Current situation analysis of electrohydrogen production under the background of "Carbon Neutralization"

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Abstract. As an energy carrier to promote the large-scale development and utilization of renewable energy, hydrogen energy is one of the means to drive China's economic development and energy restructuring, and to implement the "double carbon" goal. First, the development status of hydrogen energy at home and abroad has been sorted out, and the development paths of typical countries have been summarized briefly, the development trend of electric hydrogen production technology is studied and some suggestions are put forward to promote the further development of electric hydrogen production. The conclusion of this paper can provide reference for the hydrogen industry and the Energy Supply and energy use industry to implement the goal path of "carbon neutral".

1. Introduction

As a kind of clean energy, hydrogen energy not only has the unique advantages of high energy density, high combustion calorific value, wide source, storable, renewable, electrically combustible, zero pollution and zero carbon emission, but also is widely used in many fields, such as fuel automobile, aerospace, metal smelting, food processing, chemical production, residents' life, etc. China has entered a new stage of development, and economic and social development will promote high-quality development under the guidance of comprehensive green transformation. The development of hydrogen energy is of great significance to promote China's low-carbon energy transformation, guide industrial upgrading and promote the sustainable development of green economy. However, under normal temperature and pressure, hydrogen has extremely low density, low energy storage density per unit volume, flammability and explosion, which makes it difficult to transport and store hydrogen safely and efficiently. At present, hydrogen energy storage and transportation technologies mainly include gas hydrogen storage and transportation, liquid hydrogen storage and transportation, solid hydrogen storage and transportation, organic liquid hydrogen storage and transportation and natural gas hydrogen mixing pipeline transportation [1]. Compared with the storage and transportation of hydrogen energy, hydrogen production is the key to the development of the whole hydrogen energy industry chain, and it is also the focus of this paper.

Hydrogen production is the key to realize the development of the whole hydrogen energy industry chain and the premise of large-scale development of hydrogen energy [2]. Hydrogen production methods mainly include industrial by-product hydrogen, electrolytic water hydrogen, chemical raw material hydrogen, fossil fuel hydrogen and other new hydrogen production methods. At present, most of the hydrogen comes from fossil fuels. Hydrogen produced from fossil fuels is called "grey hydrogen", which has low cost but high carbon intensity. Hydrogen production from fossil energy and
industrial by-product hydrogen by adding carbon capture and storage technology is called "blue hydrogen", which greatly reduces carbon emissions on the basis of gray hydrogen [3]. Hydrogen is produced from renewable energy such as wind power and solar energy, and there is no carbon emission in the hydrogen production process. Hydrogen produced by electrolysis of renewable energy is called "green hydrogen", which will be an important direction of hydrogen energy development in the future.

Vigorously developing renewable energy is an important means to implement the goal of "carbon peaking and carbon neutralization" and promote the adjustment of energy structure. Electric hydrogen production is an effective way to solve the consumption of renewable energy. In the future, electric energy and hydrogen energy will jointly serve as the terminal form of green energy such as wind power and photovoltaic. By combing the development status of hydrogen energy at home and abroad, summarizing the development path of hydrogen energy in typical countries, deeply analyzing China's electric hydrogen production technology, this paper predicts the development trend of electric hydrogen production technology, and puts forward some suggestions for promoting the development of electric hydrogen production technology.

Table 1. Development of hydrogen energy in typical foreign countries.

