Chapter 5
Hydrogen Production from Offshore Wind Power in South China

Zhibin Luo, Xiaobo Wang, and Aiguo Pei

Wind power hydrogen production converts the electricity generated by wind power directly into hydrogen through water electrolysis hydrogen production equipment and produces hydrogen that is convenient for long-term storage through water electrolysis. With the development of offshore wind power from offshore projects, construction costs continue to rise. Turning power transmission into hydrogen transmission will help reduce offshore wind power construction costs. This chapter analyses ways of producing hydrogen from offshore wind power, including alkaline water electrolysis, proton exchange membrane electrolysis of water, and solid oxide electrolysis of water. In addition, the chapter outlines economic and cost analyses of offshore wind power hydrogen production. In the future, with the development and progress of water electrolysis hydrogen production technology, hydrogen production from offshore wind power will be more economical and more practical.

Keywords: Hydrogen production, water electrolysis, offshore wind power

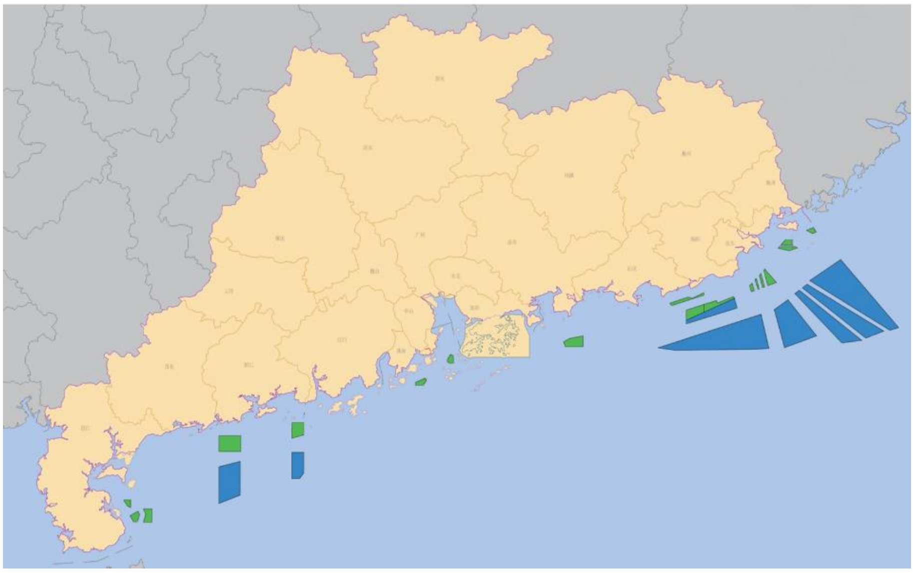
1. Introduction

In 2010, the first phase of the Shanghai Donghai Bridge Offshore Wind Farm, China's first domestic demonstration project of large-scale offshore wind farms, was officially put into operation. In the following years, the construction of offshore wind farms in coastal provinces such as Guangdong, Jiangsu, Zhejiang, and Fujian has gradually accelerated. Take Guangdong Province, which has a relatively large-scale offshore wind power development as an example. In 2012, the National Energy Administration approved the 'Guangdong Province Offshore Wind Farm Project Plan'. In 2016, the Guangdong Provincial Energy Administration initiated the revision of the 'Guangdong Province Offshore Wind Power Development Plan (2017–2030). According to the distribution of wind energy resources (Figure 5.1), taking into consideration factors such as construction conditions, industrial base supporting facilities, and project economics, the province plans to build 23 offshore wind farm sites with a total installed capacity of 66.85 million kilowatts (kW), including 15 sites in shallow offshore areas (within 35 metres of water depth), with an installed capacity of 9.85 million kW, of which 4.15 million kW is in eastern Guangdong seas, 1.5 million kW in Pearl River Delta seas, and 4.2 million kW in western Guangdong seas. Eight offshore deep water (35–50 metres water depth) wind farm sites are planned, with an installed capacity of 57 million kW, distributed in the eastern and western waters of Guangdong. Offshore deep water sites will be mainly used as reserve sites for the long-term development and construction of offshore wind power in the province. After the technology matures and the development and construction cost decreases, the development of offshore deep water sites will be promoted within reason.

While offshore wind power is developing rapidly, it is also facing several problems (Fernández-Guillamón et al., 2019; Babarit et al., 2018).

1) The plant site in the shallow offshore area is limited, with a capacity of 9.85 million kW, accounting for only 14.7%. Most of the wind farms in offshore shallow water areas with good wind resources have started construction, and the stock of offshore shallow water areas is limited.
2) Planning is mostly concentrated in deep water areas, with a capacity of 57 million kW, accounting for 85.3%. In the deep sea areas, offshore wind power construction costs are high, and construction is difficult. The construction costs of submarine cables, sea booster stations, and wind turbine foundations have doubled.
3) With the popularisation of offshore wind power, feed-in tariff policy subsidies have gradually reduced. According to the 'Notice of the National Development and Reform Commission on Improving the Policy of Wind Power Feed-in Tariff (Development and Reform Price [2019] No. 882)' issued by the National Development and Reform Commission in May 2019, onshore wind power will achieve parity on the grid in 2021. It is an inevitable trend to reduce subsidies for offshore wind power.
4) Irregular intermittent fluctuations of offshore wind power have a great impact on the grid.
5) In order to cope with the high proportion of new energy structures, grid companies will have higher requirements for the quality of new energy power connected to the grid, and management will become more stringent. The 'Implementation Rules for the Grid-connected Operation and Auxiliary Service Management of Wind Power Farms in the Southern Region' has been issued. The grid-connected wind power needs to pay auxiliary service fees to subsidise peak shaving costs (Franco et al., 2021).

