

## Hydrogen Energy Supply Chain: Production, Storage, and Applications – An Exploratory Study

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Ho-Hsiang Lin \*\*

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### Abstract

This study explores the role of hydrogen as a clean and efficient secondary energy source in the global energy transition. Hydrogen has gained significant attention in energy research due to its zero carbon emissions, high heat value, safety features, and versatile applications. The research aims to comprehensively understand the role and impact of hydrogen in future energy systems. Through current survey methods and data analysis, the study elucidates the trends in hydrogen technology development, influence of policies, regulations, and its position in the global energy transition. The technological evolution of the hydrogen supply chain, including green hydrogen, blue hydrogen, hydrogen storage, and transportation, is highlighted. Government support, especially driven by Taiwan's hydrogen development goals and related regulations, has accelerated the growth of the hydrogen industry. In the global energy transition, hydrogen emerges as a key factor in achieving goals due to its zero emissions, diverse applications, and advantages in energy storage. However, hydrogen still faces challenges in technology and cost. Therefore, future research is recommended to focus on addressing technical bottlenecks in hydrogen production, storage, transportation, applications, while enhancing international cooperation and technological innovation. Additionally, further understanding of the practical impact of government policies on the hydrogen industry is essential to promote its broader application in the global energy system.

**Keywords:** Hydrogen Technology, Policy and Regulation, Global Transition, Supply Chain Innovation.

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\* Professor, Civil Engineering, Hindustan Institute of Technology and Science, Chennai, India.

\*\* Ccorresponding, Researcher, Yung Chun Technology Co. Ltd. Taiwan, E-Mail: [hohsianglin23388@gmail.com](mailto:hohsianglin23388@gmail.com)

## Introduction

### Background

Hydrogen, as a clean and efficient secondary energy source, holds significant importance in constructing a clean, low-carbon, safe, and efficient energy system. It has ascended to a strategic energy position at the national level and is expected to play a crucial role in the grand processes of carbon peaking and carbon neutrality (Caineng et al., 2021).

### Research Motivation

Hydrogen energy possesses multiple advantages, making it a focal point in current energy research. Some key advantages include zero carbon emissions, high heat value, environmental friendliness, high energy content, addressing climate change and improving air quality (Apak et al., 2017).

### Research Purpose

Environmental and climate issues associated with traditional energy use urge us to focus on renewable energy sources. In this context, hydrogen, as a potential clean energy source, has sparked widespread interest. Its motivation for research lies not only in its apparent advantages, such as zero carbon emissions and high heat value but also in its potential to be a key element in achieving energy transition goals.

### Research Questions

How is the urgent need for energy transition triggered by environmental and climate issues resulting from traditional energy use? What aspects embody the motivation for hydrogen energy research, including features like zero carbon emissions and high heat value? What specific progress has been made in the current state of hydrogen energy research in terms of technological development and achievements? How is the diversity of hydrogen research reflected in various countries globally? As the core for realizing hydrogen applications, what are the main components of the hydrogen supply chain, and what are the technological challenges and application prospects associated with each stage?

## Literature Review

### Major research achievements in international hydrogen energy studies

#### 1. Historical Development of Hydrogen Energy

The historical development of hydrogen energy can be traced back to the early 19th century when chemist Henry Cavendish first discovered hydrogen gas (West & Cavendish, 2014). However, it was not until the early 20th century that hydrogen's applications began to capture people's attention. Early experiments and fuel cell discoveries in the early 19th century, the decomposition of water and the discovery of hydrogen gas laid the foundation for hydrogen. In 1800, Henry Cavendish successfully separated hydrogen gas through experiments (Sandstede et al., 2010). Subsequently, Swedish scientist Sven Otto and British scientist William Grove proposed the concept of fuel cells in 1839 and 1842, respectively, and achieved the conversion of hydrogen and oxygen into electricity (Lucia, 2014).

Hydrogen in industrial and aviation applications (during early 20th century), hydrogen found wide applications in ammonia production and in aviation, such as in airships and hydrogen balloons. However, due

to the highly explosive nature of hydrogen gas, it led to significant accidents, most notably the 1937 Hindenburg airship disaster (DiLisi, 2017).

During petroleum era and rediscovery of hydrogen fuel (Late 20th Century), with the rise of the petroleum industry, interest in hydrogen gradually waned. However, in the late 20th century, rising oil prices and concerns about energy security and the environment renewed interest in hydrogen as a clean energy source. During this period, fuel cell technology further developed, and exploration of hydrogen applications in transportation began. Rise of modern hydrogen energy (during 21st Century), with the rise of climate change and the sustainable energy agenda, hydrogen energy once again became a focus. Countries worldwide invested in hydrogen technology development, promoting the production of green hydrogen for applications in vehicles, energy storage, and more. The use of hydrogen fuel cell vehicles and hydrogen fuel cell buses expanded gradually in the transportation sector (Kim et al., 2021).

