Green Energy and Fuel Research (GEFR)

Review

A Brief Overview of Green Hydrogen on Production, Regulations, and Commercialization

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Abstract: With the deadline for meeting the net-zero emissions target by 2050 fast approaching, developing low-carbon energy sources has become a priority for governments worldwide. Green hydrogen is considered a promising low-carbon energy in response to the urgent need for net-zero energy. In this minor review, we have provided an overview of the progress made in the commercialization of green hydrogen, focusing on aspects such as manufacturing, regulations, and patent analysis for achieving environmental sustainability and net-zero emissions. In addition, the developemental progress achieved in green hydrogen by various countries such as Europe, United States, Japan, and South Korea is also highlighted, emphasizing their determination and commitment to exploit and incorporate hydrogen energy industry into existing energy policy. Key challenges identified include the difficulty of ensuring a stable supply source, optimizing transportation and storage infrastructure, and reducing energy consumption costs. The international regulations and patents related to green hydrogen are also discussed. This review provides insights into the current state of green hydrogen industries of various countries as we aim to achieve net zero emmissions and improve sustainability.

Keywords: green hydrogen; hydrogen energy; net zero; commercialization; regulations; environmental sustainability

1. Green Hydrogen Production

According to EN ISO 14067, green hydrogen is defined as hydrogen produced through green power, while green power is produced from the electrolysis of water using renewable energy power. The mature renewable energy infrastructure is crucial for developing the green hydrogen industry [1]. According to the data from the International Energy Agency, over 90% of the global hydrogen supply came from grey hydrogen in 2020, while the supply of green hydrogen accounted for less than 10% of the total [2]. The lack of stable green electricity is one of the main reasons for this issue. Currently, green hydrogen production can be categorized into four types, namely Solid Oxide Electrolyser Cells (SOEC), Electrified Steam Methane Reforming (ESMR), Anion Exchange Membranes (AEMs), and Direct Air Electrolysis (DAE) [1]. Among these, SOEC exhibits the highest hydrogen production efficiency, approximately 90% [1]. In 2024, three internationally renowned companies Topsoe (Denmark), ABB (Switzerland), and Fluor (United States) announced that they would develop SOEC technology jointly. Topsoe is distinguished for its technologies that reduce carbon emissions. ABB is a pioneer in the facilities of electrification and automation. Fluor is a frontrunner in engineering, procurement, and construction services. Topsoe is building its first SOEC factory in Herning, Denmark, which is expected to start operating by 2025 [3]. A search conducted on the database of Web of Science on 26 June 2024, identified 466 literatures related to SOEC and hydrogen production, 29 literatures related to ESMR, 561 literatures related to AEMs, and 103 literatures related to DAE. These indirectly indicate that the production technology of green hydrogen is still in the germination stage. Figure 1 shows the distribution map of green hydrogen literature using VOSviewer.

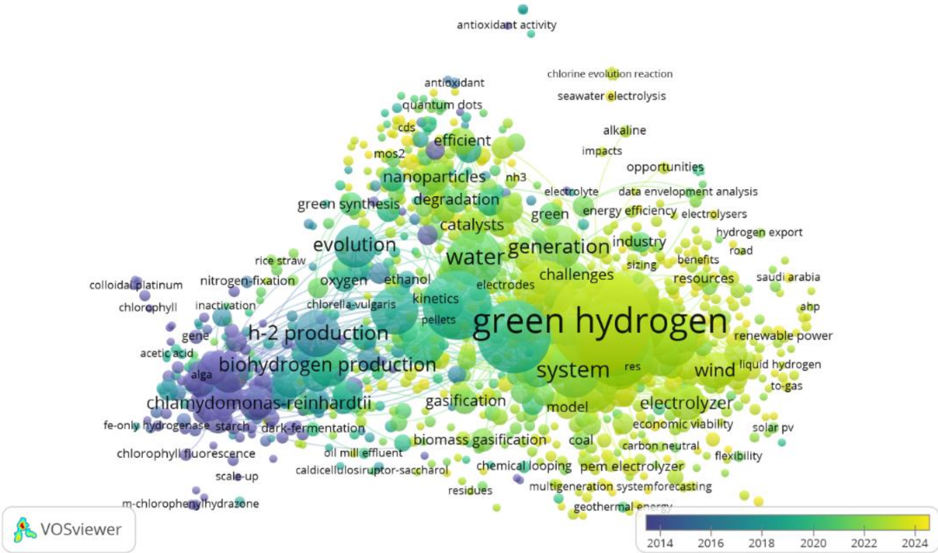

Figure 1. Distribution map of green hydrogen literature.