Figure 5.1: Distribution of Planned Offshore Wind Power Plants in Guangdong Province (2017–2030)



The green areas indicate the shallow offshore areas, and the blue areas indicate the deep offshore areas.
Source: Guangdong Provincial Development and Reform Commission.

Hydrogen energy is a clean secondary energy, which has the advantages of wide source, high calorific value, high energy density, storable, renewable, electric and combustible, zero pollution, and zero carbon emission, amongst others (Veers et al., 2019; Kojima, 2019). It is known as controlling the earth temperature rise in the 21st century, the 'ultimate energy' to solve the energy crisis (Yan 2018; Abdin et al., 2020). The scientific and industrial circles recognise that hydrogen energy is the best solution to control the earth temperature rise and solve the energy crisis (Dincer and Acar, 2018; Dawood, Anda, and Shafiullah, 2020; Kovač, Paranos, and Marciuš, 2021). It is not only because hydrogen has a wide range of uses and involves all aspects of traditional energy, but also comes from its excellent storage properties. Hydrogen energy can effectively make up for the shortcomings of poor electrical energy storage and support the development of a high proportion of renewable energy (Liu, Feng et al., 2020; Liu, Wang et al., 2020).

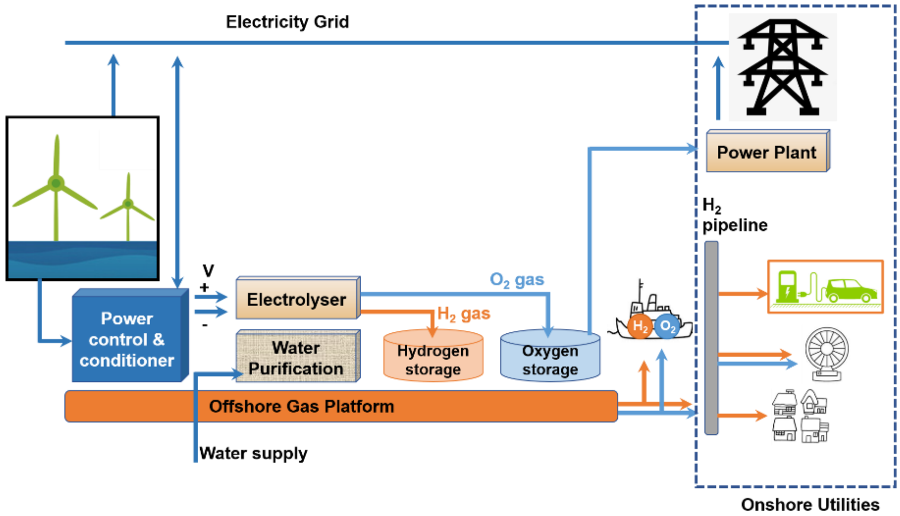
The hydrogen energy industry has developed rapidly and has been commercialised in the field of hydrogen fuel cell vehicles (Walter et al., 2010). In March 2019, Premier Li Keqiang mentioned 'promoting the construction of hydrogen refuelling and other facilities' in a government work report, and society's attention to hydrogen energy has further increased. Coastal provinces such as Guangdong and Jiangsu, which have large-scale offshore wind power construction, are also provinces with rapid development of hydrogen energy and fuel cells. The development of the hydrogen energy industry in cities such as Foshan in Guangdong Province, and Guangzhou, Yunfu, and Rugao in Jiangsu Province is leading the country and requires a large amount of high-purity hydrogen. The purity of hydrogen produced by electrolysed water from renewable energy reaches 99.999%, which can be directly applied to fuel cell vehicles, saving the cost of hydrogen production from fossil energy and the purification of by-product hydrogen. As a secondary energy source, hydrogen energy can be produced by reforming fossil energy sources such as coal, oil, and natural gas, biomass pyrolysis, or microbial fermentation. It can also come from industrial by-product gas such as coking, chlor-alkali, iron and steel, and metallurgy (Nagpal and Kakkar, 2018). The use of electrolysed water, especially in combination with renewable energy power generation, can not only achieve a green and clean life cycle, but also expand the use of renewable energy (Qi, Zhang, and Cao, 2018).

The consumption of hydrogen energy is currently mainly in the industrial sector. With the maturity of fuel cell technology, the transportation and energy fields are becoming a new breakthrough for development, realising the transition of hydrogen energy from auxiliary energy to main energy (Abe et al., 2019). At present, the United States, Japan, Republic of Korea, Europe, and China regard hydrogen energy as an important part of their future energy strategies. The application of hydrogen energy in the transportation sector is more advanced and technologically advanced in Japan. The consumption demand for hydrogen energy will grow rapidly in the future (Bartela, 2020; Goltsov and Goltsova, 2014). A large part of the consumption in the industrial sector comes from the production capacity of chemical by-products. To meet the new demand for hydrogen energy in the large-scale transportation sector, it is necessary to develop clean power electrolysis of water hydrogen production capacity.