## 2. Current Research Status of the Hydrogen Energy Supply Chain

The following are some key aspects of the current research status of the hydrogen energy supply chain:

**Research on Hydrogen Production Technologies:** Researchers are dedicated in developing more efficient, economical, and environmentally friendly hydrogen production technologies. Various hydrogen production methods, including water electrolysis, natural gas steam reforming, and biomass gasification, are under investigation (Zhu et al., 2023). Additionally, the production of green hydrogen, using renewable energy for water electrolysis, photocatalysis, crucial for reducing the carbon footprint of hydrogen production.

**Research on Hydrogen Storage and Transportation Technologies:** Research focuses on developing efficient and safe hydrogen storage and transportation technologies (Moradi & Groth, 2019). Various technologies, including liquid hydrogen, solid adsorption, and hydrogenation storage, are being explored to ensure the effective storage and transportation of hydrogen.

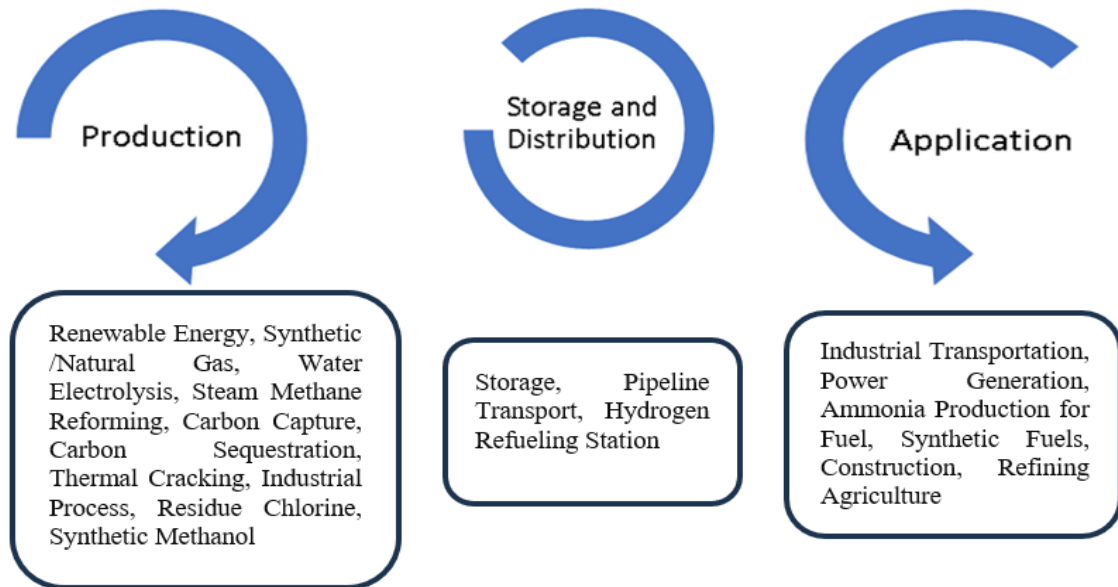
**Research on Hydrogen Energy Application Technologies:** In terms of hydrogen energy applications, fuel cell technology is a significant research area. Researchers aim to improve fuel cell efficiency, reduce costs, and expand its applications in various sectors such as transportation, industry, and households. Additionally, technologies like hydrogen fuel cell vehicles and hydrogen energy storage systems are actively being researched and developed.

**Research on Hydrogen Energy Policies and Regulations:** Governments worldwide formulate policies and regulations related to hydrogen energy to facilitate its development. This includes funding support, establishing standards and regulations, and promoting industry cooperation.

**Global Hydrogen Energy Cooperation and Experimental Projects:** International organizations and countries collaborate on hydrogen energy, jointly advancing the development of hydrogen technology. Moreover, large-scale experimental projects, such as hydrogen production demonstration plants and hydrogen infrastructure construction, are underway to verify the feasibility and scalability of hydrogen energy technologies.