| Country     | Overview                                                                                                                                                                                                 |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| United States | In 2003, the National Renewable Energy Laboratory launched a wind powered hydrogen demonstration project in the United States. The American fuel cell and Hydrogen Energy Association released the road map of hydrogen energy economy in November 2019. It aims that by 2025, the total hydrogen demand for various applications will reach 13 million tons, and there will be 125000 hydrogen fuel cell vehicles. According to relevant estimates, by 2050, hydrogen energy will help meet 14% of the final energy demand of the United States, equivalent to more than 2468 TWH per year. |
| Germany     | In 2013, Germany completed the first commercial multi-energy complementary project to produce hydrogen from wind power. The project is capable of providing 250 MWH of electricity and nearly 6,500 kg of hydrogen per year. Germany has designed a 1MW hydrogen storage system that can efficiently convert excess local wind power into clean hydrogen that can be stored and distributed over the long term using Germany's existing natural gas pipeline network, according to the demand of real-time electricity, the energy is reconverted into electricity through hydrogen application terminals such as fuel cells. In 2019, Germany began building offshore wind farms to produce hydrogen. By 2040 at the latest, Germany will build 10GW electrolytic "green hydrogen" capacity. |
| Japan       | Japan launched its "basic hydrogen strategy" as early as 2017, becoming the first country to elevate hydrogen into a national strategy. The infrastructure construction of Japan's hydrogen energy industry is currently in a leading position in the world. A considerable number of hydrogen filling stations in Japan are mobile stations and some are self-service stations in transport hubs such as airports, which fully play the role of convenient and instant hydrogenation. According to the analysis of some experts, Japan in the process of electric hydrogen production, can be faced with the lack of renewable energy power supply. |
| Korea       | As a solution to its energy transformation, South Korea is pressing ahead with the development of a nationwide hydrogen energy industry, with more hydrogen filling stations planned than in Japan. The government plans to expand fuel cell production to 15GW by 2040, to 6.2 million hydrogen fuel cell vehicles and to 1,200 hydrogen filling stations. |
2. Hydrogen energy development status of typical countries

2.1. Development of hydrogen energy abroad
The attention of various countries to hydrogen energy has reached a new peak. In the prediction of the proportion of hydrogen in energy consumption in 2050, the International Renewable Energy Agency thinks it is 12%, the Hydrogen Energy Council thinks it is 18%, and the target announced by the EU is 24% [4]. At present, more than 30 countries have formulated strategic plans for hydrogen energy. In general, Japan’s strategic basis for developing hydrogen energy is to improve energy security, consolidate industrial advantages, and focus on the application of hydrogen energy in transportation and construction; Germany’s strategic starting point is to promote energy transformation, carry out in-depth emission reduction, and put its foothold in the field of carbon emission reduction that cannot be solved by conventional technology; The development of hydrogen energy in the United States is to reserve strategic technology [5]. This paper briefly combs the development process of hydrogen energy in typical countries, and the summary is shown in Table 1.

2.2. Domestic hydrogen energy development
Domestic hydrogen energy development China's current hydrogen production is about 25 million tons, accounting for one-third of the world's hydrogen energy production. It is the largest hydrogen producing country in the world. Electricity to gas (PTG) or electricity to liquid mode with hydrogen production from renewable energy power as the core and gas to electricity mode with fuel cell power generation as the core are the focus of hydrogen energy layout of power companies at home and abroad [6]. The utilization of hydrogen energy is mainly concentrated in key fields such as industry, transportation and construction. The specific utilization of hydrogen energy in key fields is summarized as shown in Figure 1.

![Figure 1. Utilization of hydrogen energy in key areas.](image)

In recent years, China attaches great importance to the development of hydrogen energy, and the central and local governments have issued supporting policies. In 2020, the National Energy Administration issued the energy law of the people's Republic of China (Exposure Draft), which included hydrogen energy into the definition of energy for the first time. The development of hydrogen energy has been written into the government work report, and documents such as the development plan of new energy vehicle industry (2021-2035) have been issued to support the standardized development of hydrogen energy industry. By the beginning of 2021, more than 20 provinces and more than 40 cities have issued special plans and promotion subsidy policies for hydrogen energy, formulated objectives such as industrial output value and promotion of hydrogen fuel cell vehicles, and supported subsidies such as vehicle purchase and construction of hydrogenation stations. Since 2016, the construction of hydrogenation stations in China has accelerated. Sinopec plans to build 1000 hydrogenation stations or combined oil and hydrogen stations, 5000 charging and exchange stations and 7000 distributed photovoltaic power generation stations by 2025, making use of the layout advantages of the original 30000 gas stations and 870 gas stations, so as to provide comprehensive energy for the public.
3. Development status and trend analysis of electric hydrogen production technology

3.1. Application value analysis of electric hydrogen production technology

At present, China is actively deploying various tasks to implement the "double carbon" goal. The application of electric hydrogen production technology is of great significance to the development of energy supply side and end consumer demand side. It can be applied in many scenarios, such as renewable energy consumption scenario, power grid peak shaving scenario, user side comprehensive energy application scenario and so on.

