic methanation reactors operate within a broader temperature and pressure spectrum. Metals like nickel (Ni), ruthenium (Ru), rhodium (Rh), and cobalt (Co) to drive the conversion reaction serve as catalysts for promoting efficient chemical kinetics and facilitating the methanation reaction (Götz et al., 2016). Both biological and catalytic methanation reactor types play crucial roles in real-life applications like renewable energy storage. While biological methanation offers environmentally friendly and sustainable solutions, catalytic methanation provides high efficiency and scalability.

3 PERFORMANCE ANALYSIS OF P2G

3.1 Efficiency of P2G

In contemporary times, PEM electrolysis and alkaline electrolysis are the two most popular technological methods. Currently, alkaline electrolyzers lead the market in maturity and affordability, yet PEM electrolyzers, though early in their commercial journey, possess significant prospects for enhancements in cost savings, longevity, and operational efficiency moving forward. Recently, the rate at which hydrogen is produced for each stack and the durability of the cells stand as significant constraints for PEM electrolyzers. Ohmic losses, concentration polarization, and activation polarization are the main reasons for the losses of Alkaline (Maroufmashat and Fowler, 2017).

Methanation is a method that can turn hydrogen into synthetic natural gas. There are two kinds of methanation reactors that can produce synthetic natural gas (SNG): catalytic and biological. The limitations imposed by the Sabatier reaction cap the efficiency of each methanation method at 80% (Table 1) (Maroufmashat and Fowler, 2017).

Table 1: Technical, operational, and economic information for Alkaline and PEM electrolyzers (Maroufmashat and Fowler, 2017)

	Current Alkaline Electrolyzer	Improved Alkaline Electrolyzer	Current PEM Electrolyzer	Improved PEM
System Efficiency (%HHV)	62-82	67-87	74-87	82-93
System Efficiency (kWh/Nm³)	4.5-7.0	4.3-5.7	4.5-7.5	4.1-4.8
Cell Area (m²)	4	-	<1.5	-
H_2 Production per Stack (Nm³/h) | <760-1000	<760-1,000	>1,500	<30	<250
System Lifetime (years)	20-30	30	10-20	20-30
Hydrogen Purity	99.90%	-	>99.90%	-

3.2 Sustainability-Related Performance

P2G technology offers a solution to convert excess renewable energy into hydrogen or synthetic natural gas (SNG), reducing reliance on fossil fuels. It leverages fluctuating renewable sources like wind and solar energy to effectively decrease carbon emissions.

Indeed, emission charges are relevant for renewable methane since the carbon it contains is derived from fossil sources. Failing to allocate emission costs to the generation of electricity with renewable methane would lead to the discharge of fossil carbon into the atmosphere. Nonetheless, this release of carbon is delayed because it was initially captured during the generation of electricity from natural gas and is later emitted upon the burning of renewable methane. Consequently, PtG should be viewed as a carbon recycling strategy that ultimately lessens the dependence on fossil fuels (Vandewalle, Bruninx and haeseleer, 2015).

4 ISSUES NEED TO BE SOLVED

4.1 Efficiency Improvement

To assess the performance of the P2G conversion process, the system under consideration incorporates existing electrolysis methods such as AEL and PEM that produce hydrogen at 25 bars with a 70% electrical efficiency. The methanation reactor operates at 20 bars and reaches an efficiency of 78%, which is the maximum chemical efficiency achievable. To preserve this efficiency, CO_2 is pre-compressed to 20 bars, which helps prevent a 2% efficiency loss in the methanation reaction (Götz et al., 2016).

Efficiency enhancement efforts in P2G technologies face numerous technical difficulties. The primary challenge lies in the energy loss inherent to the electrolysis process, where the efficiency of electrolyzers is constrained by thermodynamic limits, material performance, and operational specifics. Additionally, achieving high catalytic efficiency and longevity for both electrolysis and methanation poses a significant obstacle. The task of selecting and fine-tuning catalysts, which are vital for the reactions' speed and energy efficiency, demands significant ongoing research and development. Additionally, the challenge of integrating P2G systems with inconsistent renewable energy supplies complicates the achievement of consistent operational efficiency amid fluctuating input scenarios (Götz et al., 2016).

4.2 Cost of P2G Technology

Costs linked to P2G technology fundamentally fall into three categories: upfront investments, ongoing operational and maintenance expenses, and costs related to energy use. Upfront investments encompass expenditures for establishing the necessary infrastructure, such as electrolyzers, catalysts, and storage units. These costs are subject to variation based on technology selection, project scale, and geographical location. Operational and maintenance expenses pertain to daily operational outlays as well as equipment replacement and repair essential for ensuring sustained system functionality. Lastly, the expenses for energy consumption are tied to the electricity needed for the electrolysis and methanation processes, which are largely determined by the cost and efficiency of the electricity supply (Schiebahn et al., 2015).