### Overview of the Hydrogen Energy Supply Chain

#### 1. Upstream, Midstream, and Downstream of the Hydrogen Industry



**Figure 1** illustrates the main components of the hydrogen energy supply chain.

#### Production stage

Hydrogen production from fossil fuels: Hydrogen production from fossil fuels is currently the primary source of hydrogen, including coal-based and natural gas-based hydrogen production technologies. Coal-based hydrogen production is stable, efficient, and cost-effective. The estimated cost of hydrogen production is approximately 12.64 CNY/kg, when the raw coal price is 800 CNY/ton. Among natural gas-based hydrogen technologies, steam methane reforming is mature and widely used internationally. The estimated cost of natural gas-based hydrogen production is approximately 12.79 CNY/kg, when the natural gas price is 2.5 CNY/Nm<sup>3</sup>, with natural gas raw material costs accounting for over 70% of the total cost (Steinberg & Cheng, 1989).

Hydrogen production from renewable energy: Industrial by-product hydrogen resources are abundant and can serve as a transitional hydrogen source in the early stages of hydrogen development. Hydrogen production from industrial by-products includes hydrogen by-product from coke oven gas, hydrogen by-product from chlor-alkali chemical industry, hydrogen by-product from alkane dehydrogenation, hydrogen by-product from synthetic ammonia and methanol (Amin et al., 2022).

Hydrogen production from industrial waste: Hydrogen production from industrial waste is a green and sustainable method, typically involving gasification or chemical conversion processes. Possible methods include gasification processes, catalytic conversion, biological reactions, and methane reforming. Different types of waste and hydrogen production methods affect efficiency, cost, and environmental impact. Ensuring environmental friendliness and safety in the hydrogen production process is crucial. As technology advances and the hydrogen economy develops, research and applications of converting industrial waste into hydrogen will continue to receive attention (Kapdan & Kargi, 2006).

Electrolysis of water for hydrogen production: Water electrolysis for hydrogen production includes alkaline electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC). Alkaline electrolysis is mature, with low equipment costs and higher economic viability. PEM electrolysis has become the mainstream electrolysis technology due to its adaptability to renewable energy generation fluctuations and higher energy conversion efficiency. According to data from the International Energy Agency (IEA), PEM electrolysis accounted for over 80% of global newly installed electrolysis capacity from 2015 to 2019.

#### Storage and Transportation Stage

Hydrogen storage methods include high-pressure gaseous hydrogen storage, low-temperature liquid hydrogen storage, solid-state hydrogen storage, and hydrogen gas pipeline transportation. Currently, high-pressure gaseous hydrogen storage technology is relatively mature and is the primary storage and transportation method.

Liquid hydrogen: Liquid hydrogen refers to the process of cooling hydrogen gas to  $-252.72^{\circ}\text{C}$  under standard atmospheric pressure and storing it in specially designed highly vacuum-insulated containers. Liquid hydrogen has a density 845 times that of gaseous hydrogen at room temperature and pressure, making it suitable for long-distance and large-scale transportation. However, it involves significant equipment investment and higher energy consumption (Aziz, 2021).

Hydrogen gas compression storage: Gaseous hydrogen is typically stored in 20 MPa steel hydrogen cylinders and transported by long tube trailers, suitable for short-distance and small-scale transportation (Barthélémy et al., 2017).

Solid-state hydrogen storage: Solid-state storage uses materials such as metal hydrides, chemical hydrides, or nanomaterials as hydrogen carriers, storing hydrogen through chemical and physical adsorption. Solid-state hydrogen storage has advantages such as high storage density, good safety, and high hydrogen purity. However, the technology is complex, costly, and lacks large-scale applications (Walker et al., 2008)

Hydrogen gas pipeline transportation: Pipeline transportation is a crucial method for large-scale, long-distance hydrogen transportation, but it involves substantial construction costs (Witkowski et al., 2017).

#### Hydrogen applications

Hydrogen is used in various sectors such as industrial, transportation, power generation, construction industries, agricultural, refining, production of ammonia and synthetic fuels.

### **Research methods adopted for hydrogen research.**

#### Data collection methods

This study adopts a current situation survey method, collecting relevant data from various databases, consolidating it, and cross-verifying it with accessible literature.

#### Analysis methods

The countries or regions associated with hydrogen research include the European Union, China, Japan, and Taiwan. The analysis focuses on the most recent decade's data.

Key Issues and Challenges in the Hydrogen Energy Supply Chain

Application Stage of Hydrogen Energy

Hydrogen gas exhibits diverse applications and potential environmental benefits across various sectors. In the field of hydrogen fuel cell vehicles, this technology is gaining attention for its advantages such as zero emissions, rapid refueling, long driving range, and low noise. However, challenges faced include the establishment of hydrogen infrastructure, reduction of manufacturing costs, and enhancement of the green production of hydrogen. In industrial applications, hydrogen is utilized in processes such as chemical manufacturing, steel smelting, metal reduction, and glass production to replace some fossil fuel usage, thereby reducing carbon emissions. Additionally, hydrogen is considered an energy conversion medium in industries, applicable for thermal energy production or power generation through hydrogen combustion, aiming to improve efficiency and reduce dependence on traditional energy sources.

