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Analysis of the Current Situation of Green Hydrogen Technology and Market Development

Ziyi Gan

College of Resources and Environment, South-Central Minzu University, Wuhan, China
202321241271@mail.scuec.edu.cn

Abstract. With the acceleration of the global energy transition process, green hydrogen, as a key carrier for achieving deep decarbonization, has drawn significant attention to its market size and regional competitive landscape. Although existing studies generally depict a promising market growth outlook, there is still a lack of in-depth analysis of the differentiated policy effectiveness driving the development of regional markets, which hinders the formulation of precise strategies. This study aims to systematically analyze the current industrial chain of green hydrogen technology and the current market development status of green hydrogen. To achieve this, the research comprehensively employs the comparative case analysis method. Firstly, it analyzes and summarizes the preparation and storage technologies of green hydrogen. Subsequently, it delves into the scale of the global green hydrogen market and makes predictions for its future scale, as well as analyzes the green hydrogen-friendly policies proposed by major countries and the shaping effect of these policies on the market structure. The research results show that, first, among the green hydrogen production technologies mentioned, alkaline electrolysis for hydrogen production is the most mature and has the highest degree of market application. Second, hydrogen has the potential for cross-regional transportation and large-scale storage. Third, the global green hydrogen market is growing exponentially. It is expected to exceed 19.92 billion US dollars by 2034, with the Asia-Pacific region firmly maintaining the largest regional market due to policy support. In summary, the green hydrogen market is currently in a period of rapid expansion driven by policies.

Keywords: Green Hydrogen, New Energy, The Green Hydrogen Market

1. Introduction

The greenhouse effect and global warming have become severe challenges for human society's development. Promoting the green and low-carbon transformation of the energy system is the core measure to address this challenge. With the in-depth implementation of the Paris Agreement, more than 130 countries around the world have set targets for carbon neutrality. However, there are many bottlenecks in the process of the transition to new energy. Renewable energy sources such as wind and solar power are characterized by intermittency and instability; electricity is difficult to directly replace fossil fuels in high-energy-consuming fields such as heavy industry, heavy transportation, and chemical synthesis.

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In this context, the strategic value of green hydrogen is becoming increasingly prominent. Green hydrogen refers to hydrogen produced through the use of renewable energy to generate electricity, and then using this clean electricity to electrolyze water. The entire production process of green hydrogen achieves zero carbon emissions. The efficiency of its preparation, storage, and transportation is 57.94%, 62.10%, and 95.01% respectively [1]. Compared with other energy sources, it cannot only convert redundant renewable electricity into chemical energy for large-scale and long-term storage, effectively solving the problem of temporal and spatial mismatch in energy supply and demand, but also can be directly used as raw materials and fuels in fields that are difficult to be electrified, such as the steel and chemical industries.

Given its significant potential, this article will analyze the green hydrogen technology and the current development status of the existing market. It mainly covers two parts: the green hydrogen industry chain and the current market status and competitive landscape. The green hydrogen industry chain includes the mainstream methods of green hydrogen production, storage technologies, and means. The market status and competitive landscape include the global distribution of the green hydrogen market and the relevant support policies of major countries. Based on the analysis of the global prospects and regional patterns of the green hydrogen market, the core purpose of this research is to systematically summarize the existing green hydrogen industry chain, in order to provide a theoretical basis and practical reference for understanding and optimizing the development path of the green hydrogen industry.

2. Green hydrogen industry chain

2.1. Preparation technology

2.1.1. Electrolysis of water to produce hydrogen

Electrolyzing water to produce hydrogen involves passing an electric current through water molecules, which then undergo a series of reactions to split the water into hydrogen and oxygen. ($2H_2O \rightarrow 2H_2\uparrow + O\uparrow$) Under different reaction conditions, the reactions that occur are different, and the products formed are also different. Under alkaline conditions, the hydroxide ions at the anode lose electrons and are oxidized to form oxygen. ($4OH^- + 4e^- \rightarrow O_2\uparrow + 2H_2O$) The water at the cathode is reduced to hydrogen gas. ($4H_2O + 4e^- \rightarrow 2H_2\uparrow + 4OH^-$) Under acidic conditions, the hydrogen ions at the cathode gain electrons and are reduced to hydrogen gas. ($4H^+ + 4e^- = 2H_2$) The anode water is oxidized into oxygen. ($4H_2O + 4e^- \rightarrow O_2\uparrow + 4H^+$)