By examining the evolution of the global hydrogen energy industry chain, we identify three mainstream fields of energy, industry, and transportation as the current application fields of hydrogen energy [4]. The transportation field includes hydrogen refueling stations, hydrogen-powered cars, hydrogen buses, hydrogen trains, hydrogen aircraft, and others [5–9]. Synthetic fuel, power generation, and heating are the three applications of hydrogen in the energy field. While in the industrial field, hydrogen can be applied to industrial raw materials, ammonia production, refining, etc. [10]. Figure 2 shows the applications of green hydrogen in Power-to-X (PtX) mode. PtX is currently the primary model that is adopted by countries worldwide for the diversified application of hydrogen energy [11,12]. This model uses power generated from renewable energy to electrolyze water into hydrogen and oxygen. The produced green hydrogen is then stored or further utilized as a crucial resource in gaseous energy [13], hydrogen fuel cell vehicles [14], and the industry of using hydrogen to produce ammonia [15,16]. This PtX mode approach reflects the global trend towards the sustainable use of hydrogen energy. Under the PtX model framework, the Australian government has actively promoted projects such as Power to Gas, Power to Mobility, and Power to Ammonia in recent years. In 2021, the Danish Energy Agency projected the potential of the global PtX hydrogen market by 2035. They proposed that green hydrogen production is a mainstream potential market worth approximately 141.1 billion euros [17].

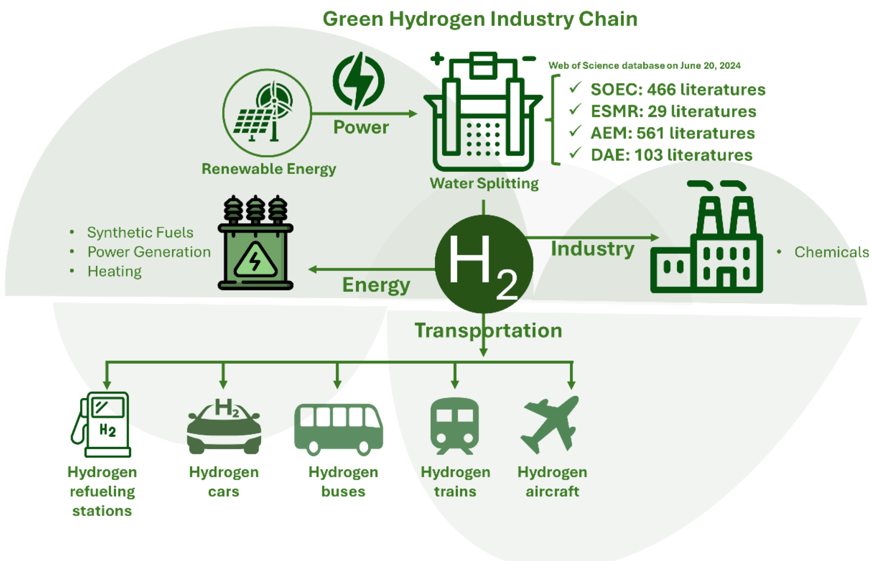

Figure 2. Applications of green hydrogen in PtX mode.

2. Regulations

Hydrogen is a colorless, odorless, non-toxic flammable gas [18]. Hydrogen comprises two hydrogen atoms, with a density of about 0.09 kg·m^{-3} under standard conditions (0 °C and 1 atm) [19]. Since its density is lower than air, which is 1.225 kg·m^{-3} [20], hydrogen disperses more readily than air. When using hydrogen, special attention should be paid to the possibility that combustion reactions can easily occur when the concentration of hydrogen in the air falls within the range of 4% to 75% [21]. Furthermore, hydrogen has an autoignition temperature of 576 °C in air [22]. These observations highlight the importance of safety in manufacturing, transportation, storage, supply, and end-use, with the aim of preventing potential fire or explosion.