According to the statistics of the China Hydrogen Energy Alliance, it is estimated that by 2030, China's hydrogen demand will reach 35 million tons, accounting for 5% of the final energy system, and hydrogen energy will account for at least 10% of the final energy system by 2050. The demand for hydrogen energy will reach 60 million tons of which 33.7 million tons will be used in the industrial sector and 24.58 million tons will be used in the transportation sector. Hydrogen in the transportation sector will account for about 19% of the energy consumption by 2050. It is the main driving force for the growth of hydrogen energy consumption in this sector. The increase in hydrogen energy consumption in the industrial sector will mainly come from the steel industry. By 2030, hydrogen energy consumption will exceed 50 million tons of standard coal and will further increase to 76 million tons. By 2050, hydrogen consumption in the transportation sector will reach 1 million tons of standard coal, the proportion of hydrogen produced from renewable energy will reach 70%. As far as Guangdong Province is concerned, primary energy sources such as coal and natural gas are scarce. Hydrogen produced from coal and hydrogen produced from natural gas cracking also violate the original intention of using hydrogen energy as a zero-carbon clean energy (Fouquet and Pearson, 2012). The amount of by-product hydrogen in Guangzhou is limited. Most of the by-product hydrogen has a low hydrogen concentration of 20–30%. The use of hydrogen in high-purity fuel cells requires complicated purification processes, and the purification costs are relatively high (Thomas et al., 2020). Guangdong Province has a good industrial foundation for hydrogen energy and fuel cells and requires a large amount of high-purity hydrogen. At the same time, Guangdong Province has the second Huizhou petrochemical base in the country and the third Maoming petrochemical base in the country, which has a 1 million-ton-level hydrogen supply demand every year. Hydrogen production from renewable energy could be the foundation to achieve green and sustainable development of the entire hydrogen energy industry chain (Jorge et al., 2019). Similar to the situation in Guangdong Province, hydrogen is urgently needed for its industrial development. However, hydrogen could not be self-sufficient in Guangdong due to the lack of primary energy sources such as coal and natural gas, and land-based renewable energy is limited (McDonagh et al., 2020). When ‘green hydrogen’ is an inevitable development trend, the development of hydrogen produced from offshore wind power is one of the key ways to solve the stable and reliable supply of hydrogen. The process of offshore wind power hydrogen production is outlined in Figure 5.2, reflecting the production process and basic uses of hydrogen. Combined offshore wind power and purified water from the sea, electrolysers can generate hydrogen and oxygen continually, which is used in offshore transportation and onshore utilities.

However, the rapid development will also be accompanied by the same dilemma faced by the wind power industry in other countries. Even Germany, which is known for its scientific planning and rigorous rigor, cannot escape. The lagging power grid construction speed cannot meet the rapidly expanding offshore wind power transmission needs. Direct hydrogen production by offshore wind power avoids the difficulties of power system construction and provides a feasible idea for the development of offshore wind power. Shell, Siemens, and TenneT jointly called on European governments to accelerate the use of offshore wind power hydrogen production technology research and proposed to consider launching offshore wind power hydrogen production project bidding, effectively alleviating the contradiction between the rapid growth of offshore wind power and the slower speed of power grid construction, thereby promoting European offshore wind power development. Shell, Siemens, and TenneT proposed the ‘Power to Gas’ programme, which is to balance the power supply and demand relationship in the power grid by producing hydrogen and oxygen through electricity. Besides, led by Ørsted, the largest developer of offshore wind power, with participation of the hydrogen energy company ITM Power and energy consulting company Element Energy, the project named ‘Gigastack’, a low-cost offshore wind power hydrogen production demonstration project, has received funding support of £500,000 from the British government.

Figure 5.2: Offshore Wind Power Hydrogen Production



Source: Dinh and McKeogh (2019).

Conventional ways of energy storage cannot provide long-term storage due to practical and economic limitations (Franco et al., 2021; Ghorbani, Zendehboudi, and Moradi, 2021; Delpierre et al., 2021). The development trend of hydrogen production from offshore wind power is inevitable. Therefore, this chapter first provides insight into the cost analysis of offshore wind power construction. Then, the chapter analyses and summarises the common ways of hydrogen production from offshore wind power, including alkaline water electrolysis, proton exchange membrane electrolysis of water, and solid oxide electrolysis of water. Electrolysed water hydrogen production equipment and economic analysis are introduced specifically. With the development and progress of water electrolysis hydrogen production technology, hydrogen production from offshore wind power will be more economical and widespread.

2. Cost Analysis of Offshore Wind Power Construction

Take an offshore wind farm in Guangdong Province as an example. The wind farm site has a water depth of about 31 to 37 metres (m), is 20 kilometres (km) offshore, with an installed capacity of 400 megawatts (MW), and a total of 73 wind turbines with a single capacity of 5.5 MW were built. The main equipment of the wind farm includes an offshore wind turbine generator (including foundations), a 35 kilovolt (kV) current collection submarine cable, a 220 kV sea booster station (two transformers), a 220 kV landing cable, and a land booster station (500 kV, share). The total static investment of the wind farm project is about CNY6.17 billion, and the static investment per kilowatt is about CNY15,500/kW.

Referring to the offshore shallow water area cost, the far-sea deep water area cost (assuming 60 km offshore, water depth 50 m), the procurement and installation cost of the landing submarine cable is three to four times that of the offshore shallow water area; the power generation equipment submarine cable procurement and installation cost is two to three times that of the offshore diving zone. The construction cost of the sea booster station in the deep water area is twice that of the shallow water area; the basic cost of the wind turbine is one and a half to two times that of the shallow water area; other costs are basically unchanged. The cost of the far-sea deep water sea ascending station, submarine cable, land ascending station (shared), and centralised control centre is approximately CNY1.70 million, accounting for about 22% of the total investment. The unit cost of offshore wind power in the deep water areas is CNY19,500/kW, which is 40% higher than that in the shallow water area of CNY15,500/kW, mainly due to the increase in the basic costs of submarine cables, sea booster stations, and wind turbines. For the wind turbine foundations, Europe has developed floating offshore wind power, which can reduce the basic cost of wind turbines in deep water areas. How to reduce the cost of submarine cables and sea booster stations is a topic worth studying.