AWE (Electrolysis for Water Energy) (as shown in Figure 1a) is the first generation of an electrolysis system. Its electrolysis reaction performance is affected by the activity of the point catalyst and the resistance of the electrolyte. Usually, KOH solution, which can reduce the resistance of the electrolyte, is used as the electrolyte. To effectively separate hydrogen and oxygen and prevent the occurrence of an explosion, while ensuring high OH- permeability, a porous polyphenylene sulfide mesh is commonly used as the separator in the market. At present, AWE technology in China is the most mature, and its industrial chain is relatively complete. Following closely is proton exchange membrane electrolysis (PEMWE) (as shown in Figure 1b), whose energy efficiency is expected to be less than or equal to 70% [2]. PEM uses a proton exchange membrane as the separator, which contains sulfonic acid groups and enables selective permeation of H^+ , thereby driving the electrolysis reaction. However, the selection of its catalyst material has limitations. To address this limitation, the anion exchange membrane water film (AEMWE) (as shown in Figure 1c) was developed. AEMWE uses an anion exchange membrane with selective transmission of OH^-

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as the separator, adjusting the local pH at the electrode-exchange membrane interface to be alkaline, thus allowing non-precious metals to be used as catalysts. To ensure the conductivity of AEMWE, KOH is used as the raw material water. In an alkaline environment, the hydrogen evolution catalytic activity is relatively low, and the hydrolysis rate is 30% to 50% of that in an acidic environment [3]. Finally, there is solid oxide hydration (SOWE) (as shown in Figure 1d), whose principle is to use high-temperature steam instead of liquid water as the raw material water. Yttria-stabilized zirconia is selected as the ion separator to ensure high efficiency of ion transmission. Although the operating pressure of the SOWE system cannot exceed atmospheric pressure, it has the potential advantage of reducing the required voltage for electrolysis to below 1.23 V [3].

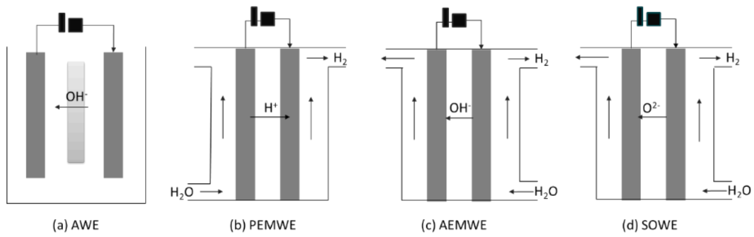

Figure 1. Theoretical diagrams of four types of electrolytic bath, (a) alkaline hydrolysis electrolytic bath; (b) proton exchange membrane hydrolysis electrolytic bath (c) anion exchange membrane electrolytic bath (d) solid oxide hydrolysis electrolytic bath (photopicture credit: original)

2.1.2. Biomass gasification

The process of generating hydrogen through biomass gasification involves sending biomass materials such as wood into the gasification chamber. In the gasification chamber, the oxygen supply is insufficient. Under these conditions, the biomass burns to produce gases. These combustible gases contain hydrogen, carbon monoxide, and other gases. Finally, the hydrogen is separated. The overall process consists of four stages: drying, pyrolysis, oxidation, and reduction. Along with the formation of coke, tar, and various gaseous products. The gasification technology can be classified into thermal decomposition gasification and reactive gasification based on the reaction mechanism. Among them, reactive gasification requires the use of gasification agents such as air, steam, or oxygen. The reactor types mainly include fixed bed, fluidized bed, and gas flow bed etc. The operation conditions, such as the type of gasification agent, reaction temperature, and catalyst usage, have significant impacts on the composition of the gas. For example, within the range of 700–900 ℃, as the temperature increases, the exothermic reaction between carbon and oxygen weakens, resulting in a decrease in the content of CO_2 [4]. The introduction of a catalyst can facilitate the cracking of tar and the gas reforming process, thereby helping to increase the hydrogen yield.