Before investing in and developing the hydrogen energy industry, governments and enterprises worldwide consider risk assessment and safety levels as primary evaluation items. One crucial consideration is the selection of appropriate container materials to prevent hydrogen leakage caused by hydrogen embrittlement, thereby triggering potential safety hazards. In the past, many explosion accidents caused by hydrogen leaks have occurred. For example, in May 2019, a venture firm located in Gangwon Technopark, South Korea, experienced a hydrogen tank explosion, resulting in two fatalities and six injuries. The explosive force was potent enough to damage buildings located 100 m away from the site. The hydrogen in the tank was produced by water splitting. The primary cause of the explosion was the inadvertent infiltration of oxygen into the hydrogen storage tank. Typically, the storage tank for hydrogen, made of steel, had a capacity of 400 L and operated at a pressure of 1 MPa [23,24]. In June 2019, a hydrogen tank truck explosion occurred in Santa Clara, United States. The hydrogen tank truck was owned by Air Products and Chemicals, Inc. The explosion primarily resulted from a leak during the refueling of a hydrogen tank truck at a gas station. A subsequent fire was induced by this explosion. Fortunately, no casualties were reported. Following the occurrence of the event, to prevent the Butterfly Effect, firefighters conducted air sampling and thermal imaging to ensure the concentration of hydrogen in the air is outside the range of 4~75%. [25,26]. In the same month, a hydrogen equipment manufacturer in Norway encountered a hydrogen leakage issue at the Kjorbo hydrogen refueling station. This is caused by incorrect assembly of the plug in the hydrogen tank. Although the incident did not result in any disasters, the company was still fined $2.96 million by the local government. The above incidents have highlighted the importance of risk consideration and safety assessment in the hydrogen energy industry chain [27,28].

Figure 3 illustrates 65 international hydrogen energy standards. These standards cover different stages of the hydrogen energy industry chain. The stages include hydrogen manufacturing, quality, transportation, storage, supply, and end-use. These standards provide important guidance for the hydrogen energy industry chain. Among these standards, approximately 7% pertain to hydrogen manufacturing, including the currently relatively mature technologies, water splitting for hydrogen production, natural gas reforming for hydrogen production, and methane pyrolysis for hydrogen production. Purification is a crucial step in determining the quality of hydrogen, and the regulations listed include pressure swing adsorption systems, hydrogen composition, and analysis methods. Storage is a key factor that determines the developmental speed of hydrogen energy industry chain. The listed regulations are designed to prevent a decrease in the hydrogen storage capacity of vessels, which can occur due to hydrogen embrittlement. Finally, most regulations on hydrogen energy applications emphasize its use in power generation and transportation.

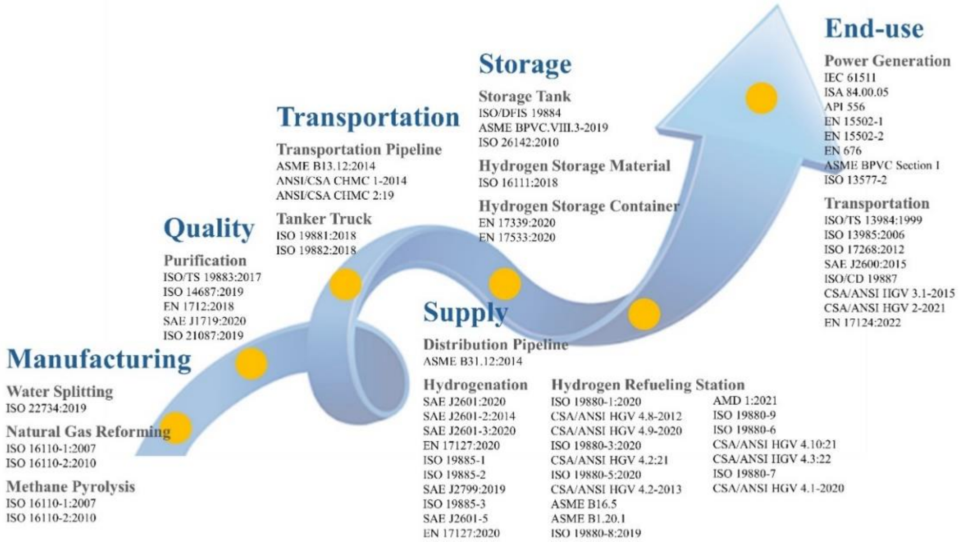

Figure 3. Hydrogen energy standards.