4.3 Access to Key Materials

P2G technologies require a range of essential materials for their functioning, notably in the hydrogen generation electrolysis process and the methanation catalytic process. This involves using precious metals such as platinum and iridium in the electrolyzers, as well as nickel-based catalysts for the methanation reaction. The effectiveness, operational efficiency, and longevity of P2G systems heavily rely on these essential materials. However, the procurement of these materials is fraught with challenges, such as a limited availability, the localized nature of resources, fluctuations in prices, and the ecological and societal consequences associated with their extraction.

4.4 Safety of P2G Technology

P2G technologies come with various safety hazards throughout their conversion, storage, and distribution stages. A significant risk is hydrogen's flammability, a key output of P2G systems. Under specific circumstances, hydrogen can create explosive blends with air, demanding rigorous safety standards in operating conditions. Moreover, the adoption of high-pressure storage solutions poses potential dangers of explosions and leakage, thus necessitating meticulous engineering and comprehensive safety protocols to reduce such threats (Gahleitner, 2013).

5 ENERGY STORAGE

5.1 Technical Principle of Energy Storage

Ensuring the availability of hydrogen and methane, produced through P2G technology, relies significantly on effective storage methods. Storage methods are crucial for maintaining a steady supply of these valuable energy sources. There are various storage methods to store hydrogen and methane. Hydrogen can be stored in compressed gas form, where it is pressurized and stored in gas tanks and gas grids. These high-pressure gas cylinders are engineered to withstand significant pressures, typically reaching up to 20 MPa (200 bar). Hydrogen can be stored in liquefied form in cryogenic tanks at 21.2 K and ambient pressure (Züttel, 2004). On the other hand, methane can be stored like compressed natural gas storage, within natural gas pipelines (Makal et al., 2012). Methane is compressed at elevated pressures to facilitate its storage and subsequent utilization.

Fuel cells, gas turbines, combined heat, and power (CHP) plants, and synthetic fuels production are the common methods available to convert stored hydrogen or methane back into electricity. Fuel cells offer a direct electrochemical process to generate electricity from hydrogen (Gahleitner, 2013). It is a highly efficient method with minimal emissions since the only byproducts are water and heat. Methane or hydrogen can be burned in gas turbines to produce mechanical energy, which is then converted into electricity via a generator. Combined heat and power plants provide an avenue, where heat is generated during electricity production captured for heating or industrial processes, enhancing efficiency. This approach is applicable to both hydrogen and methane. Hydrogen or methane can also serve as feedstock for industrial processes to produce synthetic fuels, which can then be utilized in conventional power plants for electricity generation. All of these approaches provide diverse avenues for the conversion of stored hydrogen or methane back into usable electricity, addressing different applications and operational needs.

5.2 Real Applications

P2G storage has applications across different sectors, offering solutions in difficulties in renewable energy integration and decarbonization. In regions where renewable energy sources, such as wind and solar energy, are prevalent but intermittent, P2G serves as a practicable and pivotal solution for grid stability and helps to balance the grid by storing excess energy during periods of low demand and releasing it when needed. Moreover, P2G plays an essential role in reducing carbon emissions across different sectors like transportation industrial production, replacing fossil fuels with a clean alternative.

For example, in the European Union, considerable emphasis is placed on research and development initiatives to enhance renewable energy technologies and promote sustainable energy practices. International collaboration efforts facilitate knowledge exchange and cooperation among nations, fostering collective progress towards achieving renewable energy targets and mitigating climate change impacts.

The Energiewende, a project launched by the German government, is to facilitate the switch from a carbon-based to a low-carbon energy system (Mazza, Bompard and Chicco, 2018). WindGas Falkenhagen, which is a famous P2G project operated by E. ON, is in Falkenhagen, Germany. The groundbreaking Wind Gas Falkenhagen project achieved a significant milestone of 1 MW of wind power into the local grid. This P2G project was pivotal in establishing a standardized process chain for WindGas product, including the identification and engagement for new suppliers (Patel, 2020). These efforts underscore the commitment to spearhead the transition towards a more sustainable and resilient energy future on a global scale.

5.3 Existing Problems

Despite its great potential on providing solutions to problems involved in renewable energy integration and reducing carbon emissions, P2G storage is currently facing several challengers. One primary concern is the efficiencies. The fact that P2G processes involve multiple energy conversion steps inevitably cause energy losses, and lead to low efficiency.

