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## Working Paper

# Role and development pathways of green hydrogen energy toward carbon neutrality targets

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**ADBI Working Paper Series**

**ROLE AND DEVELOPMENT  
PATHWAYS OF GREEN HYDROGEN  
ENERGY TOWARD CARBON  
NEUTRALITY TARGETS**

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**Abstract**

Hydrogen energy plays a pivotal role in the world's energy transformation, especially green hydrogen energy that produces no carbon emissions. In the future renewable-dominated energy system, on the one hand, green hydrogen energy can be used as long-term energy storage to cooperate with renewable energy with the characteristics of randomness and volatility, thereby improving the utilization rate of renewable energy and the reliability of the power grid; on the other hand, green hydrogen energy can help reduce carbon emissions in industries in which it is difficult to achieve deep decarbonization through electrification. To date, over 40 countries and regions have released strategies for developing hydrogen energy, highlighting its importance in promoting new energy policies. This paper provides a comprehensive review of the role and development pathways of hydrogen energy. The current status and development trends of green hydrogen production technologies, as well as the role and applications of green hydrogen energy, are analyzed in depth first. Then, the policies and related documents of hydrogen energy development in several countries and regions, including the European Union, the United States, Japan, the Republic of Korea, the People's Republic of China (PRC), and Australia, are surveyed. This paper provides several principles for promoting green hydrogen for countries aiming to formulate the development pathways of hydrogen energy.

**Keywords:** green hydrogen energy, production technologies, role and applications, development pathways

**JEL Classification:** O33

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# 1. INTRODUCTION

According to the United Kingdom (UK) Energy and Climate Intelligence Unit (ECIU) and other organizations, 137 countries had proposed carbon neutrality or net-zero emission targets by early June 2021 (Energy and Climate Intelligence Unit, Carbon Neutrality Coalition and Climate Action Tracker 2021). Hydrogen energy plays a pivotal role in the global pathway toward carbon neutrality. Recently, a series of major hydrogen energy projects have made significant progress, and hydrogen energy's footprint has spread across the globe. According to a study by Frost and Sullivan, with the support of government sustainability goals, the global hydrogen energy market will more than double in the next decade. By 2030, global hydrogen energy production will increase from the current 71 million tons to 168 million tons; and the industry's market revenue will increase from \$177.3 billion in 2020 to \$420 billion in 2030 (Frost and Sullivan 2020). Countries worldwide have considered the hydrogen-based economy to address growing concerns about carbon emissions, energy security, and climate change. The International Energy Agency predicts that the global demand for hydrogen energy will reach 520 million tons by 2070 (International Energy Agency 2020). As an essential step to address climate change and accelerate the energy transition, an increasing number of economies are giving more attention to developing hydrogen energy.

According to whether there is carbon emission in the process of hydrogen production, hydrogen can be classified as gray hydrogen, blue hydrogen, or green hydrogen. Gray hydrogen is produced through fossil fuel combustion and produces carbon dioxide emissions during the process. The vast majority of hydrogen is gray hydrogen at present, accounting for about 95% of the global hydrogen production. Blue hydrogen is made from natural gas through steam methane reforming or autothermal steam reforming. It uses advanced technologies such as carbon capture, utilization, and storage (CCUS) to capture greenhouse gases to reduce carbon emissions in the production process. Green hydrogen is made from renewable energy, such as by electrolyzing water through renewable power generation, with no carbon emissions in the production process. Green hydrogen will be the dominant trend in developing hydrogen energy in a renewable-dominated energy system. According to a recent report by Frost and Sullivan, green hydrogen will grow at a compound annual growth rate of 57% to 5.7 million tons by 2030 (Frost and Sullivan 2020). According to Goldman Sachs, the total potential green hydrogen market will probably reach \$250 billion by 2030 and \$1 trillion by 2050 (Goldman Sachs 2022).

Hydrogen could play a crucial role in achieving the goal of carbon neutrality, and many countries and regions have already released their hydrogen development strategies. However, there is currently no comprehensive review on future hydrogen development strategies. This study can provide a reference for countries and regions that have not yet published their hydrogen development strategies. This paper starts with policies and related documents on hydrogen energy development in major countries and regions worldwide. It then describes the role and development pathway of hydrogen energy in a renewable-dominated energy system with respect to the aspects of renewable energy hydrogen production technology and the development trend, the role and application fields of hydrogen energy, and the development pathways of hydrogen energy in different countries under the goal of carbon neutrality.

## 2. CURRENT STATUS AND DEVELOPMENT TREND OF GREEN HYDROGEN PRODUCTION TECHNOLOGIES

Currently, hydrogen produced from fossil fuels is still the main source of the global hydrogen supply. However, under the temperature control target of the “Paris Agreement,” renewable energy will gradually replace traditional fossil energy and occupy the dominant position in the energy system. The main carriers of renewable energy are electricity and hydrogen, and as a carbon-free industrial raw material, green hydrogen energy is irreplaceable in some applications. So using renewable energy to produce green hydrogen and promote the development of green hydrogen has become a meaningful way to achieve carbon neutrality.

### 2.1 Green Hydrogen Production Technologies by Water Electrolysis

The main technologies used in green hydrogen production include water electrolysis, photoelectrochemistry, cycle coupling of solar energy and thermochemistry, biomass gasification and steam conversion, and biomass pyrolysis (Wan, Xiong, and Wang 2022). Among them, water electrolysis is the most commonly used technology. Green hydrogen production technology by water electrolysis can be divided into three categories: alkaline, proton exchange membrane, and solid oxide, depending on the electrolyte material. A parameter comparison of three green hydrogen production technologies by water electrolysis is shown in Table 1 (Cheng, Liu, and Cao 2022).