The rapid development of hydrogen production by electricity can promote the large-scale consumption of renewable energy. China is rich in renewable energy. On the energy production side, the rich renewable energy will be transformed into electric energy for efficient utilization, so as to expand the consumption space for renewable energy. Electrolytic water hydrogen production has high purity, less impurity gas, easy combination with renewable energy and great development potential. It is one of the ways to realize the nearby and effective utilization of renewable energy. With the help of electric hydrogen conversion and storage devices, it can realize the storage and regulation of renewable energy power across seasons, industries and long cycles. Based on hydrogen production from electricity, large-scale renewable energy can be guided to convert from electric energy to terminal energy for industry, transportation, construction and so on. Hydrogen production by electricity and hydrogen chemical products provide a local way to absorb the abundant electric energy in the new energy base, and can also alleviate the long-distance transmission pressure of the power grid to a certain extent. At the same time, they can supply hydrogen for industries, transportation and other fields and reduce carbon emissions in various fields. In 2020, the national abandoned wind power will be 16.61 billion kwh, and 300000 tons of hydrogen can be produced according to the power consumption of electrolytic water hydrogen production of 5.5kwh/m³. According to the calculation that the average hydrogen consumption per 100 km of buses is 7kg and the average daily driving distance is 200km, it can be used as fuel for 60000 buses.

Hydrogen produced by electrolyzing water with renewable energy can provide a new technical means for peak shaving and valley filling in power grid. With the high proportion of new energy penetration and large-scale access, the stable operation of power grid is facing challenges, and the need to tap flexible resources on the demand side is becoming more and more urgent. Hydrogen energy can be used as a large-scale controllable load to participate in power grid peak shaving and frequency modulation, and support the stable operation of a high proportion of new energy power grid [7]. Because hydrogen is easy to store, it is conducive to improve the quality of wind power generation with high volatility. With the improvement of the maturity of electric hydrogen production and hydrogen storage and transportation technology and the decline of cost, it will provide the large power grid with cross space-time energy storage and peak shaving capacity, participate in the power grid peak shaving network, and improve the security and operation efficiency of the power grid. [8] At the same time, electric hydrogen production equipment, as a controllable load, participates in power auxiliary services and receives peak shaving subsidies.

Hydrogen production by electricity can promote comprehensive energy utilization and enhance the coupling between the power industry and other industries. Hydrogen can be used directly in pure form or as the basis for the synthesis of liquid or gaseous hydrogen-based fuels (synthetic methane or synthetic diesel) and other energy carriers [9]. As an efficient and clean secondary energy and a flexible and intelligent energy carrier, hydrogen energy has rich conversion channels and scenarios. It can span the three fields of electricity, heating and fuel, promote the integration of energy supply ends and improve energy efficiency. It is an important part of a diversified clean energy supply system. PTX technology converts electric energy into a variety of energy, realizes the conversion of electric hydrogen energy, and can build an integrated energy Internet with electricity as the centre and multi energy integration of cold heat electricity gas, so as to realize the flexible interconnection and joint regulation of power network, gas network, heat network and transportation network. The specific application scenario of PTX technology is shown in Figure 2.
Figure 2. PTX technology based on electric hydrogen production and its application.