In the power generation sector, hydrogen can serve as a clean fuel applied in fuel cell systems or gas turbine generators, diminishing the demand for fossil fuels while achieving water vapor emissions. Moreover, hydrogen can be employed as a form of energy storage, converting surplus electricity into hydrogen to address the intermittency issues of renewable energy, thereby enhancing grid stability. Overall, hydrogen demonstrates its potential for diverse applications in these fields and plays a crucial role in the global energy transition, although continuous innovation and infrastructure development are essential for its widespread adoption.

Hydrogen Production and Market Analysis

Global Hydrogen Energy Industry Planning

According to the International Renewable Energy Agency (IRENA) Hydrogen Report, the two most promising markets in the global hydrogen energy industry are the upstream hydrogen production end with electrolysis and the downstream transportation sector with fuel cells. The potential market for fuel cells globally is estimated to reach as high as USD 21 billion to USD 25 billion by 2050 (Sokolov et al., 2019). Summary of Hydrogen Energy Industry Planning in Major Global Economies is tabulated in Table 1. H2 production methods

Hydrogen Production (10,000 tons)

**Table 1:** Summary of Hydrogen Energy Industry Planning in Major Global Economies

Country	H2 production methods	Year				
		2020	2025	2030	2035	2050
China	Hydrogen Production (10,000 tons)	3,342	3,715	5,276	9,690	-
	Electrolyzer Installed Capacity (GW)	10	>35	>200	>500	-
	Hydrogen Production Method	Industrial By-product Hydrogen Purification, Green Hydrogen Pilot Operation	Low Carbon Emission Hydrogen Production, Liquid Hydrogen Transportation	Zero Carbon Emission	-	-
			Hydrogen Production, Liquid Hydrogen Main Artery, High-Pressure Gas Microvascular Storage			

\* 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

Table 1: (Cont.)

Country	H2 production methods	Year				
		2020	2025	2030	2035	2050
EU	Annual Hydrogen Production (10,000 tons)	980	-	-	-	-
	Electrolyzer Installed Capacity (GW)	1	6	40	-	-
	Hydrogen Production Method	1.4% Green Hydrogen Share	Annual Production of 1 million Tons of Green Hydrogen, Excess Renewable Energy Production	Annual Production of 10 million Tons of Green Hydrogen, Large-scale Hydrogen Production	1/3 of All Hydrogen Production is Ultra-low Carbon Hydrogen, Large-scale Hydrogen Power Generation Demonstration Projects	Large-scale Deployment of Renewable Hydrogen, Accounting for 1/4 of Energy Demand
	Electrolyzer Cost (USD/kW)	-	300	-	-	-
USA	Operating Lifetime (hours)	-	80,000	-	-	-
	Conversion Efficiency	-	65%	-	-	-
	Hydrogen Transport Share of Energy Demand	-	2 14%	-	-	-
Japan	Annual Hydrogen Production (tons)	4,000	300,000	5-10 million	-	-
	Low-pressure Power Generation Cost (JPY/kWh)	-	25	-	-	-
	High-pressure Power Generation Cost (JPY/kWh)	-	17	12	-	-
	Hydrogen Production Cost (USD/kg)	-	3	2	-	-

Source: EU Hydrogen Strategy, USA Hydrogen Program Development Plan, Japan Hydrogen Utilization Progress Table, Japan Basic Hydrogen Strategy, China Hydrogen Industry Development Report 2020, Compiled by Guosen Securities Economic Research Institute.

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Hydrogen Refueling Station Market (China)

The hydrogen refueling station market is a big market for hydrogen energy industry. Table 2 is the market estimation of hydrogen refueling station in China (Li et al., 2021).

**Table 2:** Hydrogen Refueling Station (HRS) Market in China

Year / HRS status	→ ↓	2020	2035	2050
Completed Stations		118	-	-
Under Construction and Planned Stations		167	-	-
Operational Stations		101	-	-
Stations Ready for Operation		17	-	-
Deployment Rate		> 85%	-	-
Predicted Stations in 2035		-	1,500	10,000+
Central SOEs Plan (Stations)		-	-	-
Top 10 Provinces' Plans (2022/2023/2025)		-	-	420 / 597 / 927
2021-2025 Average Annual Investment		-	-	¥1.7-¥2.2 billion

**Source:** Statistics as of the end of 2020, Predictions from the "China Hydrogen and Fuel Cell White Paper." Central SOEs' planning data.

