Method to Reduce the Cost of Proton Exchange Membrane Water Electrolysis

Yongqi Hu

Water Supply and Drainage, East China Jiaotong University, Luoshi South Road, Hongshan District, Wuhan City, Hubei Province, 430070, China

Keywords: PEM Water Electrolysis, Low Iridium Catalyst, Water Electrolysis, Stainless Steel Bipolar Plate, Hydrogen Production Efficiency.

Abstract: Hydrogen energy is a kind of clean, pollution-free, long-term storage of secondary energy. It plays a pivotal role in an energy system dominated by renewable energy sources to relealize emissions peaking and carbon neutrality goals. The production of green hydrogen is a prerequisite for decarbonization. Proton exchange membrane (PEM) hydroelectrolysis technology is an important way to produce green hydrogen using green electricity. However, the high cost restricts the popularization of PEM electrolysis technology. To reduce the cost of hydrogen fuel, it is necessary to strengthen the research on hydrogen production technology. The study found that the cost of electrolysis is mainly composed of two parts: equipment cost and energy cost, replacing expensive materials with low-cost materials to make electrolytic equipment and catalysts, and changing the current density and temperature can reduce the cost of pem electrolytic water. However, how to make the electrolytic equipment made of cheap materials meet or exceed the requirements of electrolysis still needs further research, but how to make the electrolytic equipment made of cheap materials meet or exceed the requirements of electrolysis still needs further research. This paper summarizes and analyzes the cost structure of PEM electrolysis and the ways to reduce the cost and looks forward to the improvement direction of PEM electrolysis system from two aspects of equipment cost and energy cost.

1 INTRODUCTION

Nowadays, the water electrolysis of hydrogen production process mainly includes alkaline water electrolysis (ALK), proton exchange membrane water electrolysis (PEM), anion exchange membrane water electrolysis (AEM) and solid oxide water electrolysis (SOEC). Among them, the proton exchange membrane water electrolysis hydrogen production technology has developed rapidly in recent years and is considered as one of the most promising water electrolysis technologies to produce hydrogen at this stage. PEM has compact structure, high current density, small floor area, fast response speed, electrolytic hydrogen production efficiency can reach more than 85%, wide power regulation range, good adaptation with fluctuating wind power and photovoltaic, high integration degree, can achieve long-term stable operation, and simple opening and closing operation (Ge et al., 2024).

However, because the PEM electrolytic cell is working in an acidic environment, platinum and iridium need to be used as catalysts, the bipolar plate and diffusion layer use titanium-based material (Sun et al., 2024), the device cost is about 3~5 times of the alkaline electrolytic cell, and the proton exchange membrane mainly depends on import, and the service life is short. This research looks for ways to lower the cost of PEM water electrolysis and advance the technology to produce more green hydrogen using PEM water lysis.

2 PROTON EXCHANGE MEMBRANE PRINCIPLE

PEM electrolysis of water for hydrogen production is an efficient electrolysis technology based on ion exchange technology. Membrane electrode assembly (MEA), which comprises of anode and cathode

Hu, Y.
Method to Reduce the Cost of Proton Exchange Membrane Water Electrolysis.
DOI: 10.5220/0013850300004914

In *Proceedings of the 2nd International Conference on Renewable Energy and Ecosystem (ICREE 2024)*, pages 127-132
ISBN: 978-989-758-776-4

diffusion layer, anode and cathode catalytic layer, and proton exchange membrane, is the essential component of PEM electrolytic hydrogen production. Schematic of PEM electrolysis cell can be seen in figure 1. Proton exchange membrane is a kind of polymer material, mostly using Nafion membrane (Song et al., 2024), which plays an important role in isolating the cathode and anode. The membrane used in electrolysis has selective permeability, which can conduct protons, but blocks the transmission of electrons and gases. The catalytic layer is where electrochemical reactions take place, and precious metals are usually used as catalysts. The diffusion layer is the intermediate layer between the collecting plate and the catalytic layer, which transmits water, gas and current. The electrochemical reaction occurs at the three-phase interface (Wen et al., 2023), at the junction of the proton exchange membrane, catalyst and water.