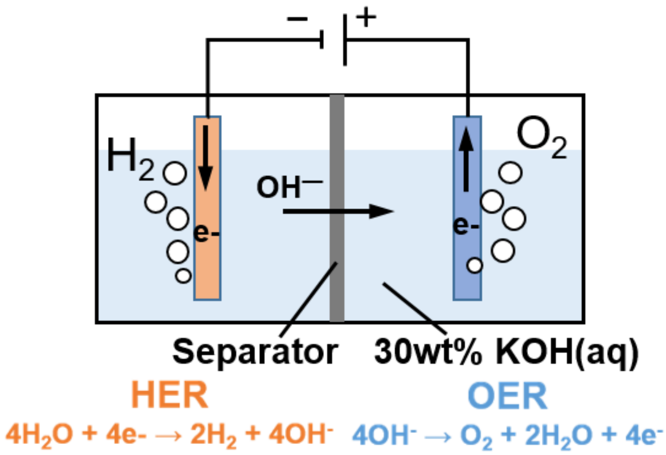
3. Electrolysed Water Hydrogen Production Equipment

Hydrogen production by electrolysis can be divided into alkaline water electrolysis (AEC), proton exchange membrane electrolysis of water (PEM), and solid oxide electrolysis of water (SOEC). SOEC has the highest electrolysis efficiency, followed by PEM, and AEC is the lowest. But SOEC is still in the laboratory stage.

3.1. Alkaline Water Electrolysis

An AEC device has mature technology, large capacity, and low cost, but a large volume. A schematic diagram of AEC is shown in Figure 5.3. In the past 10 years, China has planned to build many high-parameter, large-capacity generator sets. The generators need to be equipped with hydrogen cooling devices, which has driven the development of China's alkaline electrolysis hydrogen production technology. At present, China's alkaline electrolysed water hydrogen production technology and equipment manufacturing capabilities are in a leading position in the world, and manufacturers such as Suzhou Jingli, Tianjin Continental, and China Shipbuilding Industry Corporation 718 are in the leading position.

Figure 5.3: Principles of Alkaline Water Electrolysis

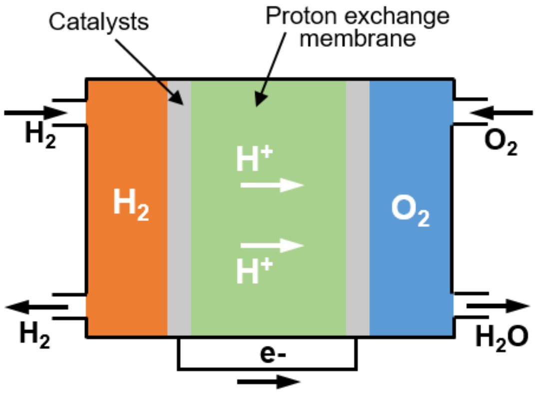


HER = hydrogen evolution reaction, KOH = potassium hydroxide, OER = oxygen evolution reaction.
Source: Prepared by authors.

3.2. Proton Exchange Membrane Electrolysis of Water to Hydrogen

PEM electrolysed water is a new technology from Canada (Zhao et al., 2021; Kilikovsky, 2017). It is the result of project research after 10 years. It is small in size and fast in dynamic response; but the price is relatively high in the initial stage of commercialisation. Hydrogen production by PEM electrolysis of water is the reverse process of proton exchange membrane fuel cell (PEMFC) power generation of hydrogen energy proton exchange membrane fuel cells for automobiles on the market. The main components include cathode and anode end plates, cathode and anode gas diffusion layers, cathode and anode catalyst layers, and proton exchange membranes (Figure 5.4) (Steinberger et al., 2018). Amongst them, the end plate plays the role of fixing the electrolytic cell components, guiding the transfer of electricity and the distribution of water and gas. The diffusion layer plays the role of collecting current and promoting the transfer of gas and liquid. The core of the catalytic layer is composed of a catalyst, electron conduction medium, and proton conduction. The three-phase interface formed by the medium is the core place where the electrochemical reaction occurs; the proton exchange membrane acts to isolate the gas generated from the anode, and the anode prevents the transfer of electrons, and transfer protons at the same time.

Figure 5.4: Principles of Proton Exchange Membrane Electrolysis of Water to Hydrogen



Source: Prepared by authors.

In PEM technology, hydrogen ions in water pass through a proton exchange membrane and combine with electrons to form hydrogen atoms, and hydrogen atoms combine with each other to form hydrogen molecules. This technology allows the electrolyser to work at high current density and high pressure, and is suitable for situations where space is limited, or when renewable energy is used to generate hydrogen when the electricity is unstable. The hydrogen produced by PEM electrolysed water has a high purity and can be directly used by vehicle fuel cells; the purity of by-product oxygen reaches 99.5%, which meets the standard for medical oxygen use. In 2014, Canada’s hydrogen's MW-level PEM electrolyser was officially put into production, which performed very well. The PEM water electrolysis device has been produced in China. The capacity of a single PEM produced by Shandong Saikesaisi and other manufacturers has reached the MW level. Table 5.1 shows the main technical parameters of the 200 normal cubic metre per hour (Nm^3/h) PEM device. In China, PEM electrolysed water hydrogen production technology has been applied in the military with good performance. However, PEM is in the early stage of commercialisation, the scale of mass production is small, the core equipment components need to be imported, and the high cost of catalysts make the current price high.