#### (1) Green hydrogen production by alkaline water electrolysis

Alkaline water electrolysis uses the alkaline solution as the electrolyte. It is a mature technology and is the most economical way to produce hydrogen by water electrolysis. The electrolyte material is 20%–30% KOH solution or NaOH solution. The advantages of this hydrogen production are the long service life of its equipment (about 60,000 h) and the low cost (500–1,500 \$/kW). However, the electrolysis efficiency is relatively low (60%–75%), and the unit energy consumption is high (4.5–5.5 kWh/m<sup>3</sup>). Moreover, corrosive liquid exists during the production, thereby complicating later operation and maintenance.

#### (2) Green hydrogen production by water electrolysis with proton exchange membrane

Compared with alkaline water electrolysis, the electrolytic current density of this hydrogen production technology can be increased to 10,000–30,000 A/m<sup>2</sup>, the electrolytic efficiency can reach 70%–90%, and the unit energy consumption can be reduced to 3.8–5.0 kWh/m<sup>3</sup>. It has the advantages of a small size and fast response time, which is more suitable for the new energy generation scenarios with fluctuating, intermittent, and random characteristics. So it is seen as a promising approach in the field of green hydrogen production (European Commission 2014). However, most of the proton exchange membrane is made of precious metals, resulting in high equipment costs (1,100–1,800 \$/kW) and a degradation problem in the use process. The current technology has not yet achieved a breakthrough, making it difficult to achieve large-scale commercial applications.

## (3) Green hydrogen production by water electrolysis with solid oxide

Compared with the water electrolysis with a proton exchange membrane, this hydrogen production technology requires no precious metal catalyst and has the advantages of low energy consumption (2.6–3.6 kWh/m<sup>3</sup>) and high energy conversion efficiency (85%–100%). However, this technology needs to decompose water vapor at a high temperature (700–800°C) to produce hydrogen, which is still in the laboratory stage.

**Table 1: Parameters Comparison of Three Green Hydrogen Production Technologies by Water Electrolysis**

	Alkaline Water Electrolysis	Water Electrolysis with Proton Exchange Membrane	Water Electrolysis with Solid Oxide
Electrolyte material	20%–30% KOH or NaOH solution	proton exchange membrane	ceramic (Y <sub>2</sub> O <sub>3</sub> / ZrO <sub>2</sub> )
Operating temperature (°C)	60–90	30–80	700–1,000
Electrolytic efficiency	60%–75%	70%–90%	85%–100%
Energy consumption (kWh/m <sup>3</sup> )	4.5–5.5	3.8–5.0	2.6–3.6
Response speed	++	+++	+
Lifetime (h)	60,000	5,000–8,000	–
Equipment cost (\$/kW)	500–1,500	1,100–1,800	–
Hydrogen purity	> 99%	≥ 99.9995%	> 99%
Requirements of operation and maintenance	complicated	simple	–
Technology stage	practical	verification	development

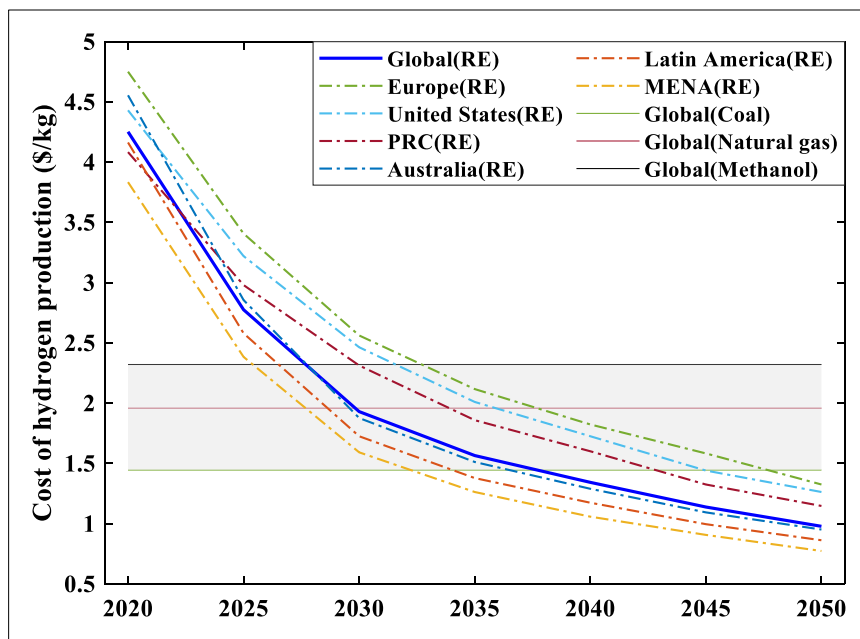
## 2.2 Future Cost of Green Hydrogen Production

The cost of hydrogen production by water electrolysis from renewable energy includes the costs of energy generation, water electrolysis equipment, and raw material (water), along with other operation and maintenance costs. The cost of renewable energy generation is the most critical factor affecting the cost of green hydrogen, and for every 0.1 \$/kWh reduction in generation cost, the cost of hydrogen can be reduced by 5.5 \$/kg (European Commission 2020). According to Hemado Green Energy, the average electricity cost of green hydrogen production in 2020 was 44 \$/MWh, accounting for 56% of the total cost; the electricity cost to produce green hydrogen in 2050 is estimated at 17 \$/MWh, which will account for 70% of the total cost. Moreover, the lower cost of water electrolysis equipment cannot compensate for the impact of high electricity prices (German Government 2020).