At present, the task of carbon emission reduction is severe. Based on the green electric hydrogen technology, through the collaborative utilization of renewable energy, electricity and hydrogen, it can realize the substitution of fossil energy in the production process. This indirect power substitution can promote the transformation and upgrading of the industry to a certain extent and achieve green, low-carbon and high-quality development. Hydrogen metallurgy technology based on electric hydrogen production is a scheme to reduce carbon in the iron and steel industry: firstly, green electricity is used to produce hydrogen, secondly, iron ore is directly reduced to metal iron with hydrogen, and then the reduced products and scrap are added to electric furnace steelmaking according to a certain proportion. Electric hydrogen production is used to replace sintering, coking and blast furnace processes that are difficult to realize electrification, so as to help the iron and steel industry reduce carbon emissions. Similar to the iron and steel industry, the process flow of "green electricity to green hydrogen - green electricity to nitrogen-hydrogen nitrogen synthesis ammonia" based on green electric hydrogen, that is, using green electricity and green hydrogen to replace thermal power and coal, can help to reduce carbon in the synthetic ammonia industry. Hydrogen is produced by electrolyzing water, and methanol is synthesized from CO₂ and hydrogen, so as to realize green electricity instead of coal and promote carbon reduction in methanol industry.

Electric hydrogen production can effectively reduce carbon dioxide. Using renewable energy to produce green hydrogen energy is regarded as the key measure of power grid decarbonization and transportation decarbonization. Complete combustion of 1 kg of gasoline will emit 3.15 kg of carbon dioxide. The national abandonment of electricity for hydrogen production can replace 2060 KT of gasoline, which is equivalent to reducing 6490 KT of carbon dioxide. According to the calculation of carbon dioxide tax of 30 yuan/T, 195 million yuan of carbon tax can be saved. Using valley power to produce hydrogen to increase the proportion of renewable energy power generation can also effectively reduce the carbon dioxide emission of the power industry [10].

3.2. Economic analysis of electric hydrogen production

At present, the mainstream technologies of electric hydrogen production include alkaline electrolytic water hydrogen production, proton exchange membrane hydrogen production, solid oxide hydrogen production [11]. The scale of hydrogen production by electricity in China is small, and the economies of scale have not yet been shown. The characteristics of the three mainstream hydrogen production technologies are shown in Table 2.
Table 2. Introduction of electric hydrogen production technology.

| Technology                                      | Technical overview                                                                                                                                                                                                                                                                                                                                 |
|-------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alkaline electrolysis of water to produce hydrogen | The technology is mature, the application scale is large, the hydrogen production cost is the lowest, the maximum hydrogen production capacity is up to 1000m³/h, and the service life is up to 15 years. But this technology has some problems such as slow start, corrosion, complex maintenance and many parts of equipment. It is suitable for centralized stable hydrogen production. |
| Hydrogen production by proton exchange membrane (PEM) | The technology has the advantages of fast response, wide adjustable range, no corrosion, simple maintenance and few components. It is the main development direction of large and medium green hydrogen production technology in the future. However, the cost is high, and the PEM hydrogen production technology is expected to reach the level of alkaline electrolysis hydrogen production technology in technology and cost in 10 years. At present, the hydrogen production of advanced electrolytic cells in foreign countries can reach 200 ~ 400m³/h, and the service life can reach 60000 ~ 10000h. The utility model is suitable for the photovoltaic power generation system with small scale of installation and large fluctuation. |
| Hydrogen production from solid oxide (SOEC)       | The technology works at high temperatures with the highest hydrogen production efficiency, has the advantages of carbon-neutral circulation, and is more suitable for such systems as photothermal power generation, which generates high temperature and high-pressure steam, suitable for stable hydrogen production applications with high temperature start-up heat sources. Improving the durability of ceramic materials at high temperature is still the main problem to be solved in large-scale applications. |

According to the data and viewpoints of Literature [12], the cost of hydrogen production from municipal power is about 30~40 yuan/kg, while the cost of hydrogen production from coal is about 8~9 yuan/kg, and the comprehensive cost of hydrogen production from industrial by-product purification is about 10~16 yuan/kg. At present, wind power hydrogen production does not have economic advantages.