Hydrogen Storage Cylinder Market (China)

The hydrogen storage cylinder market is also a big market, Table 3 shows the potential hydrogen storage cylinder market in China (Wang et al., 2018).

**Table 3** Future Development Forecast of China's Hydrogen Storage Cylinder Market

Year	Hydrogen Fuel Cell Vehicle Hydrogen Cylinder Annual New Market Demand (100 million RMB)	Growth Rate (CAGR)	Carbon Fiber Annual Demand for Hydrogen Cylinder Production (10,000 tons)	Growth Rate (CAGR)
2021	-	-	-	-
2022	-	-	-	-
2023	-	-	-	-
2024	-	-	-	-
2025	32	78%	0.6	88%
2030	111	-	2.5	-

**Source:** Provincial and municipal hydrogen fuel cell vehicle deployment plans, market estimates.



Fuel Cell Market (Japan)

The details of fuel cell market in Japan is summarized in Table 4 below

**Table 4** Details of Fuel Cell Market in Japan

Year	Project/Model	Description	Goals/Achievements	Household Purchase Quantity
2008	ENE-FARM	Japan's "ENE-FARM" Cogeneration Project	Introducing hydrogen into fuel cells for power generation in residential homes, utilizing the generated heat for heating and hot water supply, forming a micro-cogeneration system with an overall efficiency of over 90%.	Breakthrough application of hydrogen in residential homes, with a sales target of 5.3 million units by 2030. As of 2019, approximately 320,000 Japanese households have purchased the Ene-Farm system.
2014/2016	Mirai/Clarity	Toyota and Honda Clarity Models	Promoting fuel cell vehicles, with Toyota introducing the second-generation Mirai in 2019, boasting a range exceeding 850 km, becoming a flagship product in the global fuel cell vehicle market.	-
2020	-	Addition of Fuel Cell Vehicles in Japan	Promoting fuel cell vehicles, with 761 new units added in 2020, accumulating a total of 3,902 units, expanding into areas such as buses, heavy trucks, and forklifts.	-

Source: Japan's "ENE-FARM" Cogeneration Project, Introduction of Toyota Mirai and Honda Clarity Models, Japan's Fuel Cell Vehicle Promotion Data.

Hydrogen Industry Supply Chain (Taiwan)

Taiwan is also trying to build its own hydrogen industry; Table 5 shows the recent progress of hydrogen industry supply chain in Taiwan (Lee et al., 2009).

**Table 5** Overview of Recent Operational Performance of Taiwan's Hydrogen-related Supply Chain

Company	Significant Milestones and Plans	Product Portfolio	International Collaboration	Remarks
Xing Heng	- Initiating Hydrogen Fuel Cell Procurement Project, introducing hydrogen fuel cells starting 2023, with a total capacity of up to 10MW, expected to be completed by 2026. - Total project investment exceeds 4 billion NTD.	- Hydrogen-powered motorcycles - Hydrogen fuel cell systems	Not specifically mentioned international collaborations	Seen as a significant milestone for Taiwanese companies entering the hydrogen fuel cell market.
Chunghwa Electric Power	- Launching the "Hydrogen Hwa Ya Park A+" project, establishing a hydrogen production base in the Hwa Ya Park, including methanol reformers, fuel cells, etc. - Operation began in Q1 2023, targeting markets such as India, Southeast Asia, and China.	- Methanol reforming hydrogen production units - Hydrogen fuel cells - Hydrogen stacks and power units - Hydrogen-powered logistics vehicles - Hydrogen refueling stations - Smart microgrids	Not specifically mentioned international collaborations	Early entrant into technology for hydrogen applications.
CTCI Corporation	- Successfully securing orders from global fuel cell manufacturer Bloom Energy, manufacturing key components for hydrogen fuel cells. - CTCI, with a focus on heat treatment technology, manufactures heat pumps for Bloom Energy.	Heat reaction box ("Hot Box") - Hard-soldered plate heat exchangers	Included in South Korean SK Group's approximately \$4.5 billion hydrogen fuel order; CTCI is responsible for manufacturing fuel cell reaction furnaces and related components.	Benefiting from the U.S. "Reducing Inflation Act," promoting the development of the battery industry with notable achievements.
Consus	- One of Bloom Energy's hydrogen fuel cell suppliers. - Supplies fuel cell power supplies to Bloom Energy.	Fuel cell power supplies	In the context of Bloom Energy's numerous orders, Consus has increased shipments of hardware power products.	Participating in Bloom Energy's hydrogen fuel cell supply, enhancing hardware power product sales.