According to the Innography database, there is a total of 148,364 patents related to green hydrogen worldwide. These patents cover various aspects of green hydrogen technology, reflecting the widespread attention and investment in green hydrogen technology globally, as shown in Figure 4a. Among these patents, utility model patents account for more than 99%, design patents make up less than 0.1%, and even fewer are invention patents. This indicates that the number of utility model patents far exceeds that of other patents. Of all 148,364 patents, 99,266 have expired and approximately 33% are still valid. Figure 4b collects the number of green hydrogen patents over the past 20 years. Notably, the annual growth rate of applied patents has gradually increased since 2020. Before 2020, the annual growth rate of patents is just approximately 10–15%. China holds the most patents worldwide, with approximately 19,000. The United States follows with around 11,000 patents, South Korea with about 4600, Japan with around 4500, and Germany with about 1400. The rest of the countries all have fewer than 1000. This distribution of active patents suggests a concentrated development of green hydrogen technology in specific countries, such as China and the United States. Although China has the largest number of green hydrogen-related patents, most patents do not belong to industry but to universities.

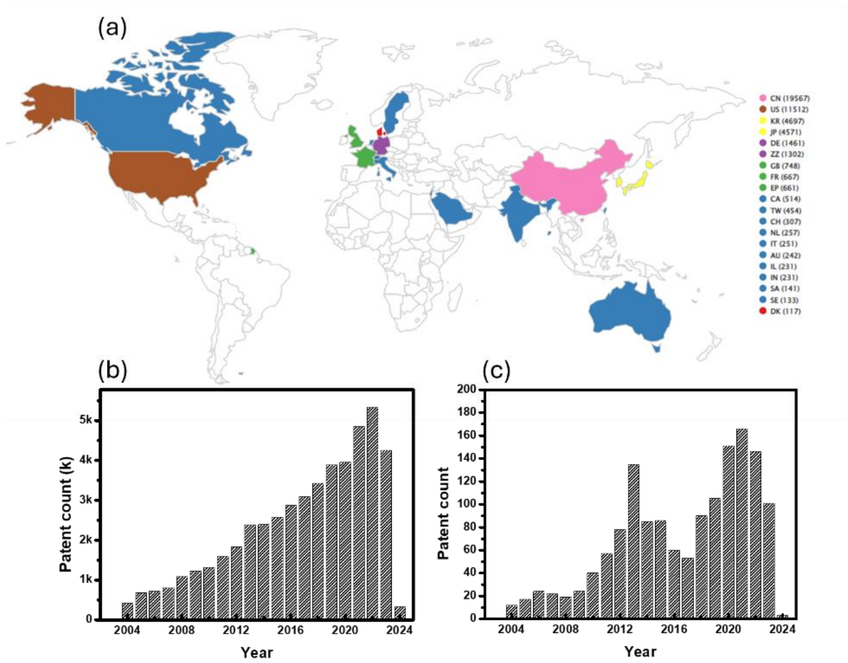

Figure 4. (**a**) Distribution map and the number of green hydrogen patents over the past 20 years (**b**) Global, (**c**) Samsung Electronics Co., Ltd. (Suwon, South Korea).

To understand the correlation between applied patents and industries, further discussion is needed to understand the implications of this distribution for the global green hydrogen industry. Samsung Electronics Co., Ltd. in South Korea currently holds the most patents about green hydrogen globally, with over 1400 patents. Following Samsung, the companies with the most patents are Universal Display Corporation with 855 patents, Sumitomo Chemical Company, Limited with 666 patents, LG Display Co Ltd. with 532 patents, and FUJIFILM Holdings Corp with 509 patents. An analysis of the patent portfolio of Samsung reveals that over 80% of the patent portfolio is related to the field of hydrogen separation membranes. Hydrogen separation membranes can effectively separate hydrogen from other gases during hydrogen production, to ensure the purity of the hydrogen produced, making it suitable for further use or storage. Figure 4c shows the number of patents about green hydrogen on Samsung Electronics Co., Ltd. over the past 20 years.