Water is decomposed with electricity, generating O2 and H+ on the anode side. The reaction occurring in the PEM electrolytic cell is performed as in equation (1) to equation (3).

$$\text{Anode: } 2H_2O \rightarrow 4H^+ + O_2 + 4e^- \quad (1)$$

$$\text{Cathode: } 4H^+ + 4e^- \rightarrow 2H_2 \quad (2)$$

$$\text{Whole reaction: } 2H_2O \rightarrow 2H_2 + O_2 \quad (3)$$

Specifically, in the proton exchange membrane electrolytic cell engineering, under the action of input power and catalyst, water molecules in the anode is decomposed into oxygen, H^+ and electron e^-, H^+ and water molecules into hydration ion H_3O^+, through the membrane to the cathode under the electric field, while the electron through the external circuit to leave the electrolytic cell to the cathode, hydration ion H_3O^+ and electron e-in the cathode and solution interface reduction reaction to produce hydrogen.

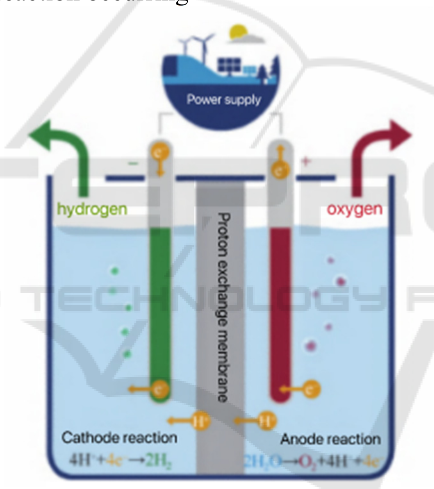

Figure 1: Schematic of PEM electrolysis cell (Song et al., 2024)

3 INFLUENCING FACTOR FOR PEM PERFORMANCE

The cost of hydrogen production consists of four parts: equipment cost, energy cost, other operating cost and raw material cost (Zhao et al., 2021). Among them, the energy cost, namely the electricity cost, accounts for the largest proportion, generally 40%~60% (Guo et al., 2020; H, 2021 & Zhang et al., 2021), or even up to 80% (The China Hydrogen Energy Alliance, 2020), which is mainly affected by the efficiency factor of electrolytic hydrogen production. As a result, one crucial metric to capture the economics of hydrogen production is its efficiency of production. In order to lower the cost of producing hydrogen from PEM water, it is crucial to optimize the system's operating parameters and boost production efficiency. The price of essential parts like bipolar plates largely determines the equipment cost. Because bipolar plates typically need to be coated with Au or Pt, their cost makes up roughly 53% of the total. The innovation of material technology to ensure the performance of bipolar plates is of great significance in terms of equipment cost reduction. Less affordable alternative materials are currently being studied. The rare metal Ir is indispensable for making membrane electrodes. Although the cost of anode catalyst is not large in the total cost of the electrolytic cell is large, the demand for iridium will increase greatly with the popularization of iridium technologies, such as PEM hydro electrolysis for hydrogen production (Figure 2).