Future costs of green hydrogen production globally and in several regions are shown in Figure 1. The global cost of green hydrogen production will decrease yearly from 4.2 \$/kg (2020) to 1 \$/kg (2050). It will be lower than the cost of hydrogen production from methane, almost the same as the cost of hydrogen production from natural gas in 2030, and lower than the cost of hydrogen production from thermal power in 2040. The cost of green hydrogen production is highest in Europe and lowest in the Middle East and North Africa. The difference in electricity cost directly contributes to the regional disparity in green hydrogen cost.



**Figure 1: Future Costs of Green Hydrogen Production Globally and in Several Regions**



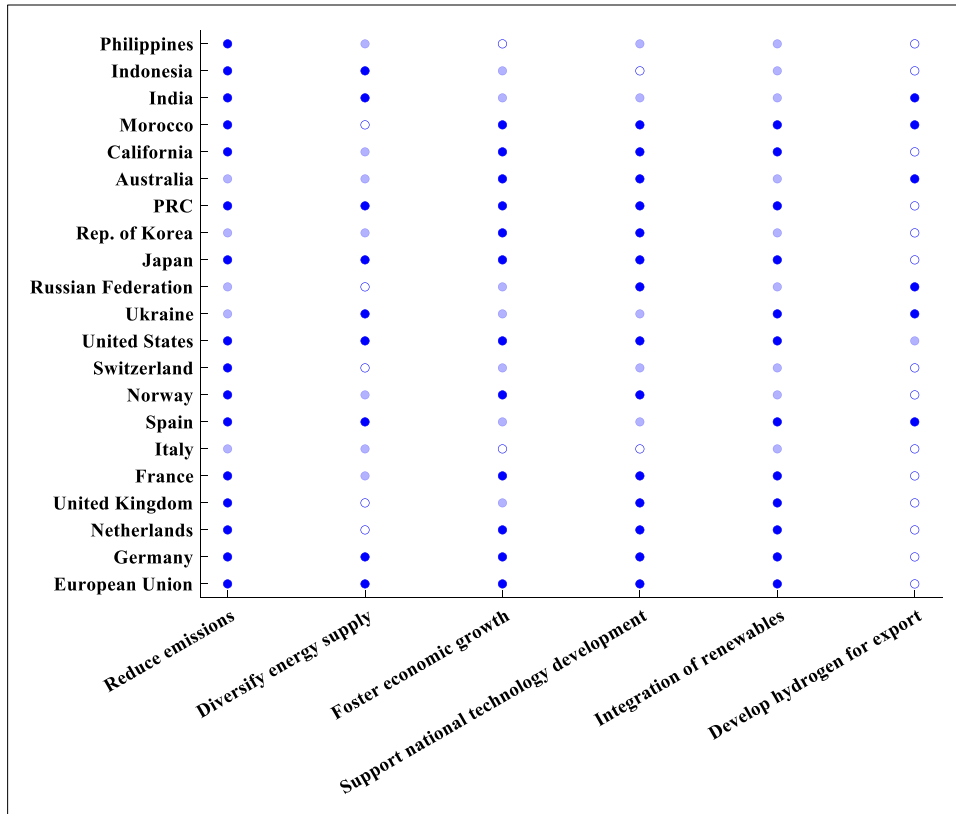
### 3. THE ROLE AND APPLICATION AREAS OF GREEN HYDROGEN ENERGY

#### 3.1 The Role of Green Hydrogen Energy

On the one hand, green hydrogen energy can reasonably cooperate with renewable energy with the characteristics of randomness and volatility; the hydrogen can be used as long-term energy storage to improve the utilization rate of renewable energy and grid reliability. On the other hand, green hydrogen energy can help industries in which it is difficult to achieve deep decarbonization through electrification, such as logistics and industries, supporting the goal of carbon neutrality. In addition, hydrogen energy can provide more options for energy and fuel sources to ensure national energy security, provide more employment opportunities, and create economic benefits.

The main factors of national support for green hydrogen energy development include reducing emissions, diversifying the energy supply, fostering economic growth, supporting national technology development, integrating renewables, and exporting, as shown in Figure 2 (US Department of Energy 2002).

**Figure 2: Main Factors of National Support for Green Hydrogen Energy Development**



### 3.2 Applications of Green Hydrogen Energy

The main applications of green hydrogen energy include industry, energy, transportation, construction, and export. The deployment of hydrogen energy applications varies in different countries, as depicted in Figure 3 (US Department of Energy 2002).

#### (1) Industry

Green hydrogen is used in areas where it is difficult to achieve deep decarbonization through electrification in the industry field. It is applied in the following areas: 1) oil refining, where hydrotreating and hydrocracking are used to remove impurities and improve the efficiency of intermediate recycled oil; 2) chemicals, where green hydrogen is used as industrial feedstock and as fuel to synthesize ammonia, methanol, methane, etc.; 3) steel, where green hydrogen is used to replace coke and natural gas. Most countries have deployed green hydrogen energy applications in the industry field.

## (2) Power

With the further increase in deep decarbonization requirements in the power field, the main applications of green hydrogen energy are as follows: 1) using hydrogen energy as long-term energy storage to balance the volatility of renewable energy and electricity demand. It is a flexible resource in the power system; 2) using hydrogen energy as a fuel for gas turbines or fuel cells to provide electricity for essential facilities such as hospitals and communication infrastructures during power outages, thereby improving the reliability of the electricity system; 3) hydrogen can be converted into ammonia and co-fired with pulverized coal to reduce the carbon intensity of traditional coal-fired power stations. Fifteen countries and regions have deployed hydrogen energy applications in the power field, not including Italy, Norway, and Switzerland.