3. Commercialization

With the rapid development of the global hydrogen energy industry in recent years, hydrogen has become an important energy carrier. It has gradually expanded into many fields such as electric energy and kinetic energy conversion. Green hydrogen costs an estimated US$3.7 to 5.3 per kilogram, while gray hydrogen costs only US $1.6 per kilogram [29]. To accelerate the sustainable development of the hydrogen energy industry, the proportion of green hydrogen supply is expected to increase significantly to 25% in the next ten years [30]. By 2050, it is projected that the proportion of green hydrogen supply will exceed 62% and become the main source of global hydrogen supply [31]. According to the International Energy Agency, global hydrogen demand is expected to surge to 520 million tons by 2070 [32].

Governments worldwide have begun to formulate strategies for the green hydrogen industry and have made related announcements. For instance, the china government has initiated over 100 green hydrogen projects [33]. By 2050, the Canadian government anticipates hydrogen to account for 30% of its total energy use [34]. Australia has set a goal to become one of the top three hydrogen exporters in Asia by 2030 [35]. Japan is projecting an annual green hydrogen production of 3 million tons by 2030 [36]. The United States has set a goal to reach an annual production of 50 million tons by 2050 [37]. By 2030, Germany and the United Kingdom aim to achieve a green hydrogen electrolysis capacity of 10GW. Meanwhile, the European Union has set a target of 40 GW [38,39].

Numerous prominent companies significantly shape the green hydrogen production sector. Key players include Air Products and Chemicals (Allentown, PA, USA), H&R Olwerke Schindler (Hamburg, Germany), Siemens Energy (Taipei, Taiwan), Linde Gas (Munich, Germany), Toshiba Energy Systems & Solutions (Kawasaki-shi, Japan), Nel ASA (Oslo, Norway), Guangdong Nation-Synergy Hydrogen Power Technology (Yunfu, China), and Cummins (Columbus, IN, USA). These companies are making significant strides in advancing green hydrogen technologies and shaping the future of sustainable energy [40].

3.1. Europe

Since 2021, Europe has been the host to over half of the 131 hydrogen projects initiated worldwide, as per the International Hydrogen Energy Committee and McKinsey & Company's (Brussels, Belgium) data [41,42]. These projects cover multiple industrial applications such as hydrogen production, supply, and transportation. Upon commercialization of all hydrogen projects, the International Hydrogen Energy Committee estimates a total investment of 500 billion US dollars in the global hydrogen energy field by 2030, with Europe contributing about 45% of this investment [43].

Figure 5 shows an illustration of European investment in the hydrogen energy industry chain. The Green Energy Initiative agreement, signed by Chile and the Netherlands, paves the way for future exports of green hydrogen from Chile to the Netherlands and the rest of Europe [44]. The UAE, having signed a letter of intent with German and Japanese companies, is planning to set up a green hydrogen production demonstration plant in Masdar [45]. Germany has currently built 105 hydrogenation stations and plans to increase the number annually to reach the goal of 1,000 hydrogenation stations [46,47]. Germany and Saudi Arabia are set to collaborate closely on the production, processing, application, and transportation of green hydrogen. In terms of pipeline hydrogen transmission, the European GET H_2 plan has established a cross-border long-distance pipeline network. This initiative will enable the transportation of green hydrogen through pipelines by refineries, steel mills, and other factories by 2030, resulting in an estimated reduction of around 16 million tons in CO_2 emissions [48]. The UK has been invested 28 million pounds to the HyNet hydrogen energy project in 2020, with the hydrogen production capacity expected to hit 5GW by 2030 [49]. By 2050, hydrogen energy is expected to make up 20% to 35% of the UK's total energy consumption [50]. Italy initiated the SNAMTEC plan in 2019, targeting the deployment of 25,000 fuel cell vehicles by 2025 [51,52]. Concurrently, France has formulated a plan to establish an electrolyzer capacity of 6.5GW by 2030, aiming to produce 700,000 tons of renewable or low-carbon hydrogen and reduce CO_2 emissions by 6 million tons [53,54]. These initiatives reflect the global commitment to sustainable energy and carbon reduction.