Table 5.1: Parameters of Unit Electrolysis Hydrogen Production Equipment

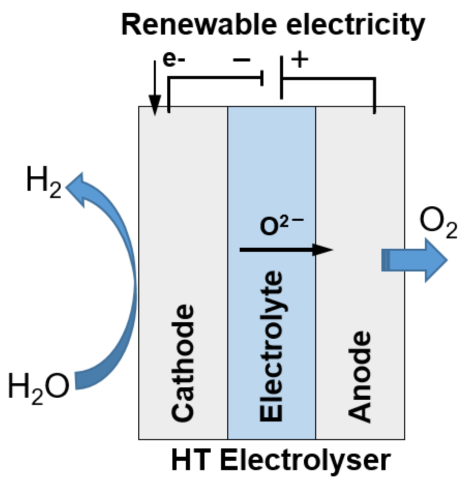
System	Power consumption per hour (kWh)	Hydrogen production per hour (Nm^3)	Water consumption per hour (kg)	Equipment cost (CNY million)	Civil engineering and installation cost (CNY million)	Area (m^2)
AEC	5000	1000	1000	8	2	800
PEM	1000	200	200	5	0.2	100

AEC = alkaline water electrolysis, PEM = proton exchange membrane electrolysis of water, kg = kilogram, kWh = kilowatt hour, m^2 = square metre, Nm^3 = normal cubic metre.
Source: Prepared by authors.

3.3. Hydrogen Production by Solid Oxide Electrolysis

SOEC uses solid oxide as the electrolyte material, works at a high temperature of 650°C–1,000°C, can use heat for electro-hydrogen conversion, has the advantages of high energy conversion efficiency, does not require the use of noble metal catalysts, and is highly efficient in three electrolytic water hydrogen production technologies (Figure 5.5) (Kim et al., 2018). SOEC is the only device that can directly electrolyse seawater to produce hydrogen (the alkaline electrolyser has completed the laboratory demonstration for direct electrolysis of seawater, 1,000 hours). The SOEC electrolysis process can simultaneously absorb CO_2 greenhouse gases, which is a 'negative carbon' emission process. SOEC technology is still in the laboratory stage. Research institutes such as the Huazhong University of Science and Technology have a technical basis for single electrolytic cells, but SOEC system integration has a certain gap with foreign technology. Its technological maturity requires catalytic verification of demonstration projects.

Figure 5.5: Principles of SOEC Water Electrolysis



HT = high temperature, SOEC = solid oxide electrolysis.
Source: Prepared by authors.

4. Offshore Wind Power Hydrogen Production

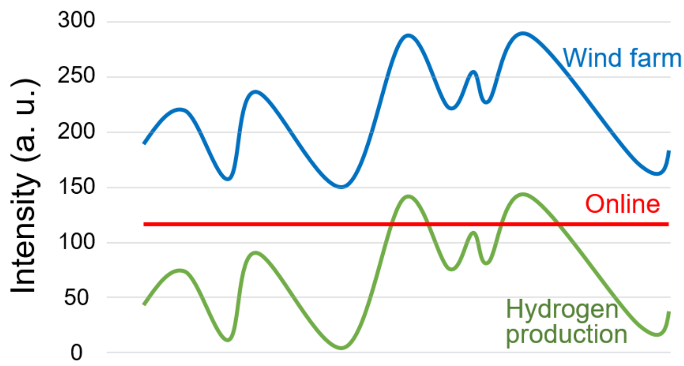
In view of the large impact of offshore wind power on the power grid and the high cost of construction in deep sea areas, research on offshore wind power hydrogen production technical solutions is conducted. Through the configuration of hydrogen production equipment, a flexible control system is constructed to efficiently, safely, and reasonably allocate on-grid electricity and hydrogen production and achieve optimal distribution of wind power and hydrogen production. By optimising the integration of hydrogen production equipment in the wind turbine tower, direct hydrogen production by offshore wind power on-site can eliminate the construction cost of submarine cables and sea booster stations and reduce the cost of offshore wind power. Through the study of offshore wind power storage schemes, zero wind power curtailment in offshore wind power is achieved, and the paid auxiliary service fees paid by wind power companies are reduced. The offshore wind power industry, the hydrogen energy industry, and the grid system promote each other, coordinate and orderly develop, and jointly build a 'clean, low-carbon, safe, and efficient' energy structure system (Apostolou and Enevoldsen, 2019).

In view of the impact of offshore wind power on the power grid and the high cost of offshore wind power construction in deep water areas, a hydrogen production plan for offshore wind power is proposed, combined with an analysis of the demand for high-purity hydrogen in the transportation and energy sectors. It is divided into four parts. Research on technical solutions for onshore hydrogen production by offshore wind power, research on offshore hydrogen production technical solutions with integrated hydrogen production devices in offshore wind turbine towers, research on off-grid direct hydrogen production technical solutions for offshore wind power, and off-grid offshore hydrogen production technology for offshore wind power. The program study has four steps, and it is studied step by step. First, for the large-scale construction of offshore wind power, the onshore hydrogen production station is configured to absorb fluctuating power, so that offshore wind power becomes a grid-friendly 'peak shaving power source'; then, it will study the integration of hydrogen production equipment in the wind turbine tower. From onshore hydrogen production to offshore hydrogen production, the integration of equipment is improved, the area is reduced, and the technical reserves for all hydrogen production of offshore wind power. For offshore wind power in deep water areas, a full hydrogen production plan for offshore wind power is proposed, and the energy storage system is configured to achieve off-grid hydrogen production by offshore wind power saves the cost of submarine cables and sea booster stations and reduces construction costs. Finally, for the medium and long-term deep water floating offshore wind power, SOEC hydrogen production devices that can directly electrolyse seawater are used to eliminate soft water supply pipelines and hydrogen and oxygen transmission pipelines to realise offshore wind power off-grid and offshore operation.