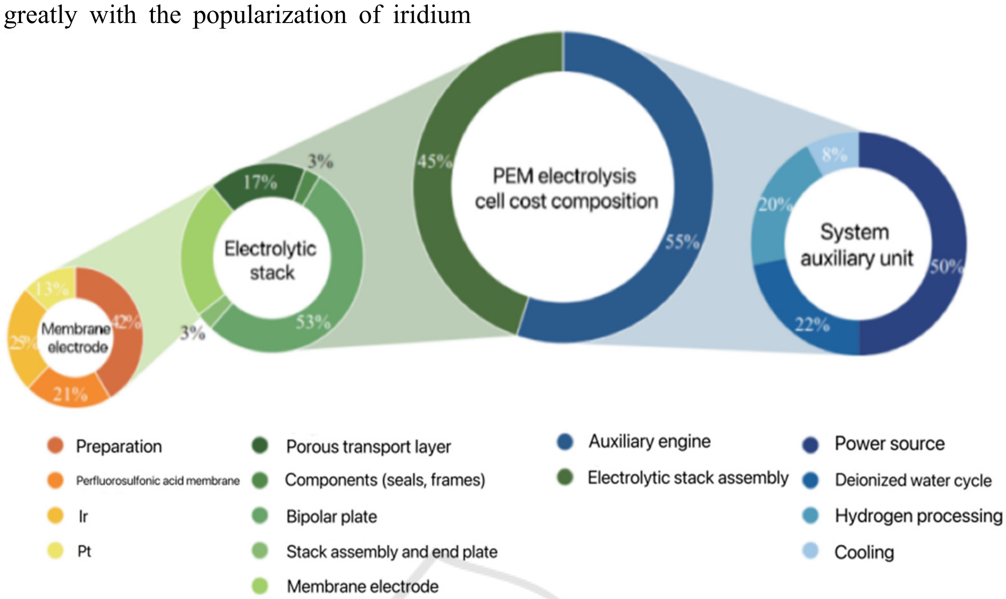

Figure 2: Cost break down for 1MW PEM electrolyser (International Renewable Energy Agency, 2020)

4 RESOLVENT FOR PEM PERFORMANCE ENHANCEMENT

4.1 Reduce the Equipment Cost

4.1.1 Change the Material of the Bipolar Plate

The bipolar plate functions to provide mechanical support to separate the membrane electrodes in the stack, conduct heat and current in the stack, and disperse water inside the PEM stack to deliver the generated gas to the outlet. Generally, with gold-plated or platinum-coated titanium plate as a bipolar plate. The oxide film on the surface of the titanium plate is low, and the oxide film on the surface must be removed before coating. In addition, electroplating needs to be punched on the surface, which will reduce the corrosion resistance, and the coating thickness needs to be increased to reduce the impact of the pinhole. The thick coating and the complex manufacturing process make the manufacturing cost of the bipolar plate high, accounting for 18%~21% of the total cost of the electrolytic cell (GAOAS et al., 2026). In recent years, researchers have tried to use non-precious metal material as the main material of bipolar plate and modify its surface. Rojas et al. (2021) used CrN/TiN, Ti/TiN, Ti and TiN as coatings, and different models of stainless steel SS321, SS316L, and SS904L as substrates. They were made by PVD method. After testing the performance of the electrolytic cell, they found that the performance of CrN/TiN combination was comparable to that of titanium-based bipolar plates coated with platinum.

4.1.2 Low-Cost HER Catalysts

Cathodic catalyst catalyzes the hydrogen evolution reaction (HER) in the process of water electrolysis, generally using platinum-based precious metal. The platinum-catalyzed hydrogen evolution is three orders of magnitude faster than the order of anode (Hong, Gu and Zhen, 2024). Although the amount of cathodic platinum is much lower than that of anodal iridium, the amount of Pt still will increase significantly with the large-scale application of PEM hydroelectrolysis. Therefore, the development of low Pt catalysts such as single atom catalyst, Pt alloy catalyst and non-PT catalyst can effectively reduce the cost of HER catalyst. Recently, it was found that materials such as phosphide (CoP), sulfide (MoS2) and nitride may replace Pt in the manufacture of cathode catalysts, which have higher activity, better stability and lower cost, although their performance is still inferior to that of Pt (Ma et al., 2022).

4.1.3 The OER Catalyst for the Low Ir

Compared with the cathode hydrogen evolution reaction, the reaction dynamics is slower and the working potential is higher (> 1.23V) (Hong, Gu and Zhen, 2024). The catalyst material needs to withstand the high potential, strong oxidation and strong acidic environment of the anode, which only some precious metals can meet.