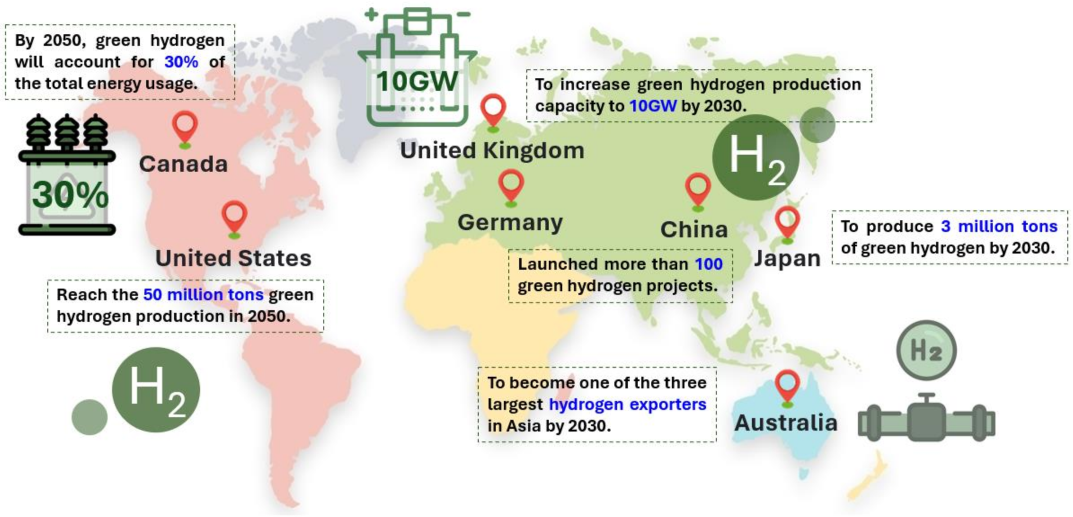

Figure 5. Illustration of European investment in the hydrogen energy industry chain [55–58].

3.2. United States

Since 1990, the U.S. government has formulated a series of policies to promote the development of the hydrogen energy industry [59,60]. In 2002, the U.S. Department of Energy released a document of "National Hydrogen Energy Roadmap" [61]. The main goal of this is to establish a systematic hydrogen energy system, thereby maintaining a leading position in the field of global energy technology in the long term. This reflects the strategic foresight of the U.S. in recognizing the potential of hydrogen energy and its commitment to leading the development of this technology on a global scale. In 2020, the U.S. Department of Energy released a report titled "Hydrogen Strategy - Enabling a Low-Carbon Economy" [62]. The report emphasizes the importance of advancing the technical research and application of integrating hydrogen into the fossil fuel. The report suggests that efforts to support hydrogen energy should be focused on areas such as power generation, transportation, heating, and industrial raw materials [62]. This reflects the strategic direction of the U.S. in promoting the development and application of hydrogen energy in various sectors. According to the "U.S. Hydrogen Energy Economic Roadmap Executive Summary Report" published by the Fuel Cell and Hydrogen Energy Association (FCHEA) [63], the U.S. Department of Energy provided annual funding of approximately 100 million to 280 million U.S. dollars for the field of hydrogen energy and fuel cells from 2010 to 2019. This demonstrates the U.S. government's emphasis on hydrogen energy and fuel cell technology, and its active investment of resources to promote the development of related technologies. By 2030, the US expects total hydrogen demand across various applications to exceed 17 million tons. By 2050, the US expects hydrogen to account for 14% of energy needs. The United States currently operates 17 MW of electrolytic hydrogen production projects and maintains a hydrogen pipeline capacity of 1.4 GW [63].