## (3) Transport

Hydrogen has long been seen as a potential transportation fuel and as a clean alternative to oil and natural gas. The hydrogen power system is one of the few options for achieving rapid emission reductions in transportation due to its zero carbon emissions and wide adaptability. The main applications of hydrogen fuel cells in transportation include: 1) road transportation, such as small cars, buses, trucks, and other vans; 2) maritime transportation, such as ships and ports; 3) rail transportation and air transportation. Using hydrogen as a fuel for vehicles has the advantages of a short refueling time and long endurance mileage compared with pure electric vehicles. Transportation is the main application field of hydrogen energy; 18 countries and regions have deployed hydrogen energy applications in the transport field.

## (4) Building

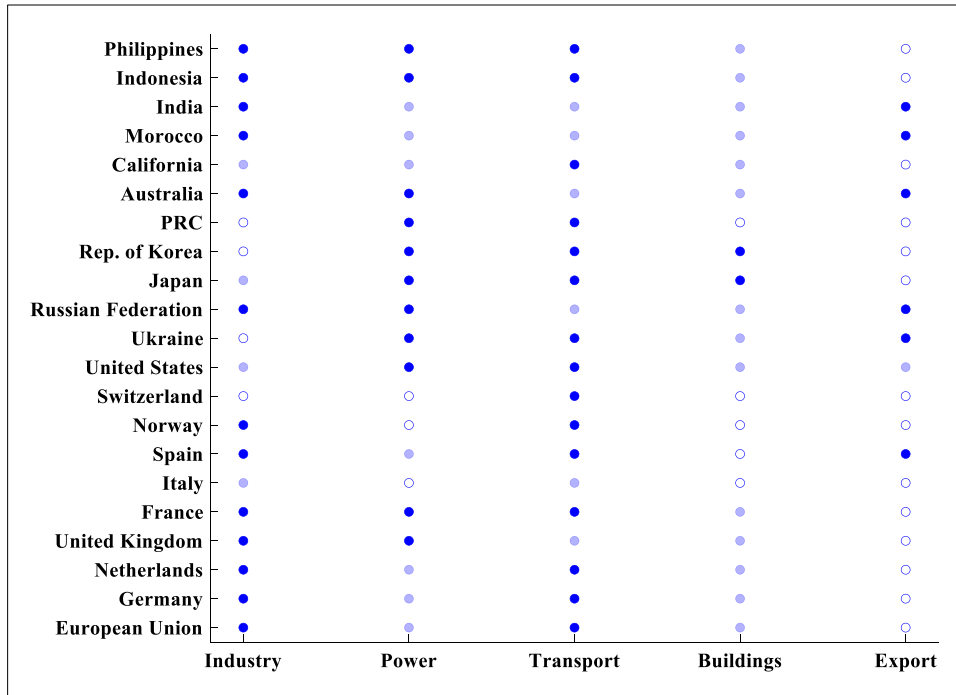
The heating of buildings is basically provided by traditional energy at present. On the one hand, hydrogen energy can be used to heat buildings and communities; on the other hand, it can be used as a backup power source to realize the interconnection and complementation with electricity and other energy varieties to improve the utilization efficiency of energy.

Compared with natural gas, hydrogen has the advantages of being less dense, easier to ignite, and having greater combustion heat per unit mass. Furthermore, since hydrogen is easy to diffuse in the air, it has a low aggregation risk. The application of hydrogen energy for building heating can change the way of heating from being centralized in thermal power plants to distributed and can solve the problem of high investment in infrastructure construction, such as heat pipe networks and power grids. Among the aforementioned 21 countries and regions, most have less hydrogen energy deployment in the building field.

## (5) Export

Countries such as India and Australia have deployed strategic plans to export hydrogen energy to maintain their status as energy exporters.

**Figure 3: Deployment of Green Hydrogen Energy Applications in Different Countries and Regions**



## 4. POLICIES AND RELATED DOCUMENTS ON GREEN HYDROGEN ENERGY DEVELOPMENT IN SEVERAL COUNTRIES AND REGIONS

To date, more than 40 countries and regions have released hydrogen energy development strategies, treating hydrogen energy as an important part of promoting the new climate and energy policy. Many countries and regions are actively laying out the hydrogen energy industry. They promote hydrogen energy development by developing a specific roadmap, strengthening policy support, increasing infrastructure investment, establishing industrial development alliances, strengthening international cooperation, etc. (Fuel Cell and Hydrogen Energy Association (FCHEA) 2019; US Department of Energy 2020). This section focuses on the policies and related documents of hydrogen energy development in jurisdictions with sufficient progress in policy support and investments in green hydrogen, namely the European Union, the United States, the PRC, Japan, the Republic of Korea, and Australia), as shown in Table 2.

### 4.1 European Union

In December 2011, the EU formulated “Energy Roadmap 2050” (Japan Government 2017), which prioritized the development of hydrogen and fuel cells as one of the ten elements that would influence the change of the energy system in the future. The European Commission released “A Hydrogen Strategy for a Climate-Neutral Europe” (Japan Government 2021) on 8 July 2020, which described the development plan for hydrogen energy in Europe over the next 30 years, making green hydrogen a priority for future development in the EU. Hydrogen from renewable energy will be expanded

for large-scale applications in challenging industries to decarbonize by lowering the cost of renewable power and accelerating the development of related technologies, ultimately contributing to the goal of being “Climate Neutral” by 2050. Germany is the most representative country for hydrogen energy development in the EU. In 2020, the German government released “The National Hydrogen Strategy” (Agency for Natural Resources and Energy 2022), which defined the strategic position of green hydrogen as it aimed to become the global leader in the field of green hydrogen.