4.1. Onshore Hydrogen Production

In response to the problems caused by intermittent, volatile, and irregular offshore wind power grids, combined with shallow water offshore wind farms, a large-scale alkaline electrolysed water system is installed near the land riser station (a small amount of PEM electrolysed water equipment is equipped to achieve fast load tracking). The hydrogen production station uses electrolysed water to produce hydrogen to absorb part of the fluctuating power of offshore wind power, and the remaining stable power transmission network effectively solves the impact of offshore wind power fluctuations on the grid system (Figure 5.6). It is necessary to construct a flexible electrical energy control and distribution system to efficiently, safely, and reasonably distribute the grid power and hydrogen power. At the same time, the hydrogen production station can receive the control and dispatch of the grid system and control the hydrogen production consumption according to the grid load demand, indirectly achieving the goal of controlling the load of offshore wind power. The final goal is to achieve zero wind curtailment for offshore wind power and promote offshore wind power to become a grid-friendly peak shaving power source.

Figure 5.6: Load Distribution of Offshore Wind Power Generation Hydrogen Production



Source: Prepared by authors.

4.2. Offshore Partial Hydrogen Production

The power of offshore wind power fluctuates greatly. The selection of equipment, the calculation of the submarine cable section, and the capacity and foundation of the sea booster station are designed according to the maximum power generation capacity of the wind turbine. The probability of high load operation of the equipment is low, and the construction cost allocation is high. The PEM hydrogen production equipment is directly integrated in the fan tower barrel, shown in Figure 5.7, directly from the direct current (DC) bus bar of the fan to the electrolytic water hydrogen production device. The bottom of the fan tower barrel has a diameter of about 6.5 m, which is enough to accommodate 2400*1700*2000 size PEM electrolysis equipment (Figure 5.8). This solution has the following advantages while realising the function of hydrogen production peak shaving:

- The wind turbine generates hydrogen directly, eliminating the loss of power transmission and voltage conversion, and improving the power utilisation efficiency.
- It saves land and integrates the system in the wind turbine tower. The hydrogen production device could be highly integrated in the bottom of the wind turbine tower instead of building large-scale hydrogen production station onshore.
- The capacity of submarine cables and ocean booster stations can be selected and designed according to the conventional power generation of wind turbines, and the equipment utilisation is high and reduces construction cost.

Figure 5.7: Integrated Hydrogen Production at the Bottom of the Fan Tower

Source: The General Electric Company.

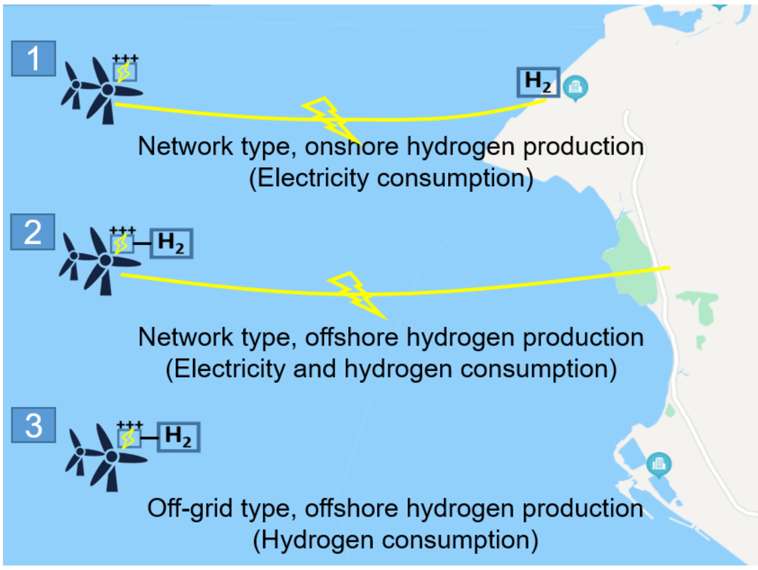
Figure 5.8. Equipment of 200 Nm^3/h (1 MW) PEM (size: 2400*1700*2000)

MW = megawatt, Nm^3/h = normal cubic metre per hour, PEM = proton exchange membrane.
Source: Shandong Saikesaisi Hydrogen Energy Co., Ltd.

4.3. Off-grid Direct Hydrogen Production

The PEM hydrogen production equipment with the same rated power generation capacity of the fan is integrated in the wind turbine tower. The power generation is onsite, and the hydrogen and pure oxygen are transported ashore to realise off-grid operation. It eliminates submarine cables, sea booster stations, and transformers in wind turbines, alternate current/direct current (AC/DC) inverters, and other equipment. It adds hydrogen production equipment, onshore pure water pipelines, and hydrogen and oxygen return pipelines. The AC power generated by the wind turbine is directly converted into hydrogen production equipment through the AC/DC inverter, eliminating the need for AC/DC inverters, wind turbine transformers, sea booster stations, submarine cables, land-based voltage reduction equipment, hydrogen production rectifier equipment, and other intermediate power transmission and transformation links to improve power utilisation. The produced high-purity hydrogen can be directly used in fuel cell vehicles to provide a green hydrogen source for the development of the hydrogen energy industry in Guangdong Province; the purity of oxygen can reach medical standards and has good commercial value. PEM electrolysed water hydrogen production equipment QLS-M200 (output 200 Nm^3/h) weighs about 8 tons, the 5.5 MW fan is equipped with six sets of configurations, the total weight is less than 50 tons, and the equipment is installed at the bottom of the tower. At the same time, the weight of the AC/DC inverter and 690 V-35 kV AC transformer can be omitted. Compared with the wind turbine with a weight of nearly 1,000 tons, the influence on the selection and design of the wind turbine foundation and the cost is almost negligible. The comparison of the different methods of electrolysis production and the according consumption is illustrated in Figure 5.9.