In Li Xueqin's research, it is indicated that there are still many challenges and issues that need to be addressed in the current technology of producing hydrogen through biomass gasification. For instance, during the process of hydrogen production from biomass gasification, various by-products are often generated, such as tar, fly ash, nitrogen compounds, and sulfides. These by-products not only reduce the overall efficiency of the gasification process but also enter the subsequent systems along with the gas, causing difficulties in gas-solid or gas-liquid separation and affecting the separation of hydrogen and the effectiveness of oxygen-enriched gas usage. Among them, the formation of particles such as carbon black significantly increases the complexity and operating costs of the dust removal process, and causes damage to key equipment such as gas turbines, thereby

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restricting the long-term stability and efficient operation of the gasification system. Tar, as a large molecule substance with benzene ring structures, is prone to liquefaction under low-temperature conditions, causing problems such as pipeline blockage, equipment corrosion, and instrument contamination. Studies have shown that the type of gasifier has a significant impact on the generation of tar. For example, the gas produced by the upward suction gasifier contains a relatively high amount of tar, up to 50 g/m³, while the fluidized bed gasifier has a relatively lower content, approximately 6 g/m³ [4]. The average content of tar produced by the downward-flowing gasifier is approximately 2 g/m³ [4]. Furthermore, the ash is prone to sintering, agglomeration and deposition at high temperatures, which further aggravates equipment corrosion. For instance, alkali metals can react with SiO_2 to form silicates, or combine with sulfur to form sulfates. These low-melting-point substances deposit on the reactor walls or particle surfaces, ultimately leading to sintering and a decrease in desulfurization efficiency [4].

2.1.3. Photocatalytic water decomposition for hydrogen production

The principle of photocatalytic water splitting for hydrogen production is similar to the photosynthesis process of plants in nature. Therefore, photocatalytic water splitting can be regarded as an artificial process that mimics natural photosynthesis. The specific process is that a certain amount of incident light causes the electrons in the valence band to transition to the conduction band, and these electrons combine with holes to form pairs. At the surface of the material, an oxidation-reduction reaction occurs with water molecules, resulting in the release of H_2 .

The core of photocatalytic technology is photocatalytic materials. The materials used for photocatalytic water decomposition to produce hydrogen currently include titanium dioxide, carbon nitride materials, sulfides, and new types of photocatalysts. Among them, titanium dioxide has the longest history, dating back to 1967. It was discovered in a laboratory experiment conducted by Tsuneyuki Fujimori that it absorbs light and decomposes water to produce hydrogen [5]. In the research conducted over the past ten years, black titanium dioxide has a wider range of light absorption compared to white titanium dioxide. It can absorb energy from both visible light and infrared light, and is used as an efficient photocatalyst [6].

2.1.4. Photocatalytic hydrogen production

Photocatalytic hydrogen production is an advanced oxidation process that combines photocatalysis and electrocatalysis. Under the combined drive of an external electric field and sunlight, this technology generates photogenerated electron-hole pairs on the semiconductor photocatalyst electrode ($e^- - h^+$). It also utilizes the electric field force to promote its efficient separation, thereby overcoming the problem of carrier recombination that is common in simple photocatalysis. Compared with traditional photocatalytic hydrogen production, the separation efficiency of electron-hole pairs has significantly improved. Compared with conventional water electrolysis for hydrogen production, it can decompose water at a lower applied voltage, effectively reducing the consumption of electrical energy.

A typical reaction system is mainly composed of a photoelectrode (working electrode), a counter electrode, a reference electrode, and an electrolyte solution. Taking a n-type semiconductor photovoltaic electrode as an example, under the combined action of light and an applied bias voltage, its band structure bends, and holes (h^+) migrate to the electrode surface to catalyze the oxidation of water to produce oxygen, while electrons (e^-) flow through the external circuit to the cathode and participate in the proton reduction reaction to generate hydrogen. This mechanism

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effectively inhibits the recombination of charge carriers, thereby improving the hydrogen production efficiency of the entire system.

2.2. Storage technology

Hydrogen is hailed as the "ultimate energy source for the 21st century", and its final product is water, truly achieving zero carbon emissions. However, one of the core challenges in the hydrogen energy chain is the storage and transportation of hydrogen. Due to its low energy density (0.003 kWh/L), gaseous state at normal temperatures, and flammable and explosive properties, the storage of hydrogen becomes a highly technical and challenging project [2]. Under atmospheric conditions, the density of hydrogen is (90 g/m^3). Its storage requires a large amount of space. Therefore, it is necessary to increase its density through compression. Currently, compressing hydrogen and storing it in steel cylinders is the commonly used method [2]. For different hydrogen application scenarios, the pressure for hydrogen storage is also different. For instance, hydrogen compressed under a pressure of 150-200 bar is typically used in industries or laboratories. Currently, the most frequently used hydrogen compression technology is the use of mechanical compressors [2]. Apart from the physical compression method, there are also technologies such as deep cryogenic liquefaction, material adsorption, and chemical reactions, as well as hydrogenation and dehydrogenation cycles, which store hydrogen in different forms (Table 1).