## 4.2 United States

The United States was the first to incorporate hydrogen energy into its national energy strategy. In November 2002, the US Department of Energy (DOE) released the “National Hydrogen Energy Roadmap” (Ministry of Economy, Trade and Industry 2022), which clarified the traditional approach to building a hydrogen energy system. On 6 November 2019, the Fuel Cell and Hydrogen Energy Association (FCHEA) released the “Road Map to a US Hydrogen Economy – Reducing Emissions and Driving Growth Across the Nation” (Korea Government 2019). On 12 November 2020, the US DOE released the “Hydrogen Program Plan” (Korea Government 2020), which proposed an overarching strategic framework for hydrogen energy research, development, and demonstration over the next decade and beyond. In March 2022, the US DOE announced an investment of \$28 million for the Front End Engineering Design (FEED) program for clean hydrogen energy, which aimed to develop the next-generation hydrogen production technologies; produce clean hydrogen at low cost from municipal solid waste, residual coal waste, waste plastics, and biomass feedstocks; and promote the realization of the “Hydrogen Energy Research Plan.”

## 4.3 Japan

After the Fukushima nuclear disaster, Shinzo Abe proposed the goal of building a “hydrogen energy-based society.” In December 2017, Japan became the first country to release a basic hydrogen energy strategy with the “Hydrogen Basic Strategy” (Korea Government 2021). The “strategy” proposed to establish a commercial-scale supply chain around 2030, purchase about three million tons of hydrogen every year, and realize a hydrogen cost of about 30 JPY ¥/m<sup>3</sup>. In November 2021, the Japanese government updated “The Sixth Basic Energy Plan” (The National Development and Reform Commission and the National Energy Administration 2016), which proposed that the share of hydrogen energy in the energy structure should reach 11% by 2030. In 2022, the Agency for Natural Resources and Energy (ANRE) released “Building a Large-scale Hydrogen Energy Supply Chain with the Goal of Achieving a Hydrogen Energy Society” (China State Council 2016), and the Ministry of Economy, Trade, and Industry (METI) released the “Current Status and Future Research Directions of Hydrogen/Ammonia” (National Energy Administration 2019), both of which elaborated on the future development of hydrogen energy in Japan. In addition, Japan has reached cooperation agreements with Australia, Brunei Darussalam, Norway, and Saudi Arabia on procuring hydrogen fuel.

## 4.4 Republic of Korea

Hydrogen energy has been positioned by the Republic of Korea government as an important intermediary for improving energy efficiency and optimizing the renewable energy power system. In order to achieve the strategic goal of hydrogen energy, the Republic of Korea government took the “Hydrogen Economy” as one of the three

strategic investment areas in 2018, along with artificial intelligence and big data. In 2019, the Republic of Korea released the more sophisticated “A Blueprint for the Development of Hydrogen Economy” (National Development and Reform Commission and the National Energy Administration 2022), which specified the main goals and sector targets regarding hydrogen and fuel cell technology. On 4 February 2020, the Government of the Republic of Korea officially enacted the first law on hydrogen energy, the “Law on the Promotion of Hydrogen Economy and Hydrogen Safety Management” (Ministry for Energy and Emission Reduction and Ministry for Resources and Northern Australia 2019), laying the legal foundation for the government’s commitment to hydrogen energy and the implementation of facility safety standards. In 2021, Prime Minister Kim Boo-kyum chaired the fourth meeting of the Hydrogen Economy Council and released the Republic of Korea’s first “Basic Plan for Hydrogen Economy Development” (Luo 2017), which elaborated on the future development of hydrogen energy in the Republic of Korea.

#### **4.5 PRC**

The PRC is the largest hydrogen energy producer and has the world’s biggest installed renewable energy capacity. It has great potential to supply clean and low-carbon hydrogen energy. In 2016, the PRC released the “Roadmap of Key Innovation Actions for the Energy Technology Revolution” (Li et al. 2021), which proposed to achieve large-scale, low-cost production, storage, transportation, and application of hydrogen. In the same year, the “13th Five-year Plan on Technology and Innovation” (Ma, Liu, and Ding 2022) proposed to focus on developing hydrogen energy and other disruptive technologies that could lead to an industrial revolution. Hydrogen energy was first included in the national government report in 2019, and the National Energy Administration issued the “Green Industry Guidance Catalogue” (Deng, He, and Miao 2020) to encourage the development of hydrogen energy. In March 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the “Medium and Long-term Plan for the Development of Hydrogen Energy Industry (2021–2035)” (Hemado Green Energy 2021). This plan clarified the energy attribute of hydrogen and made clear that hydrogen energy is an integral part of the future national energy system. Green hydrogen energy should be fully exploited to promote the green and low-carbon transformation of end-use energy (such as transportation, industry) and other high-consumption and -emission industries. Furthermore, it made it clear that hydrogen energy is the key direction of strategic emerging industries and is the new growth point for building green and low-carbon industrial systems.

#### **4.6 Australia**

In 2018, the Australian Energy Council officially recognized the economic and environmental benefits of hydrogen and formulated a vision for the hydrogen industry. In November 2019, the Australian government published “Australia’s National Hydrogen Strategy” (Ludwig-Bölkow-Systemtechnik GmbH 2020), which identified 15 development goals and 57 joint actions, with a view to becoming a major participant in the global hydrogen energy industry by 2030 and reaching 30 million tons per year of green hydrogen production capacity by 2050.