The cost of hydrogen production from electrolytic water mainly includes initial equipment investment, electricity, operation and maintenance expenses, asset depreciation, etc. The most important cost is electricity, which generally accounts for about 50%-80% of the total cost. Electricity consumption is about 3.5-5.5kwh per 1m³ of hydrogen production. Therefore, reducing the cost of electricity is an important link to reduce the cost of hydrogen production by electricity.

For hydrogen production from electricity supplied by the power grid, the effective use of low valley electricity price for hydrogen production is also a strategic choice to reduce the power cost, that is "hydrogen production from valley electricity price and energy supply from peak electricity price". According to the hydrogen production process of electrolytic water, the power consumption per 1m³ of hydrogen is about 5.5kwh. Valley power (general electricity price is about 0.3 yuan/kWh), plus the fixed cost other than electricity charge (0.3~0.5 yuan /m³), the comprehensive cost is 1.95~2.15 yuan/m³. According to the calculation of hydrogen density of 0.09kg/m³, the cost of hydrogen production by electrolysis of water in low valley is 21.7~23.9 yuan/kg [12]. Datong Datang Yungang photovoltaic hydrogen production project adopts the form of "spontaneous electricity during the day + low electricity at night", that is, it is used by itself during the day. At 22:00 p.m., the hydrogen production equipment is started during the low electricity period, and its power consumption cost is controlled at a low level.

At present, the cost of "green hydrogen" produced by electrolysis of renewable energy is high. However, if waste hydropower and surplus power are used for hydrogen production by water
electrolysis, the power cost required for hydrogen production is low and has certain economic advantages. If the electricity abandonment price of renewable energy is calculated at 0.1 yuan/kWh, the cost of hydrogen production can be reduced to about 10.6 yuan/kg [13]. Zhangjiakou Harper hydrogen production project uses large power grid for power supply, participates in the four-party power supply agreement ("government + power grid + power generation enterprise + user side"), trades with wind power plants on the trading platform, and uses some abandoned wind power [14]. According to the survey and calculation, the power consumption cost is about 0.3-0.36 yuan/kWh and the hydrogen production cost is about 40 yuan/kg. In the future, with the vigorous development of renewable energy, the cost of green hydrogen will be gradually reduced. It is estimated that when the power cost reaches about 0.2 yuan/kWh, its cost is equivalent to the cost of gray hydrogen, and its economic competitiveness will be further enhanced.

From the aspect of hydrogen production, the cost of hydrogen production from electrolytic water is 2~4 yuan/m³ (considering that the hydrogen density is about 0.09kg/m³), which is greater than that from industrial by-product hydrogen production (1.0~1.5 yuan/m³) and natural gas oil hydrogen production (0.8~1.5 yuan/m³). However, the transportation costs of industrial by-product hydrogen production and natural gas hydrogen production are 1.4~1.8 yuan/m³ and 0.9~1.9 yuan/m³ respectively, and the total cost of hydrogen transported to the hydrogenation station is 2.7~3.3 yuan/m³ and 1.7~3.4 yuan/m³ respectively. If the electrolytic water hydrogen production technology adopts wind power and photoelectric, there is still some room for decline in the future. The scheme of hydrogen production from renewable energy electrolytic water and injection into natural gas pipeline network provides a solution to the "gas shortage" of new energy and natural gas. According to the calorific value and combined with the local gas price, the scheme is economical when the hydrogen cost is less than 0.83 yuan/m³.

3.3. Existing problems
The development of hydrogen energy lacks top-level design and the market mechanism is imperfect. The development steps of the whole industrial chain such as hydrogen production, hydrogen transmission, hydrogen storage and hydrogenation do not match, the overall synergy is not high, the relevant supporting facilities are not perfect, the policy guidance is insufficient, and the market cultivation is not perfect, which restricts the large-scale development of hydrogen energy. Technological innovation needs to be broken through, and some key technologies are limited. Some core components still need to be imported and urgently need to be overcome.