The cost of electrolyzers is also high, with an investment of approximately 1088 dollars/kW for Alkaline Electrolyzers. This figure may vary slightly depending on specific conditions such as pressure and size, which is significantly important in determining the exact cost. The investment of Polymer Electrolyte Membrane Electrolyzes is a minimum of 2177 dollars/kW, but the cost shows decrease trend in which it reached a cost of less than 1088 dollars/kW in 2018. Solid Oxide Electrolyzes have an investment cost of about 2406 dollars/kW which is also set to decrease to a cost of less than 1088 dollars/kW in the year 2030. The cost for both biological methanation and chemical CO_2-Methanation is projected to fall to 900 dollars/kW and 642 dollars/kW accordingly. Renewable electricity cost depends on location, time of day, and availability of incentives or subsidies (Götz et al., 2016).

Moreover, the availability of renewable energy source for P2G operations is subject to intermittency and seasonality. This will largely affect the reliability and utilization of P2G facilities. Thereby, the intermittent characteristic of renewable energy source is a facing challenge, and it is essential to ensure a stable and cost-effective renewable energy supply in order to maximize the utilization of P2G assets.

There is a risk for potential hazards to occur is also highly probably as hydrogen is highly flammable and requires careful handling and storage to mitigate safety risks. Another downside of the storage system is the significant amount of water requires throughout the whole system. It may lead to water scarcity and raise environmental and social concerns. Also, the infrastructure for storage, transport, and distribution is underdeveloped. This poses challenges for scaling up the P2G power plant's capacity, and the constructions of the infrastructure will lead to a heavy financial burden.

6 FURTHER TREND

As the worldwide shift towards renewable energy accelerates, P2G technology emerges as a pivotal solution. It presents a long-term storage option with its capability to convert renewable electrical energy into gaseous chemical energy carriers. This not only increases the flexibility of the electrical system but also facilitates integration across different energy systems (Götz et al., 2016). A lot of emphasis will be placed on research and development to develop new technologies that are more efficient and cost less. Regarding storage, there are diverse methods to store hydrogen and methane, including compression and liquefaction, for efficient utilization and transportation. The pathways for converting the stored gas back to electricity include fuel cells, gas turbines, combined heat and power (CHP) plants, and synthetic fuels production. Research and development are emphasized to offer varied options for re-converting stored hydrogen or methane back to usable electricity to meet different applications and operational needs (Götz et al., 2016).

On the development and implementation front, manufacturers are actively working on developing electrolysis technologies to improve efficiency and reduce costs. The United States, being one of the largest gas power generating countries, promotes the advancement of renewable energy technologies through federal funding and tax incentives. The European Union emphasizes research and development initiatives, with international collaboration efforts aimed at knowledge exchange and cooperation towards achieving renewable energy goals and mitigating climate change impacts.

In terms of technology feasibility, P2G plays a crucial role in enhancing the overall efficiency of energy systems, energy density, and the duration of energy storage. Actions are being take to solve the facing challenges related to energy loss during storage and the speed of electricity generation. Cost considerations include expenses for electrolyzes, methanation, renewable electricity, and operation and maintenance.

Overall, despite the challenges associated with energy losses and significant capital costs, P2G technology provides an effective solution for integrating intermittent renewable energy sources, enhancing grid stability and reliability, and achieving sustainability through the production of zero or low-carbon fuels. Moving forward, through technological innovation and optimization of operational processes to improve energy efficiency and density, and reduce system costs, P2G technology is expected to realize its greater potential in a renewable energy-dominated future (Götz et al., 2016).

7 CONCLUSION

P2G technology emerges as a promising solution for the renewable energy sector, including the intermittent nature of renewable sources and the need for long-term energy storage. P2G technology converts excess renewable electricity into hydrogen or methane, serving as an effective energy storage solution. Additionally, it significantly contributes to lowering carbon emissions within the energy system and improving grid stability. Despite its potential, P2G technology currently grapples with challenges such as low efficiency in energy conversion processes, high costs of electrolyzers and methanation technologies, and the necessity for significant infrastructure developments. Furthermore, the sporadic availability of renewable energy sources and the necessity for a stable supply underscore the importance of ongoing research, development, and scaling up of P2G technologies. Future trends in P2G point towards a focus on overcoming these challenges through technological innovations aimed at improving efficiency and reducing costs. The ongoing advancements in electrolysis and methanation processes, coupled with the development of more efficient storage and conversion methods, promise to enhance the viability and effectiveness of P2G systems. Moreover, international cooperation along with support from governments and industries is crucial in promoting the adoption of P2G technologies and aiding the shift toward a more sustainable and renewable-focused energy system. Ultimately, successfully integrating P2G technology into the energy landscape demands a multidisciplinary approach that merges advancements in engineering, economics, and environmental science. By continuing to address the current challenges and leveraging the opportunities for improvement, P2G technology can significantly contribute to achieving a sustainable, reliable, and low-carbon energy future.

AUTHORS CONTRIBUTION

All the authors contributed equally, and their names were listed in alphabetical order.

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