**Table 2: Policies and Related Documents of Hydrogen Energy Development in Several Countries and Regions**

Country/Region	Released Year	Policies and Related Documents	Source
European Union	2011	Energy Roadmap 2050	European Commission
	2020	A Hydrogen Strategy for a Climate-Neutral Europe	European Commission
United States	2002	National Hydrogen Energy Roadmap	US DOE
	2019	Road Map to a US Hydrogen Economy – Reducing Emissions and Driving Growth Across the Nation	FCHEA
Japan	2020	Hydrogen Program Plan	US DOE
	2017	Hydrogen Basic Strategy	Japanese Government
	2021	The Sixth Basic Energy Plan	Japanese Government
	2022	Building a Large-scale Hydrogen Energy Supply Chain with the Goal of Achieving a Hydrogen Energy Society	ANRE
	2022	Current Status and Future Research Directions of Hydrogen/Ammonia	MEIT
Rep. of Korea	2019	A Blueprint for the Development of Hydrogen Economy	Rep. of Korea Government
	2020	Law on the Promotion of Hydrogen Economy and Hydrogen Safety Management	Rep. of Korea Government
	2021	Basic Plan for Hydrogen Economy Development	Rep. of Korea Government
PRC	2016	Roadmap of Key Innovation Actions for the Energy Technology Revolution	NDRC and NEA
	2016	13th Five-year Plan on Technology and Innovation	China State Council
	2019	Green Industry Guidance Catalogue	NEA
	2022	Medium- and Long-term Plan for the Development of Hydrogen Energy Industry (2021–2035)	NDRC and NEA
Australia	2019	Australia's National Hydrogen Strategy	Australian Government

## 5. DEVELOPMENT PATHWAYS OF GREEN HYDROGEN ENERGY UNDER CARBON NEUTRALITY TARGET

### 5.1 European Union

According to “A Hydrogen Strategy for a Climate-Neutral Europe” (European Commission 2021) published by the European Commission, there are three phases in developing a clean hydrogen economy in the EU.

#### (1) Phase I (2020–2024)

This phase is aimed at reducing the carbon emissions of existing hydrogen production processes and expanding the application areas of hydrogen energy. The installed capacity of hydrogen production equipment by water electrolysis from renewable energy should reach at least 6 GW, and the annual green hydrogen production should reach one million tons in 2024.

(2) Phase II (2025–2030)

This phase is aimed at making hydrogen energy an important component of an integrated energy system. The installed capacity of hydrogen production equipment from renewable energy should reach at least 40 GW, and the annual green hydrogen production should reach 10 million tons in 2030. The applications of hydrogen energy will gradually extend to industry and transportation. At this stage, hydrogen energy will still be produced close to the application terminals or in areas with rich renewable energy resources to realize a regional eco-energy system.

(3) Phase III (2031–2050)

The aim of this phase is to realize the large-scale application of hydrogen energy. The technology for producing hydrogen from renewable energy will gradually mature; hydrogen energy will be deployed on a large scale to replace industries that struggle to decarbonize and help to achieve carbon neutrality.

## 5.2 United States

The US Fuel Cell and Hydrogen Energy Association (FCHEA) released a report on the “Road Map to a US Hydrogen Economy” at the 2019 Fuel Cell International Symposium and Energy Show. According to this report, the hydrogen economy development pathway in the US can be divided into four phases (Fuel Cell and Hydrogen Energy Association 2019).

(1) Phase I (2020–2022)

The development goals in this phase are to identify reliable and technology-neutral decarbonization targets at more state and federal levels, bring relatively mature hydrogen applications to market, increase the public awareness and acceptance of hydrogen and continue to experiment with other applications of hydrogen, expand mature applications (such as forklifts) and near break-even applications (such as backup power), and drive market demand growth to match the production capacity of hydrogen.

(2) Phase II (2023–2025)

This stage is the initial scale development stage, aimed at achieving large-scale hydrogen production and building the first large-scale, low-carbon, or zero-carbon hydrogen production facilities. With the expansion of hydrogen production, the scale of hydrogen-related equipment (especially automotive fuel cell production equipment and fuel station equipment) will be expanded simultaneously to reduce costs and improve performance. This phase requires clear regulatory guidelines to coordinate market participants and attract investment, transitioning policy incentives from early direct support to scalable market mechanisms. The hydrogen demand in the US will reach 13 million tons in 2025.

(3) Phase III (2026–2030)

This is a phase of diversified development. Various hydrogen production technologies will be widely used, and the scale of water electrolysis will continue to expand. Hydrogen will be closely linked to the power grid and renewable energy. In 2030, the hydrogen demand will exceed 17 million tons, while 4,300 hydrogen refueling stations will operate in the US; the annual investment in hydrogen energy will reach \$8 billion.



#### (4) Phase IV (2031–)

This is a phase of extensive promotion. Hydrogen energy will be deployed on a large scale across all regions and industries in the US, and the previously supportive policies will be phased out after 2030. At the same time, hydrogen production equipment based on fossil fuel will be retrofitted with carbon capture and storage technology. Various low-cost and low-carbon hydrogen production technologies will compete. In addition to manufacturing and producing for the domestic market, hydrogen energy and the related production technologies will be exported to Europe and Asia. The annual revenue of the hydrogen energy industry in the US will reach \$750 billion in 2050.

### 5.3 Japan

The development pathways of hydrogen energy in Japan mainly include the following three aspects: 1) achieving low-cost and low-carbon emissions hydrogen production by using carbon capture and storage (CCS) technology or water electrolysis from renewable energy; 2) strengthening the infrastructure for importing and domestic hydrogen transportation; 3) promoting the extensive application of hydrogen in various sectors such as automobiles, combined heating and power in the household, and power generation.