Technical Challenges in the Hydrogen Supply Chain

Advances in Hydrogen Production Technology

Technological advancements pose a significant challenge for the future of the hydrogen supply chain. In this context, the fuel cell power system is exemplified to illustrate the ongoing developments (Lulianelli &

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Basile, 2014). A fuel cell is a device that directly converts the chemical energy of a fuel into electrical energy. The basic principle involves hydrogen entering the fuel cell's anode, undergoing decomposition into hydrogen protons and electrons with the aid of a catalyst. The generated hydrogen protons traverse a proton exchange membrane to reach the fuel cell's cathode, where they combine with oxygen to form water with the help of another catalyst. Simultaneously, electrons travel through an external circuit to the fuel cell's cathode, generating electric current. Due to this process not being constrained by the Carnot cycle, the theoretical efficiency can exceed 90%, showcasing high theoretical economic viability. Unlike energy storage batteries such as lead-acid and lithium-ion, fuel cells operate akin to "generators," predominantly producing water during the conversion of chemical energy to electricity. Moreover, the absence of mechanical transmission components eliminates harmful gas emissions and noise pollution. The core of hydrogen fuel cell vehicles lies in their fuel cell engine system, comprising the fuel cell stack, hydrogen supply system, oxygen supply system, and engine controller.

- Hydrogen Supply System: Transports hydrogen from the hydrogen tank to the fuel cell stack. The supply system consists of an air filter, air compressor, and humidifier, providing oxygen to the fuel cell stack.
- Thermal Management System: Utilizes an independent water and coolant circuit to eliminate waste heat and reaction by-products (water). This contributes to maintaining system stability and efficiency.

The electricity generated by the fuel cell system drives the electric motor through a power control unit, propelling the vehicle. Auxiliary batteries provide additional power when needed. In the future development of the hydrogen industry, enhancing the efficiency and reducing the cost of fuel cell power systems will be a key challenge. Simultaneously, research into more environmentally friendly and efficient hydrogen and oxygen supply systems will drive technological progress. This, in turn, will further accelerate the adoption of hydrogen fuel cell vehicles, providing robust support for the development of clean energy transportation.

#### Improvement in Storage and Transportation Technology

Storage and transportation of hydrogen are central to liquid hydrogen technology and related equipment. Historically, due to limitations in equipment such as heat exchangers and insulators, coupled with inadequate standards, liquid hydrogen has mainly found applications in aerospace and defence, with slow development in civilian sectors. Equipment for liquid hydrogen preparation is provided by companies like Air Products (USA), Praxair, and Linde (Germany). Currently, Japan and USA consider liquid hydrogen tankers as crucial for transporting hydrogen to refueling stations (Zhang et al., 2024).

#### Economic Challenges

Cost Issues: While externally supplied high-pressure hydrogen filling stations play a crucial role in hydrogen development, the high construction cost poses an urgent issue. Overcoming challenges in technology and cost associated with liquid hydrogen production and transportation is imperative for the accelerated application of civilian liquid hydrogen. Moreover, reducing the construction cost of externally supplied high-pressure hydrogen filling stations will contribute to the widespread adoption of hydrogen energy. Future research and development should focus on improving related equipment technology, enhancing efficiency, and reducing costs to promote the broader application of hydrogen energy.

Investment and Capital Requirements: Anticipated investment opportunities in the hydrogen energy market will be divided into two stages: the first stage includes market opportunities for key equipment and materials, while the second stage involves the trillion-dollar-scale hydrogen storage and distribution market. We are confident in enterprises currently engaged in the development of integrated hydrogen businesses. These enterprises are expected to benefit significantly from market growth under the support of national subsidies in the short term. In the long run, they are poised to share a substantial market in hydrogen sales, demonstrating positive development prospects.

#### Environmental Impact Challenges

Environmental Impact of Hydrogen Production: Recent studies highlight some challenges in hydrogen energy systems, despite being considered an environmentally friendly alternative for reducing CO<sub>2</sub> emissions. While hydrogen energy faces competition in the automotive sector, it is still seen as a potential alternative to fossil fuels in specific areas such as maritime, large trucks, trains, and industrial applications. However, studies indicate that hydrogen production processes heavily rely on fossil fuels, leading to an unavoidable carbon footprint. Thus, the environmental sustainability impact remains a significant consideration.

Impact of Hydrogen Production on Warming: Moreover, it is of concern that although hydrogen gas emits only water during chemical reactions, its impact on the Earth's climate is 11 times higher than that of carbon dioxide. This suggests that when seeking solutions to reduce CO<sub>2</sub> emissions, careful assessment of the environmental impact of other alternative energy sources is necessary. For atmospheric hydrogen releases, each ton is equivalent to an 11-ton warming effect of carbon dioxide, complicating the true environmental benefits of hydrogen energy. In summary, hydrogen energy systems face complex challenges in environmental impact and warming effects. Improving production processes, increasing the proportion of renewable energy, and preventing hydrogen leaks are urgent keys to achieving the maximum benefits of hydrogen energy.