Figure 5.9: Different Methods of Electrolysis Production and the According Consumption

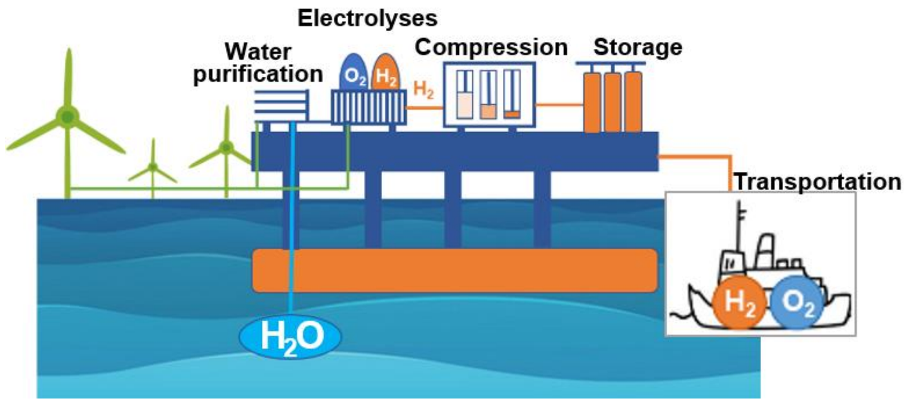


Source: Prepared by authors.

4.4. Off-grid Offshore Hydrogen Production

With the planning of offshore wind power to deep sea areas, large-capacity floating offshore wind power has become a trend and the diagram is shown in Figure 5.10. The world's largest single fan capacity GE Hailde-X reaches 12 MW, and the 8 MW fan produced by Shanghai Electric is the largest single fan capacity in China. SOEC is the only device that can directly electrolyse seawater to produce hydrogen. In the future, if the SOEC technology is mature, direct electrolysis of seawater to produce hydrogen, hydrogen and oxygen are compressed and liquefied on the offshore platform and then shipped, eliminating the need for water, hydrogen, and oxygen submarine pipelines to realise offshore wind power hydrogen production completely off-grid and offshore operation.

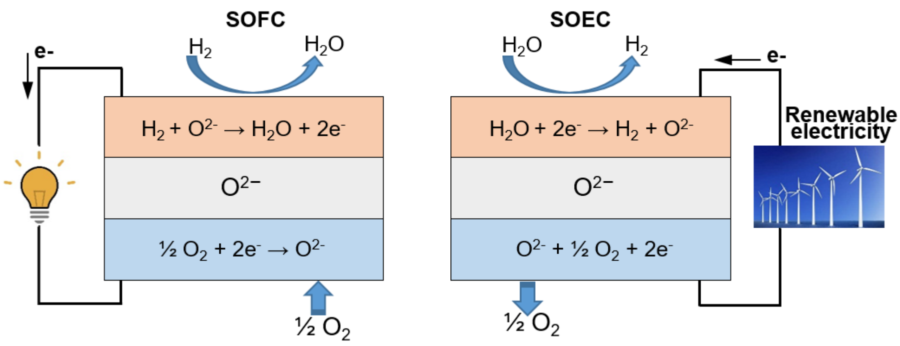
Figure 5.10: Schematic Diagram of the Isolated Island Operation Plan for Direct Hydrogen Production by Floating Offshore Wind Power



Source: Det Norske Veritas.

SOEC is the reverse process of solid oxide fuel cell (SOFC). SOEC electrolyses seawater to produce hydrogen, generates water through SOFC power generation, and produces hydrogen and stores energy while achieving desalination. It is suitable for islands and offshore oil and gas development platforms. The principle of SOEC and SOFC is demonstrated in Figure 5.11. Another working mode of SOEC is to convert CO_2 and H_2O into CO, H_2 synthesis gas and oxygen through the electrolysis reaction to efficiently use heat and electric energy to produce hydrogen while absorbing CO_2 greenhouse gases, which is a ‘negative carbon’ reaction process.

Figure 5.11: Principles of SOEC and SOFC



SOEC = solid oxide electrolysis, SOFC = solid oxide fuel cell.
Source: Prepared by authors.

5. Economic Analysis

The above four offshore wind power hydrogen production plans, combined with the feasibility, economy, market potential, and technical maturity of hydrogen production equipment, recommend all hydrogen production plans for offshore wind power off-grid. The following economic analysis is an analysis of all hydrogen production schemes for offshore wind ionisation grids.

5.1. PEM Hydrogen Production Equipment Price Forecast

There are three main reasons for the high cost of PEM electrolysis hydrogen production equipment: the low output and small scale of the equipment in the initial stage of commercialisation; the need to import core equipment components; and the high cost of catalysts. PEM electrolysis is the reverse process of PEMFC for proton exchange membrane fuel cells. Referring to the curve of PEMFC fuel cell's 10-year cost drop by 60% and the curve of lithium batteries 10-year cost drop by 70%, it can be inferred that with the large-scale production of PEM water electrolysis equipment, and the promotion of localisation of components and technological progress, the cost of PEM can be reduced to CNY10,000/Nm^3 in the next 5 years.

5.2. Cost Analysis of Offshore Wind Power Construction

This part analyses the cost of offshore wind farms in deep water with a scale of 400 MW, 73 sets of 5.5 MW wind turbines, 60 km offshore, and 50 m water depth. The cost of sea risers, submarine cables, and land risers (shared) is CNY1.7 billion. Direct hydrogen production from offshore wind power eliminates the need for AC/DC inverters and transformers in the wind turbines. The cost per unit is about CNY1.6 million, and the cost for 73 units is about CNY117 million.