Further, according to “Building a Large-scale Hydrogen Energy Supply Chain with the Goal of Achieving a Hydrogen Energy Society” (China State Council 2016) released by the Agency for Natural Resources and Energy in 2022 and “Current Status and Future Research Directions of Hydrogen/Ammonia” (National Energy Administration 2019) released by the Ministry of Economy, Trade and Industry, the hydrogen energy development pathway in Japan can be divided into the following three stages:

#### (1) Phase I (2022–2030)

Continuously expanding the application of hydrogen energy in power generation, transportation, industry, and livelihood, and researching hydrogen production technologies from renewable energy. Developing the international hydrogen energy import chain, establishing a large-scale overseas import mechanism after 2025, and developing the domestic green hydrogen supply capacity simultaneously. The commercial supply capacity of hydrogen energy should reach three million tons, and the cost of hydrogen energy is expected to fall from 100 JPY ¥/m<sup>3</sup> to 30 JPY ¥/m<sup>3</sup> in 2030.

#### (2) Phase II (2031–2050)

Vigorously developing low-carbon hydrogen production technologies, such as hydrogen production from renewable energy and hydrogen production from lignite combined with CCS. Hydrogen energy will be used in multiple fields and realize a large-scale application in power generation. The commercial supply capacity of hydrogen energy should reach 20 million tons, and the cost of hydrogen energy is expected to decrease to 20 JPY ¥/m<sup>3</sup> in 2050.

#### (3) Phase III (2051–)

The aim of this phase is to realize a large-scale application of hydrogen energy in areas in which it is difficult to achieve deep decarbonization through electrification to help achieve the goal of carbon neutrality, and to diversify the supply sources of hydrogen energy to ensure national energy security.

## 5.4 Republic of Korea

According to the “Basic Plan for Hydrogen Economy Development” (Luo 2017) released in 2021 at the Fourth Hydrogen Economy Council Meeting, the development pathway of hydrogen energy in the Republic of Korea can be divided into two stages.

### (1) Phase I (2021–2030)

Vigorously developing hydrogen-fueled vehicles and ensuring an annual increment of 100,000 hydrogen-fueled household vehicles and 2,000 hydrogen-fueled commercial vehicles. Realize the commercial application of CCUS technology and 10 MW hydrogen production equipment, providing strong support for green hydrogen production. The total hydrogen energy demand will reach 3.9 million tons, and the proportion of green hydrogen will reach 75% in 2030. The amount of self-produced hydrogen will be 1.94 million tons, and the amount of overseas-purchased hydrogen will be 1.96 million tons, accounting for about 50% of all demand.

### (2) Phase II (2031–2050)

Building 40 overseas import chains and commercializing the hydrogen production equipment of GW grade. By 2050, the number of hydrogen-fueled household cars will reach 5.15 million, and the number of hydrogen-fueled commercial vehicles will reach 110,000. The total hydrogen energy demand will be 27.9 million tons, which needs to be composed entirely of green hydrogen and blue hydrogen with low carbon emissions. The amount of self-produced hydrogen will be five million tons, and the amount of overseas purchased hydrogen will be 22.9 million tons, accounting for 82% of all demand.

In 2050, hydrogen energy will account for 33% of terminal energy consumption and 23.8% of electricity generation in the Republic of Korea, surpassing oil to become the primary energy source. In addition, the Republic of Korea will generate \$1 trillion, create 567,000 job opportunities, and reduce greenhouse gas emissions by more than 200 million tons through implementing this plan.

## 5.5 PRC

Generally analyzed with “China Hydrogen Energy Development Roadmap 1.0: How to Achieve a Green, Efficient and Economic Hydrogen Energy Supply System?” (China EV100 2020) released by China EV100 in 2020, “Mid-and-long-term Plan for the Development of Hydrogen Energy Industry (2021–2035)” (National Development and Reform Commission and the National Energy Administration 2022) jointly released by the National Development and Reform Commission and the National Energy Administration in 2022, and “Key to a New Era of Green Hydrogen Energy: China ‘Renewable Hydrogen 100’ Development Roadmap in 2030” (Rocky Mountain Institute and China Hydrogen Alliance Research Institute 2022) jointly released by the Rocky Mountain Institute and the China Hydrogen Alliance Research Institute, the hydrogen energy development pathway in the PRC can be divided into the following four stages.

### (1) Phase I (2020–2025)

Providing a fairly complete institutional and policy environment for development of the hydrogen energy industry and initially establishing a relatively complete supply chain and industrial system in 2025. The demonstration applications of hydrogen energy are expected to achieve apparent results, and the green hydrogen production technologies will make significant progress. In 2025, the

number of fuel cell vehicles will reach 50,000, and the annual production of green hydrogen will reach 0.1–0.2 million tons, becoming an important part of hydrogen energy consumption and realizing the CO<sub>2</sub> emission reduction of one to two million tons per year. At this stage, the storage and transportation of hydrogen energy are mainly through high-pressure compressed gas vessels, and liquid hydrogen transportation is promoted as a pilot. The refilling mode of hydrogen energy is mainly based on joint stations, and integrated hydrogen production stations are promoted as a pilot.

(2) Phase II (2026–2030)

By 2030, a relatively complete technological innovation system for the hydrogen industry and green hydrogen production system will be formed, and the hydrogen production technology from renewable energy will be widely applied. With the advantages of industrial agglomeration and a large-scale market, the installed capacity of hydrogen production facilities from renewable energy is expected to reach 100 GW, accelerating the scale effect.

(3) Phase III (2031–2035)

This phase is for forming a hydrogen energy industry system and building a diversified hydrogen energy application ecology covering transportation, energy storage, industry, etc. The proportion of green hydrogen in the terminal energy consumption will obviously be increased, vigorously supporting the energy transformation. In this stage, the storage and transportation mode of hydrogen energy will mainly be through liquid hydrogen, supplemented by high-pressure compressed gas vessels. The refueling mode of hydrogen energy will develop toward diversification and networking.