According to Yuan Tongbing's research, for high-pressure gaseous hydrogen, the project team independently developed a 700MPa IV-type composite material hydrogen storage cylinder, with a hydrogen storage density of 6.5wt%. For long-distance transportation, the vehicle they developed can transport hydrogen at room temperature, and can transport up to 1000kg of hydrogen to a radius of 500km [7]. For liquid transportation, their project vehicle can transport hydrogen up to the ton level, with a transportation radius of up to 1000 km. Moreover, compared to the compressed gas method, it can save 30% of the cost [7]. In the field of solid-state hydrogen storage, the hydrogen storage mass density can reach 5.5wt%, and the purity of hydrogen is as high as 99.99%. Moreover, it can complete the absorption and release of 90% of hydrogen within one hundred seconds [7].

Table 1. Comparison of main technologies for hydrogen energy storage

Hydrogen storage method	Theory	Advantage	Disadvantage
High-pressure gaseous state	Physical compression	Technologically advanced, with fast charging and discharging capabilities, and at a lower cost.	Low energy density
Low-temperature liquid	Cryogenic liquefaction	High volumetric energy density	The liquefaction process has high energy consumption, and there is also evaporation loss.
Solid-state hydrogen storage	Material adsorption, chemical reaction	High safety, high volume density, high purity	Low weight density, harsh conditions, and high cost.
Organic liquid	Hydrogenation and dehydrogenation cycle	Utilizing the existing facilities, which are safe and convenient	High dehydrogenation energy consumption, expensive catalysts, and low efficiency

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3. Market status and competitive landscape

3.1. Global market

The global green hydrogen market is experiencing a rapid growth trend overall. As shown in Figure 2, the vertical axis represents the market size (in units of billions of US dollars), and the horizontal axis represents the years (from 2024 to 2034). This market is expected to start at 87.8 billion US dollars in 2024 and undergo continuous and significant growth, reaching 165.85 billion US dollars by 2034. During the entire forecast period, the line graph of the market size shows a nearly exponential upward curve, especially after 2029, when the growth slope becomes steeper, indicating that the market expansion is accelerating.

The Asia-Pacific region is the core driving force and the largest regional market of the global green hydrogen market. Figure 3 also uses the vertical axis in billions of US dollars and the horizontal axis as years. The Asia-Pacific market is expected to grow from 58.4 billion US dollars in 2024 to 320.5 billion US dollars in 2034. Although its growth trend is consistent with the overall global trend, both being steadily rising, its scale is of great significance in the global context. This is clearly demonstrated in Figure 4. Figure 4 shows that in 2024, the Asia-Pacific region (Asia Pacific) holds a 43.2% share and occupies nearly half of the global market, making it the largest regional market. Followed closely are Europe (Europe) and North America (North America), while the share of the rest of the world (Rest of world) is relatively small.

In conclusion, the data clearly indicates that from 2024 to 2034, the global green hydrogen market will enter a golden development period with a scale exceeding one trillion US dollars and a significant annual compound growth rate. Among them, the Asia-Pacific region is not only the current market leader but will also play a core role in future growth, while Europe and North America will become important participants with the support of proactive policies.

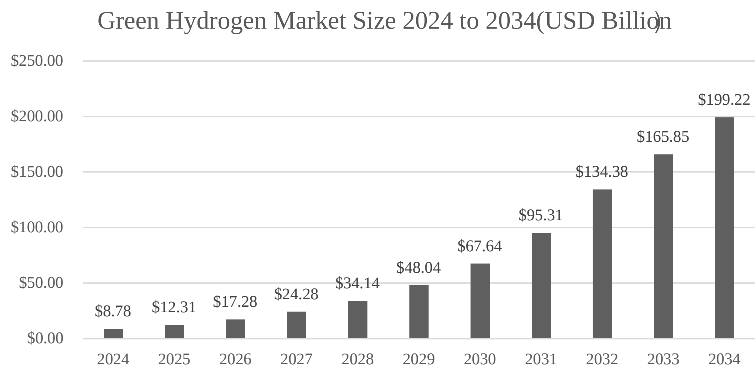

Figure 2. Global green hydrogen market size projection from 2024 to 2034 [8]