The anode catalyst of PEM electrolytic cell commonly used in industry is mainly IrBlack and its oxide IrO_2. Considering the small Ir reserves and high price, the anode catalyst becomes one of the main obstacles to reduce the cost of PEM electrolytic cells. Research and development of high activity, high stability of PEM low iridium catalyst, is the key to realize the commercial application of PEM electrolytic cell. In recent years, doping or loading Ir and oxides become the mainstream research direction, usually known as low Ir catalyst, through suitable preparation process, screening and preparation performance of excellent anode catalyst, effectively reduce the amount of precious metal Ir.

Doping other metallic elements with Iridium to Form binary or ternary composite is a method to directly reduce the Ir content in the catalyst. Its form can be abbreviated as IrxMyNzOa, where M and N are other precious metals or non-precious metals. The addition of non-precious metals can effectively expand the surface area of the catalyst and further reduce the amount of precious metals without reducing the activity. Commonly used non-precious metals include Sn, Ta, Mo, Gd, Ce and other (Wang et al., 2020 & Wang et al., 2021).

In addition to direct bonding, the doped components can also adjust the electronic structure of Ir by introducing oxygen vacancies, such as doped Fe, Co, Ni, Zn, etc., which can produce large amounts of oxygen vacancies. The crystal phase changes caused by the introduction of other elements into the iridium-based catalyst can also effectively enhance the OER activity of the catalyst, such as the preparation of perovskite-type and pyrochlorite-type iridium-based catalyst (Hong, Gu and Zhen, 2024).

Loading the precious metal on the carrier is another effective way to improve the dispersion and reduce the dosage. It can also improve the utilization rate of Ir through the carrier and the carrier to improve the intrinsic activity of the precious metal. Due to the harsh OER reaction conditions, the electrode catalyst carrier needs to have both oxidation resistance, corrosion resistance and high electrical conductivity properties. However, common electrochemical carriers cannot meet the above requirements at the same time, such as cheap metals Ni, Fe, Co have good electrical conductivity but poor corrosion resistance; SnO_2, TiO_2, SiO_2 and others have acid resistance but are all semiconductors or insulators with poor electrical conductivity. Despite their corrosion resistance and high conductivity, carbon carriers can easily oxidize at high potentials. Therefore, materials such as doped metal oxides, metal carbide and metal nitrides have become the focus of supported iridium catalyst carriers in recent years (Hong, Gu and Zen, 2024).

4.1.4 Change the Proton Exchange Membrane Material

As a key component of PEM cell, the proton exchange membrane is one of the determinants of the cost and performance of PEM cell, and it acts as a barrier to the conduction of protons and the resulting gas produced. The key indicators of the proton exchange membrane include electrical conductivity, gas permeability, dimensional stability, and chemical stability. Generally composed of polymer backbone and negatively charged ion exchange groups, additional additives and enhancers can be added to improve membrane stability and reduce gas cross-diffusion.

The most widely used in the PEM electrolytic cell is the perfluoro sulfonic acid (PFSA) membrane, also known as the Nafion membrane. The membrane internal resistance is higher, the required electrolytic voltage is higher, and the electrolytic efficiency of the electrolytic cell is lower, but reducing the thickness of the proton exchange membrane will lead to gas penetration, reduce the purity of hydrogen production, reduce the chemical and mechanical stability of the membrane, and curtail the life of the electrolytic cell. In addition, Nafion film also has disadvantages such as high cost and fluorine pollution (Beyraghi et al., 2020). Therefore, it is significant to develop low-cost proton exchange membrane materials with high conductivity.

Hydrocarbon based membrane not only low cost, high conductivity, but also has high chemical stability and dimensional stability, but also can reduce gas penetration, is the first choice to replace Nafion membrane.

The development of hydrocarbon-based membrane and ionomer has great potential for cost reduction, which is of great significance for the construction of low-cost and high-performance PEM electrolytic cell (Ma et al., 2022). Among them, sulfonated polyaromatic ether is easy to synthesize and modify and has excellent film formation, which has wide applications in the preparation of proton exchange membrane.