(4) Phase IV (2036–2060)

The supply pattern of hydrogen energy in the PRC will gradually shift to a clean and low-carbon route, with only a small amount of fossil energy hydrogen production for scenario-specific use in this phase. The installed capacity of hydrogen production from renewable energy will expand with an annual growth of 5%–10%, the cumulative installed capacity will reach 500–750 GW, and the green hydrogen production will reach 75–100 million tons by 2060, accounting for 75%–80% of all hydrogen energy production. At this stage, hydrogen energy can be stored and transported in multiple ways, such as liquid hydrogen, high-pressure compressed gas vessels, and via pipeline.

## 6. CONCLUSION

Green hydrogen energy is still very expensive compared to non-green hydrogen and renewable energy; however, it is expected that the cost of green hydrogen will fall substantially in the period 2030–2050. Furthermore, green hydrogen has the potential to play a pivotal role in the global pathway towards the carbon neutrality target, for example via the following applications. Firstly, green hydrogen energy can be used as long-term energy storage to improve the utilization rate of renewable energy and grid reliability – for example, where seasonal storage is needed. Secondly, green hydrogen energy can help industries in which it is difficult to achieve deep decarbonization through electrification (renewable energy), such as logistics and industries, including oil and natural gas extraction. The total potential green hydrogen market will probably reach \$250 billion by 2030 and \$1 trillion by 2050 (Goldman Sachs 2022).

Therefore, a comprehensive review of the role and development pathways of green hydrogen energy towards carbon neutrality target is provided in this paper, including the current status and development trend of green hydrogen production technologies, the role and applications of green hydrogen energy, the policies and related documents of green hydrogen energy development in several countries and regions, and the development pathways of green hydrogen energy under the carbon neutrality target.

According to the above research content, for countries or regions with a need to formulate the development pathways of green hydrogen energy (for example, due to the need in green hydrogen to decarbonize hard-to-abate sectors, long-term storage in the power sector, or export revenue), the development of hydrogen energy is suggested to follow the following principles. First, providing an institutional and policy environment conducive to the development of hydrogen energy industry and bringing relatively mature hydrogen applications to market (where non-green hydrogen is already used for a long time) – for example, by incentivizing the replacement of non-green hydrogen with green hydrogen by industries.

Secondly, transitioning policy incentives from early direct support to scalable market mechanisms. Hydrogen energy should be closely linked to the power grid and renewable energy at this stage. Then, forming a hydrogen energy industry system and building diversified hydrogen energy applications covering transportation, energy storage, industry, etc.

Finally, realizing a large-scale application of hydrogen energy in areas where it is difficult to achieve deep decarbonization through replacing fossil fuel with electrification (sourced from renewable energy) to help achieve the goal of carbon neutrality, i.e. hard-to-abate sectors such as steel and cement. Hard-to-abate sectors will require incentives promoting the replacement of fossil fuels with green hydrogen in order to achieve decarbonization of such sectors.

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# APPENDIX

## Development Goals of Hydrogen Energy in Different Countries and Regions

	2024	2025	2030	2035	2050	2060
European Union	<ul style="list-style-type: none"> <li>□ Hydrogen production equipment by water electrolysis from renewable energy at least reach 6 GW</li> <li>□ Annual green hydrogen production reach 1 million tons</li> </ul>		<ul style="list-style-type: none"> <li>□ Hydrogen production equipment by water electrolysis from renewable energy at least reach 40 GW</li> <li>□ Annual green hydrogen production reach 10 million tons</li> </ul>			
The United States		<ul style="list-style-type: none"> <li>□ Annual hydrogen demand reach 13 million tons</li> </ul>	<ul style="list-style-type: none"> <li>□ Annual hydrogen demand reach 17 million tons</li> <li>□ Annual investment in hydrogen energy reach 8 billion dollars</li> </ul>		<ul style="list-style-type: none"> <li>□ Annual revenue of the hydrogen energy industry reach 750 billion dollars</li> </ul>	
PRC		<ul style="list-style-type: none"> <li>□ Annual hydrogen demand reach 0.1–0.2 million tons</li> </ul>	<ul style="list-style-type: none"> <li>□ Hydrogen production equipment from renewable energy reach 100 GW</li> </ul>			<ul style="list-style-type: none"> <li>□ Hydrogen production equipment from renewable energy reach 500–750 GW</li> <li>□ Annual green hydrogen production reach 75–100 million tons, accounting for 75%–80% of all hydrogen energy production</li> </ul>
Russian Federation	<ul style="list-style-type: none"> <li>□ Export hydrogen energy 0.2 million tons</li> </ul>			<ul style="list-style-type: none"> <li>□ Export hydrogen energy 2 million tons (maximum target of 12 million tons)</li> </ul>	<ul style="list-style-type: none"> <li>□ Export hydrogen energy 15 million tons (maximum target of 50 million tons)</li> </ul>	
Japan			<ul style="list-style-type: none"> <li>□ Commercial supply of hydrogen energy reach 3 million tons</li> <li>□ Cost of hydrogen energy fall to 30 JPY ¥/m<sup>3</sup></li> </ul>		<ul style="list-style-type: none"> <li>□ Commercial supply of hydrogen energy reach 20 million tons</li> <li>□ Cost of hydrogen energy fall to 20 JPY ¥/m<sup>3</sup></li> </ul>	
Republic of Korea			<ul style="list-style-type: none"> <li>□ Total hydrogen energy demand reach 3.9 million tons, 50% from overseas</li> </ul>		<ul style="list-style-type: none"> <li>□ Total hydrogen energy demand reach 27.9 million tons, 82% from overseas</li> </ul>	