3.4. Research and judgment of development trend
From the perspective of technical economy, the economy of hydrogen production by electricity will gradually appear. The domestic and large-scale production of electrolytic cell and other core parts will be gradually realized, the installation cost of electrolytic cell will be reduced, and the power consumption of electrolytic cell will also be reduced. In addition, electrolysis and photovoltaic power generation system have better adaptability, and the cost of electric hydrogen production will be gradually economical. At the same time, with the promotion of power market reform and the participation of multiple market entities in bidding, hydrogen production electricity with low electricity price can be purchased through market transactions and other business models. The reduction of electricity cost for hydrogen production further improves the economy of hydrogen production by electricity. China hydrogen energy alliance predicts that China's hydrogen production from renewable energy is expected to achieve parity in 2030.

From the perspective of policies, emission constraint environmental policies will promote the development of hydrogen production by electricity. The supporting policies related to "double carbon" have been gradually introduced and implemented. During the effective period of the policy, renewable energy has been vigorously developed and the electrification level has been further improved, which is indirectly beneficial to electric hydrogen production. After the launch of the carbon market, carbon tax has become a means of reducing carbon. Carbon tax is subordinate to environmental tax. It is a
specific tax based on the carbon content in fossil fuels or the amount of carbon dioxide produced by their combustion [15]. The purpose of collection is to reduce the emission of greenhouse gas carbon dioxide [14]. Levying carbon tax will have a great impact on fossil energy consumption. With the increase of carbon tax rate, end energy consumers will choose cleaner energy to replace fossil energy. Driven by the policy, the application scenarios of hydrogen production by electricity will be further enriched and the development of applications will be accelerated. For example, based on hydrogen production by electricity, microgrid with hydrogen fuel cell, hydrogen heating and hydrogen doped gas multi cogeneration as multiple energy supply forms may usher in large-scale development.

China hydrogen energy alliance predicts that under the carbon neutralization scenario in 2060, the scale of hydrogen production from renewable energy is expected to reach 100 million tons, accounting for 20% of the final energy consumption. Among them, the proportion of hydrogen used in the industrial field is still the largest, about 77.94 million tons, accounting for 60% of the total hydrogen demand; 40.51 million tons of hydrogen are used in transportation, 5.85 million tons in construction, and 6 million tons in power generation and power grid balance.

4. Conclusions and recommendations
The hydrogen energy industry at home and abroad is about to enter a stage of great development. At present, the application scale of electric hydrogen production is small, the economy is not strong, and there are many restrictive problems, but the application comprehensive value is high and the development prospect is promising. Under the background of "double carbon", hydrogen production by electricity technology can realize efficient energy conversion, promote the consumption of renewable energy, promote energy transformation, and be applied to industries, transportation, construction and other fields, providing an effective way to realize carbon emission reduction in key industries. In order to ensure the development of electric hydrogen production, the following suggestions are put forward.

Actively promote electric hydrogen production technology, encourage the development of new energy power generation and hydrogen production, increase the research and development of key materials and technologies for electric hydrogen production, accelerate the realization of independent and controllable technology, greatly reduce the cost of electricity, give full play to the rapid power regulation characteristics and long-term energy storage characteristics of green hydrogen, and "cut peak and smooth Valley" for the power system.

Strengthen the top-level design of hydrogen energy and improve the system and mechanism of hydrogen energy development. In the relevant energy development system, clarify the positioning of hydrogen energy, the centralized management department of hydrogen production, storage, transportation and application, and the competent department and relevant articles of association and legal system.

Strengthen the supervision of energy and environmental policies, implement the national key regional air pollution prevention and control and "double control" policies, and give play to the role of hydrogen energy as an important carrier for realizing the deep substitution of fossil energy and an important raw material in the industrial field.

Layout electric hydrogen integration infrastructure according to local conditions. Accelerate the application of hydrogen production and storage technology of source side renewable energy in areas rich in wind and light resources in the northwest. In demand intensive areas, encourage the construction of integrated hydrogenation stations of distributed hydrogen production and charging stations, build a demonstration project of integrated electric hydrogen hydrogenation stations, and provide services such as distributed electric hydrogen production, electric hydrogen production detection, electric vehicle power exchange / fast charging / hydrogenation integration for the region.
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