4.2 Improve the Efficiency of Hydrogen Production

4.2.1 Relationship Between Current Density and Hydrogen Production Rate

According to ZHU et al. (2020), when current density rises, the electrolytic cell chamber's average electrolytic voltage rises steadily and the rate at which hydrogen is produced rises progressively as well. Figure 3 illustrates that the rate of hydrogen production is about 2.2 m3/h when the current density is 1.4A / cm^2. This is because the auxiliary equipment gradually reaches the rated load operation state, and the power utilization efficiency is gradually improved.

In general, the PEM hydroelectrolysis hydrogen production system has obvious technical economy when the current density is high than when the current density is low, which is consistent with the conclusion that GRESPI et al (2023) PEM system running 60kW.

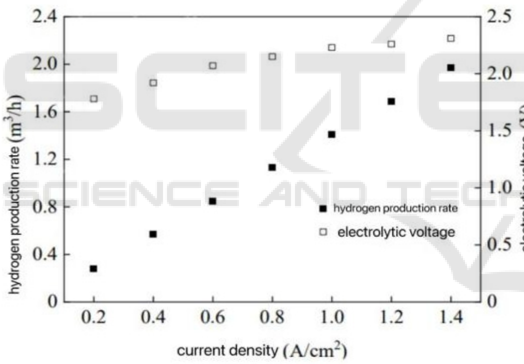

Figure 3: Relationship between current density and hydrogen generation rate (Zhu et al., 2024)

4.2.2 Relationship Between Operating Temperature and Hydrogen Production Efficiency

The holding current density is 1.4A / cm^2. The electrolytic cell's average chamber voltage sharply drops as the operating temperature rises, and the system's efficiency in producing hydrogen is likewise enhanced. Figure 4 illustrates that the efficiency of hydrogen production is around 57% at an operating temperature of 60℃. This is because raising the temperature lowers the active overpotential, quickens the rate of the electrochemical reaction, and enhances the electrolytic cell's performance. As a result, the system uses less energy to produce hydrogen per unit. OZDEMIR et al (2023) uses laboratory PEM electrolytic cell at different temperatures, and the test results are consistent with this test.

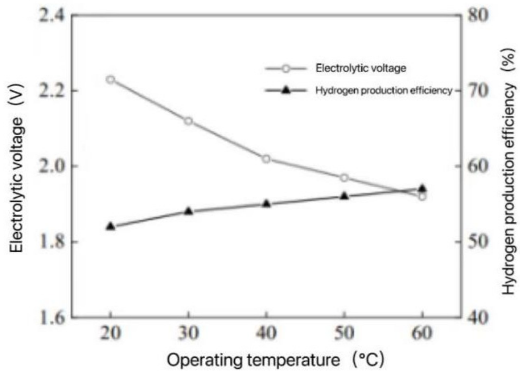

Figure 4: Cell voltage and hydrogen production efficiency (Zhu et al., 2024)

5 CONCLUSION

This paper aims to reduce the cost of pem electrolysis water, make hydrogen as a common fuel in the future, and promote the application and development of green hydrogen hydrogen production technology and equipment. In terms of equipment costs, bipolar plates, proton exchange membranes, and precious metal catalysts make the equipment cost of pem water electrolysis systems extremely high. Using stainless steel as the main material and surface modification to make bipolar plate, using cheap materials to make proton exchange membrane, using low-cost, low iridium catalyst play important roles in reducing the equipment cost. In terms of energy cost, current density and operating temperature are effective control parameters for optimizing hydrogen production efficiency. Hydrogen production efficiency is influenced by both current density and operating temperature. The peak working parameter of hydrogen production efficiency appears at the current density of 1.4A /cm2 to 1.7A/cm2, and the best working temperature is about 60℃. Under these conditions, the hydrogen production efficiency can reach 50%-70%. Maintaining the optimal operating temperature and current density, and making the low-cost equipment achieve the same electrolytic effect as the original expensive equipment is a problem that needs to be overcome.