According to the off-grid hydrogen production plan, offshore wind power costs CNY11 million PEM hydrogen production for a single 5.5 MW wind turbine, CNY803 million for 73 sets of wind turbines, and approximately CNY200 million for the procurement and installation of submarine water, hydrogen and oxygen pipelines, with a total cost of approximately CNY1 billion. The total cost of offshore wind power hydrogen production construction has been reduced by CNY800 million, and the cost is reduced by about 10%.

5.3. Economic Analysis of Electricity Sales versus Gas Sales

The current on-grid electricity price for offshore wind power is CNY0.85/kWh, and the electricity price consists of CNY0.4 on-grid fee and CNY0.45 government subsidy. According to the 'Notice of the National Development and Reform Commission on Improving the Policy of Wind Power Feed-in Tariff (Development and Reform Price [2019] No. 882)' issued by the National Development and Reform Commission, onshore wind power will achieve parity on the grid in 2021.

Offshore wind power PEM electrolysis hydrogen production, 4.5 kWh corresponds to 1 Nm^3 hydrogen. The 400 MW wind farm generates 3,000 hours of electricity annually and produces 23,800 tons of hydrogen annually.

Based on the hydrogen consumption of a hydrogen fuel cell bus of 8 kilograms (kg) per 100 kilometres (km), a bus generally runs about 250 km per day and consumes about 20 kg a day. Therefore, the electricity generated from a 400 MW wind farm can be used for annual operation of 3,300 buses. A taxi consumes 1 kg of hydrogen per 100 km, and a taxi generally consumes 6 kg per day for 600 kms. Thus, the electricity generated from a 400 MW wind farm can be used for annual operation of 11,000 buses or 100,000 family cars. Household hydrogen fuel cell passenger cars consume 1 kg of hydrogen per 100 km, and fossil fuel vehicles cost CNY50 per 100 km. The price of hydrogen at hydrogen refuelling stations is CNY40/kg (CNY3.6/Nm^3), and thus hydrogen fuel cell cars take advantage over fossil fuel vehicles without considering the storage and transportation costs of hydrogen. The price of hydrogen is calculated based on CNY2.5 or CNY2.0/Nm^3. The oxygen purity of the by-product of PEM water electrolysis hydrogen production reaches 99.5%, which meets the medical oxygen standard. It has good commercial value as medical oxygen and industrial oxygen. The oxygen price is calculated at CNY2.0 or CNY1.5/Nm^3. Table 5.2 shows the price of electricity and gas with and without offshore wind power subsidies. Due to the uncertainty of the subsidy policy in various period, we assume a different range of subsidies (CNY0.45, CNY0.35, CNY0.25 and CNY0.15) for calculation. The ratio of hydrogen and oxygen products is 2:1, and every 1 Nm^3 of hydrogen produced is accompanied with 0.5 Nm^3 of oxygen. Therefore, there are four combinations for every normal cubic hydrogen price, from CNY3.5 to CNY2.75. It is safe to conclude that selling hydrogen has more economic advantages than selling electricity without subsidies.

Table 5.2: Comparison of Electricity and Gas Prices with and without Offshore Wind Power Subsidies

Type	Amount	Price (CNY) Parity	Price (CNY) Subsidy	Total Price (CNY)	Note
Selling electricity	4.5 kWh	0.4	0.45	3.825	Need to pay ancillary service fees
	4.5 kWh	0.4	0.35	3.375	
	4.5 kWh	0.4	0.25	2.925	
	4.5 kWh	0.4	0.15	2.475	
	4.5 kWh	0.4	0	1.8	
Selling gas (take 4.5 kWh as reference)	1 Nm³ H_2	2.5	\	3.5	The prices for H_2 and O_2 are estimated based on the current market without considering the cost of storage, transportation, and refilling.
	0.5 Nm³ O_2	2	\		
	1 Nm³ H_2	2.5	\	3.25	
	0.5 Nm³ O_2	1.5	\		
	1 Nm³ H_2	2	\	3	
	0.5 Nm³ O_2	2	\		
	1 Nm³ H_2	2	\	2.75	
	0.5 Nm³ O_2	1.5	\		

CNY = yuan, kWh = kilowatt hour, Nm^3 = normal cubic metre.

Note: The cost of submarine integrated pipelines (hydrogen transmission) is much cheaper than that of submarine cables and sea booster stations (electricity transmission).

Source: Prepared by authors.

6. Conclusion

In summary, this chapter introduced the different ways of producing hydrogen and elicited offshore wind power technology. In addition, the important methods of offshore wind power hydrogen production were analysed, and cost and economic analyses were further carried out systematically. It can be concluded that combining the technical advantages of offshore wind power turbines, integrating PEM hydrogen production equipment in the wind turbine tower, and all off-grid hydrogen production solutions, is a promising route to produce hydrogen through offshore wind power technology. Moreover, this chapter suggests that by deploying offshore wind power hydrogen production models in deep sea areas in advance to solve the cost problem of offshore wind power construction, is an important path for the future development of offshore wind power hydrogen production.

This chapter also revealed that the transportation method of hydrogen is closely related to the offshore distance for the hydrogen production station. Submarine pipeline and liquid hydrogen ships are two promising hydrogen transportation methods for hydrogen production from offshore wind power. According to a preliminary estimation, selling hydrogen has more economic advantages than selling electricity without subsidies.

Further technical research is essential to push forward the development of the offshore wind power hydrogen production industry. Relevant policy support and more flexible financing methods are also necessary to compensate for the economic disadvantages in its early stage. In addition, the relevant standards for hydrogen energy, offshore wind power, and hydrogen production from offshore wind power also need to be improved as soon as possible to ensure the sustainable development of the offshore wind power hydrogen production industry.

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