## Conclusion

### Summary of Research Findings

#### 1. Technological Development Trends

The technological development of the hydrogen supply chain is currently in a phase of continuous innovation, exhibiting the following trends. Firstly, green hydrogen production technology realizes the electrolysis of water using renewable energy, emphasizing zero emissions and sustainability. Technological innovation is dedicated to increasing conversion efficiency and reducing energy consumption. Secondly, blue hydrogen technology involves the production of hydrogen through natural gas steam reforming or carbon oxide reforming while capturing and storing carbon dioxide, thereby reducing carbon emissions. Technological development focuses on improving efficiency and carbon dioxide handling. Additionally, hydrogen storage technologies include high-pressure liquid hydrogen, solid-state hydrogen storage, and hydride hydrogen storage, aiming to increase storage density, reduce energy losses, and enhance safety. Furthermore, hydrogen transport technologies encompass pipelines, liquid hydrogen, and hydrogen transport vehicles to improve transport efficiency and ensure safety. Finally, hydrogen applications in areas such as transportation, industry, and energy storage are continually evolving, including hydrogen fuel cell vehicles and hydrogen fuel cell power

generation systems. Overall, the trend in hydrogen technology development is moving towards greater environmental friendliness, efficiency, safety, and sustainability, with the potential to play a more crucial role in global energy transition.

## 2. Policy and Regulatory Impact

The impact of policies and regulations on the hydrogen supply chain cannot be ignored, particularly with the Taiwanese government actively introducing a series of regulations to promote the development of the hydrogen industry. The Taiwanese government has announced the goal of achieving a 10% share of hydrogen power generation by 2050 and has jointly established a hydrogen promotion task force with state-owned enterprises such as Taiwan Power Company (Tai power) and CPC Corporation. This task force is formulating Taiwan's future hydrogen development plan through demonstration projects, including natural gas blending for hydrogen power generation and hydrogen refueling stations. Simultaneously, relevant domestic supply chains are gradually being established, with examples such as China Steel Corporation possessing methanol reforming hydrogen production technology, and its hydrogen motorcycles have successfully entered the Indian market. In addition, the inauguration of the Xinxing Electronics', "Hydrogen Fuel Cell Power Generation System", with an investment of NT\$4 billion, is scheduled for August 14, with international hydrogen experts witnessing this significant moment. Taiwan has incorporated hydrogen into the Energy Management Act, officially entering the "Hydrogen Year". The Bureau of Energy will follow regulations to promote the formulation of the "Hydrogen Station Installation Management Rules". The active promotion of government regulations and the accelerated development of related industries highlight the need for collaborative efforts among industry, government, and academia to drive hydrogen development.

## 3. Position of Hydrogen Energy in Global Energy Transition

Hydrogen energy plays a crucial role in global energy transition, being considered a potential clean energy source to reduce greenhouse gas emissions and facilitate energy transformation. Firstly, its zero-emission characteristics make hydrogen energy a sustainable solution to address climate change and reduce air pollution. The combustion of hydrogen gas produces only water, without releasing greenhouse gases such as carbon dioxide, making it an environmentally friendly energy source. Secondly, hydrogen energy has diverse applications and can be widely used in transportation, industry, and energy storage. In the transportation sector, hydrogen fuel cell vehicles and hydrogen-powered trains have become practical alternatives to traditional energy sources. In the industrial sector, hydrogen gas is seen as a potential option to replace conventional fossil fuels in manufacturing and production processes. Thirdly, hydrogen is considered an effective energy storage method, helping to address the instability of renewable energy sources. By converting excess electricity into hydrogen gas and reconvert it into electricity when needed, it enhances the stability and flexibility of the power grid. Additionally, the consensus on international cooperation in hydrogen energy and global initiatives and projects for hydrogen energy promotion facilitate international collaboration, contributing to the sharing of technology, cost reduction, and the acceleration of global energy transition. Finally, continuous innovation in hydrogen energy technology, including green hydrogen, blue hydrogen, and methane reforming, among other production methods, contributes to increasing production efficiency and reducing costs, making hydrogen more competitive.

### Recommendations for Future Research

Currently, both large-scale renewable energy hydrogen production and the storage, transportation, distribution, and applications of hydrogen energy in industrial and transportation sectors are in the stage of technology demonstration and the localization of critical equipment, requiring strong government subsidies. From the perspective of hydrogen energy strategy, the current focus is on breaking through the key equipment and material technologies and applications in the transportation sector. This is intended to drive the development of the hydrogen energy storage and transportation segments, creating a spiral upward development dynamic. Ultimately, promoting the maturity of the terminal demand market after renewable energy hydrogen production and accelerating the rapid development of renewable energy hydrogen production are critical.