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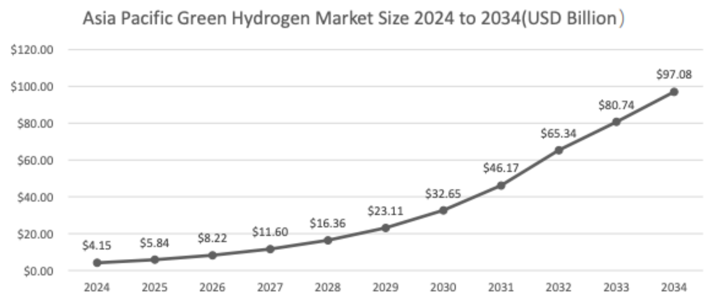

Figure 3. Projected market size of green hydrogen in the Asia-Pacific region from 2024 to 2034 [8]

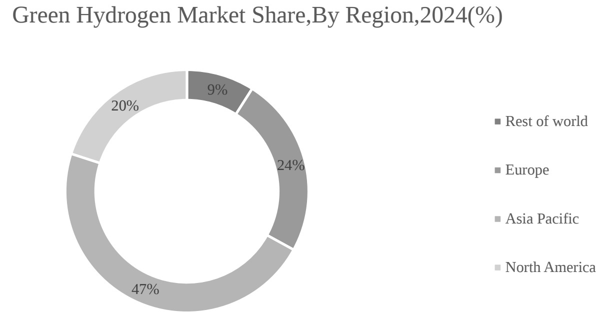

Figure 4. Proportion of green hydrogen market size in each region in 2024 [8]

3.2. Relevant policies of major countries

The major economies around the world are actively formulating policies to promote the development of the green hydrogen industry. The European Union has provided large-scale financial support and subsidies through the Clean Industry Agreement and the European Hydrogen Bank, and is striving to establish a hydrogen market mechanism. According to research, the UK is about to fully implement its green hydrogen standards, and from 2024 to 2048, this will increase the total system cost by 82 billion euros [9]. The United States, relying on the Inflation Reduction Act, provides tax credits for the production of clean hydrogen and promotes the construction of regional hydrogen centers, although the policy continuity faces certain uncertainties. China, mainly through local pilot projects, has carried out market-oriented reforms of factors in cities like Chengdu, encouraging social capital to invest in hydrogen storage and refueling facilities. China has constructed a top-level design through documents such as the Medium and Long-Term Development Plan for Hydrogen Energy Industry (2021-2035). According to official reports, China's hydrogen consumption ranks first globally in 2024, and the renewable energy-based hydrogen production capacity accounts for over 50% of the global total [10]. Japan has established a price difference support fund through the Hydrogen Society Promotion Law, attaching great importance to technical reliability and international cooperation. India has launched the "National Green Hydrogen Mission", focusing on policy frameworks, pilot projects, and research and development innovation, and emphasizing alignment with international standards.

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4. Conclusion

To achieve the dual carbon goals and comply with the Paris Agreement, the potential of the green hydrogen industry is gradually being explored. This article reviews the main hydrogen production technologies and their development processes through comparison, including four technologies in electrolyzing water to produce hydrogen: alkaline electrolysis, proton exchange membrane electrolysis, anion exchange membrane electrolysis, and solid oxide electrolysis; biomass gasification for hydrogen production; photocatalytic decomposition water for hydrogen production, and photoelectrochemical hydrogen production. Overall, the electrolysis cell technology for water electrolysis is the most mature and well-developed. Among them, the traditional alkaline electrolysis cell is widely used for water electrolysis. The biomass hydrogen production technology still has deficiencies in the generation and separation of by-products, resulting in low hydrogen energy efficiency and high production costs. Currently, it is still in the initial stage of commercialization. The photocatalytic decomposition hydrogen production technology and photoelectrochemical hydrogen production technology are not yet mature. The various storage technologies of hydrogen show that hydrogen has the potential for large-scale storage and cross-regional transportation. The existing high proportion of the Asia-Pacific region in the global market and the predicted expansion of the market size by nearly 25 times in the future, as well as the support of green hydrogen-friendly policies of various countries, all demonstrate that the green hydrogen industry is currently in a high-speed growth channel driven by policies and moving towards commercialization.

In the future, continuous tracking of dynamic factors such as the rate of decline in technology costs and international cooperation mechanisms will be crucial for grasping market developments.

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