REFERENCES

Ge Shuqiang, Bai Jie, Ding Yongchun, et al. 2024 Development status and prospect of renewable energy hydrogen production technology and its main equipment *Journal of Taiyuan University of Technology* 1-39

Sun Hao, Wu Weining, Chen Lijie, et al. 2024 Overview on the development of new energy water hydrogen production technology *Journal of Power* 1-18

Song Jie, Gao Jie, Liang Danxi, et al. 2024 Study of proton exchange membrane *Power Construction*, **45** 58-78

Wen Chang, Zhang Bohan, Wang Yaqin, et al. 2023 Research progress of high efficiency proton exchange membrane water electrolysis technology *Journal of Huazhong University of Science and Technology (Natural Science Edition)* **51** 111-122

Zhao Xueying, Li Gendi, Sun Xiaotong, et al. 2021 Key technology and application progress of electrolytic hydrogen production under the target of "double carbon" *The Global Energy Internet*, **4** 436-446

Guo Xiuying, Li Xianming, Xu Zhuang, et al. 2020 Cost analysis of hydrogen production by electrolysis of renewable energy. *Energy Storage Science and Technology*, **9** 688-695

Hu Daling. SIEMENS energy Power-to-X solution.2021 Renewable Energy Hydrogen Production Forum, Shanghai

Zhang Xuan, Fan Xinye, Wu Zhenyu, et al. 2021 Hydrogen supply chain cost analysis and suggestions *Chemical industry progress* **41** 2364

The China Hydrogen Energy Alliance. 2020 China Hydrogen energy and fuel cell industry manual. Beijing

International Renewable Energy Agency. 2020 Green hydrogen cost reduction: scaling up electrolysers to meet the 1.5℃climate goal. AbuDhabi

Gagoas, Ansarsa, Saruhanb, et al. 2026 Protective coatings on stainless steel bipolar plates for proton exchange membrane（PEM）electrolysers. *Journal of power sources*, **307** 815-825

Rojasn, Sánchez-Molinam, Sevillag, et al. 2021 Coated stainless steels evaluation for bipolar plates in PEM water electrolysis conditions. *International journal of hydrogen energy*, **46** 25929-25943

Hong Siqi, Gu Fangwei, Zhen GJinyu. 2024 Development status and prospect of low-iridium hydrogen catalyst produced by PEM water electrolysis *Chemical progress* 1-15

Ma Xiaofeng, Zhang Shuhan, He Yong, et al. 2022 Research status and application prospect of PEM water electrolysis for hydrogen production technology *The Journal of Solar Energy* **43** 420-427

Wang Yahui, Hao Shaoyun, Liu Xiangnan, et al. 2020 Ce-dopedIrO(2)electrocatalysts with enhanced performance for water oxidation in acidic media *ACS Applied Materials & Interfaces* 12 37006-37012

Wang Yibo, Hou Shuai, Ma Rongpeng, etal. 2021 Modulating crystallinity and surface electronic structure of IrO2 via gadolinium doping to promote acidic oxygen evolution. *ACS Sustainable Chemistry & Engineering* **9** 10710-10716

Beyraghi F, Mirfarsi S H, Rowshanzamir S, et al. 2020 Optimal thermal treatment conditions for durability improvement of highly sulfonated poly (ether ether ketone) membrane for polymer electrolyte fuel cell applications *International journal of hydrogen energy* **45** 13441-13458

Zhu Ningwei, Zhao Jinghui, Xie Haiyang, et al. 2024 Effect of current density and operating temperature on the energy consumption of hydrogen production by PEM water electrolysis *New energy progress* 1-5

Crespi E, Guandalini G, Mastropasqua L, et al. 2023 Experimental and theoretical evaluation of a 60 kW PEM electrolysis system for flexible dynamic operation *Energy conversion and management* **277** 116622

Ozdemir S N, Taymaz I, Okumus E, et al. 2023 Experimental investigation on performance evaluation of PEM electrolysis cell by using a Taguchi method *Fuel* **344** 128021