### Reference

- Amin, M., Shah, H. H., Fareed, A. G., Khan, W. U., Chung, E., Zia, A., ... & Lee, C. (2022). Hydrogen production through renewable and non-renewable energy processes and their impact on climate change. *International journal of hydrogen energy*, 47(77), 33112-33134.
- Apak, S., Atay, E., & Tuncer, G. (2017). Renewable hydrogen energy and energy efficiency in Turkey in the 21st century. *International Journal of Hydrogen Energy*, 42(4), 2446-2452.
- Aziz, M. (2021). Liquid hydrogen: A review on liquefaction, storage, Transportation, and Safety. *Energies*, 14(18), 5917.
- Barthélémy, H., Weber, M., & Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, 42(11), 7254-7262.
- Caineng, Z. O. U., Xiong, B., Huaqing, X. U. E., Zheng, D., Zhixin, G. E., Ying, W. A. N. G., ... & Songtao, W. (2021). The role of new energy in carbon neutral. *Petroleum exploration and development*, 48(2), 480-491.
- DiLisi, G. A. (2017). The Hindenburg disaster: Combining physics and history in the laboratory. *The Physics Teacher*, 55(5), 268-273.
- Kapdan, I. K., & Kargi, F. (2006). Bio-hydrogen production from waste materials. *Enzyme and microbial technology*, 38(5), 569-582.
- Kim, H., Hartmann, N., Zeller, M., Luise, R., & Soylu, T. (2021). Comparative tco analysis of battery electric and hydrogen fuel cell buses for public transport system in small to midsize cities. *Energies*, 14(14), 4384.
- Lee, D. H., Hsu, S. S., Tso, C. T., Su, A., & Lee, D. J. (2009). An economy-wide analysis of hydrogen economy in Taiwan. *Renewable Energy*, 34(8), 1947-1954.
- Li, Z., Wang, W., Ye, M., & Liang, X. (2021). The impact of hydrogen refueling station subsidy strategy on China's hydrogen fuel cell vehicle market diffusion. *International Journal of Hydrogen Energy*, 46(35), 18453-18465
- Lucia, U. (2014). Overview on fuel cells. *Renewable and Sustainable Energy Reviews*, 30, 164-169.
- Lulianelli, A., & Basile, A. (Eds.). (2014). *Advances in hydrogen production, storage and distribution*. Elsevier.
- Moradi, R., & Groth, K. M. (2019). Hydrogen storage and delivery: Review of the state-of-the-art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy*, 44(23), 12254-12269.
- Sandstede, G., Cairns, E. J., Bagotsky, V. S., & Wiesener, K. (2010). History of low temperature fuel cells. *Handbook of Fuel Cells*, 1, 145-218.
- Sokolov, A., Saritas, O., & Meissner, D. (2019). Global Market Creation for Fuel Cell Electric Vehicles. *Emerging Technologies for Economic Development*, 131-152.
- Steinberg, M., & Cheng, H. C. (1989). Modern and prospective technologies for hydrogen production from fossil fuels. *International Journal of Hydrogen Energy*, 14(11), 797-820.

- Walker, G. (Ed.). (2008). Solid-state hydrogen storage: materials and chemistry. Elsevier.
- Wang, Y., Dai, X., You, H., & Gao, M. (2018). Research on the design of hydrogen supply system of 70 MPa hydrogen storage cylinder for vehicles. *International Journal of Hydrogen Energy*, 43(41), 19189-19195.
- West, J. B., & Cavendish, H. (2014). Hydrogen, carbon dioxide, water, and weighing the world. *American Journal of Physiology-Lung Cellular and Molecular Physiology*, 307(1), L1-L6.
- Witkowski, A., Rusin, A., Majkut, M., & Stolecka, K. (2017). Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. *Energy*, 141, 2508-2518.
- Zhu, M., Ai, X., Fang, J., Wu, K., Zheng, L., Wei, L., & Wen, J. (2023). Optimal integration of electrolysis, gasification and reforming for stable hydrogen production. *Energy Conversion and Management*, 292, 117400.
- Zhang, L., Jia, C., Bai, F., Wang, W., An, S., Zhao, K., ... & Sun, H. (2024). A comprehensive review of the promising clean energy carrier: Hydrogen production, transportation, storage, and utilization (HPTSU) technologies. *Fuel*, 355, 129455.