3.3. Japan

Since 1978, Japan established the Hydrogen Energy Association, which is dedicated to developing hydrogen-related technologies. This demonstrates Japan's long-term commitment in hydrogen technology. In 1981, Japan launched the Moonlight Project to develop fuel cells [64,65]. In 2002, the Japan government cooperated with Toyota and Honda car manufacturers to develop a fuel cell demonstration vehicle [66–69]. This means the beginning of the upcoming application of large-scale fuel cells. In 2013, Japan formally established hydrogen energy development as a national policy and began preliminary work on the construction of hydrogen refueling stations [70]. In 2015, Japan released the Hydrogen Energy White Paper and set hydrogen energy as the third main source of domestic power generation. In 2017, the Japanese Ministry of Transport and the Australian Maritime Safety Authority signed a hydrogen energy transportation safety standards agreement. These policies and agreements demonstrate Japan's proactive attitude and actions in developing hydrogen energy [71,72]. In 2019, the Japan government established the world's largest renewable energy water splitting hydrogen production base in Fukushima Prefecture. This base primarily uses solar panels and electrolyzers to produce hydrogen, which is then used to supply the energy needs of households and fuel cell vehicles [73,74]. Green hydrogen installations in Japan currently cost about 200,000 yen per kilowatt, with projections for a decrease to 50,000 yen per kilowatt by 2030. Concurrently, hydrogen production efficiency from water splitting is set to improve from the present 5 kilowatt-hours per cubic meter to 4.3 kilowatt-hours [75]. By 2030, Japan aims to mix 30% hydrogen into methane gas power plants and achieve an annual supply of hydrogen energy reaching 3 million tons [70,76,77]. By 2050, the annual supply of hydrogen energy is expected to reach 20 million tons [78–80]. The Japanese government is actively advancing hydrogen steelmaking and water-splitting hydrogen production technologies. They are also popularizing mixed hydrogen combustion power generation, all aiming to realize pure hydrogen power generation [75].

3.4. South Korea

Since 2012, the South Korean government has implemented a policy encouraging both public and private power companies to utilize renewable energy [81]. This policy aims to promote energy transition and reduce reliance on traditional fossil fuels. In 2018, the hydrogen economy was listed as one of South Korea's three strategic investment areas. In 2019, the South Korean government unveiled a national hydrogen economy roadmap, with the development of hydrogen-powered vehicles and fuel cells as the primary strategy [82]. In 2020, the South Korean government formulated the "Hydrogen Economy Promotion and Hydrogen Safety Management Act" to promote the hydrogen economy and safety management [83]. In 2021, the South Korean government announced a policy named 'Hydrogen Leading Country Vision', to dominate the global hydrogen energy market by 2030 [84]. South Korean plans to increase its annual production capacity of hydrogen fuel cell passenger cars to 100,000 units in 2025 and produce 6.2 million hydrogen vehicles by 2040 [85,86]. For the hydrogen production part, it is expected to produce 250,000 tons of hydrogen in 2030, with the cost per kilogram falling to 3500 won [87]. Further, hydrogen production is expected to reach 3 million tons in 2050 and the cost will be reduced to 2500 won [87]. To increase the production capacity of hydrogen vehicles, the South Korean government plans to establish more than 2000 hydrogen refueling stations nationwide [85].

3.5. Conclusions and Challenges

The accelerating impacts of global climate change have necessitated a worldwide shift towards sustainable energy sources. Hydrogen energy stands out among various low-carbon energy transition strategies. Not only is it a technical solution eagerly awaited by all stakeholders, but it also represents a green resource that can be used to compete on a global scale in the future. Independent hydrogen supply system using green electricity is a key link in the green hydrogen industry chain. In recent years, governments across the world have intensified efforts to construct renewable energy infrastructure to provide a stable source of green electricity for the future green hydrogen industry. Therefore, countries should incorporate hydrogen infrastructure and transmission backbone into the national infrastructure. Priority should be given to retrofitting existing gas supply networks in industrial or transport settlements to accommodate future hydrogen delivery needs. To establish a sustainable hydrogen energy ecosystem, three primary challenges must be addressed: securing a reliable supply, optimizing transportation and storage infrastructure, and reducing production costs.

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