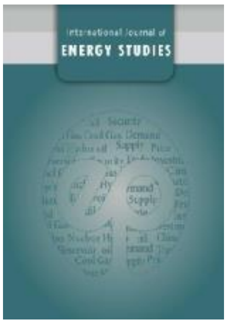
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Review Article

Int J Energy Studies, 2021;6(1):67-94

Received: 07 May 2021
Revised: 24 June 2021
Accepted: 24 June 2021

An overview on the renewable hydrogen generation market

Nima Norouzi[a,*]

[a] *Department of Energy Engineering and Physics, Amirkabir University of Technology (Tehran Polytechnic), 424 Hafez Avenue, PO Box 15875-4413, Tehran, Iran, 0000-0002-2546-4288*

*(*Corresponding Author: nima1376@aut.ac.ir)*

Highlights

- Hydrogen storage is more profitable comparing to batteries
- Energy leakage of hydrogen storage is lesser than other storage systems
- Hydrogen storage capacity and energy density is higher comparing other technologies
- Hydrogen storage has lower levelized cost comparing to other technologies
- Hydrogen storage and production market is emerging in many countries, including China

You can cite this article as: Norouzi, N. "An Overview on the renewable hydrogen generation market", *International Journal of Energy Studies* 2021:6(1);67-94.

ABSTRACT

As high-quality secondary energy, hydrogen has huge application potential in energy storage and utilization and helps solve renewable energy consumption in the power system. This article proposes a new type of energy-carrying form that uses electricity and hydrogen as energy carriers—an electric-hydrogen energy system to further increase the proportion of renewable energy in primary energy consumption. The article discusses the significance of the development of the electric hydrogen energy system, gives the structural framework of the electric hydrogen energy system, and reviews the relevant research foundation and key technologies from the aspects of generation (manufacturing), storage, transmission, distribution, and utilization. Finally, the electric hydrogen energy system has prospected from economic analysis, system integration, and the near-term implementation path.

Keywords: *Hydrogen energy system, high-proportion renewable energy, energy storage, hydrogen production, fuel cell*

1. INTRODUCTION

The gradual depletion of traditional fossil energy sources and the increasingly prominent environmental problems have always been important problems plaguing countries worldwide, restricting the further development of human society [1-2]. Therefore, promoting the energy transition and consumption revolution and building a green, low-carbon, safe, and clean energy system with renewable energy as the mainstay are the strategic choices of China and even most countries in the world [3]. The proportion of renewable energy sources such as wind, solar, and hydropower in primary energy consumption is the core indicator of this energy transition [4]. The International Energy Agency (IEA) pointed out that the global new renewable energy power generation capacity in 2019 was 190.9 GW, of which China's new renewable energy power generation capacity was 65.4 GW, accounting for 34.3% of the global new capacity [5]. As of the end of 2019, China's installed renewable energy power generation capacity reached 794 GW, accounting for approximately 39.5% of the total installed power capacity, of which hydropower, wind power, and photovoltaic power generation capacity were 356,210,204 GW, respectively; on the other hand, the whole year The amount of wastewater, wind and electricity are 30.0, 16.9, and 4.6 TW·h respectively [6], and the problem of renewable energy consumption is very prominent. Energy storage technology, expansion of transmission infrastructure, backup power generation, demand-side management, and load reduction are important measures to achieve a high proportion of renewable energy consumption [7]. Compared with other measures, energy storage technology is more difficult to implement than other measures. However, there are advantages in transfer volume and other aspects, which have attracted more and more attention and research. Literature [8-10] pointed out that energy storage technology has power system frequency modulation functions, peak shaving, line congestion management, ensuring power quality, improving power supply reliability, and playing an important role in absorbing a high proportion of renewable energy.

In the research on power systems with a high proportion of renewable energy, hydrogen is only regarded as a form of energy storage, and its application potential as a terminal energy source has not been explored. At present, hydrogen is mainly used in the chemical industry as a raw material for synthetic ammonia, methanol, and petroleum refining and has commercial value in the metal smelting, electronics, and glass industry [11]. With hydrogen fuel cell technology development, hydrogen can be directly used as a terminal energy source in more fields. For example, hydrogen fuel cells can be applied to different types, purposes, and transportation scales, such as light cars, buses, and heavy vehicles. Compared with electric vehicles, hydrogen fuel cell vehicles do not have self-discharge and have the advantages of high energy density, no noise, zero pollution, long driving range, short refueling time, etc. [12]; hydrogen can also be based on different types of Fuel cell technology realizes distributed power generation/medium-scale cogeneration (100 kW~3 MW) and small-scale household cogeneration (power less than 25 kW), etc. [13-14]. It can be seen that hydrogen as a terminal energy source has a huge application space.

On the other hand, thanks to the low cost of hydrogen production, almost all of the world's existing hydrogen energy is converted from traditional fossil energy sources, of which the proportions of hydrogen production from natural gas and hydrogen production from coal gasification are 76% and 23% respectively [15]. With the continuous expansion of installed capacity of intermittent renewable energy power generation such as wind and light, surplus renewable energy to generate electricity will effectively reduce the cost of electricity generation. In addition, the hydrogen produced by electrolysis has a higher purity than natural gas reforming and other methods. Therefore, it can be used in chemical production and hydrogen fuel cell power generation. As a flexible and dispatchable power generation method, hydrogen fuel cell power generation is conducive to the safe and stable operation of the power system, and at the same time, can promote the absorption of intermittent renewable energy such as wind and light in the power system.

Therefore, as high-quality secondary energy complements electricity, hydrogen can play a greater role in the future energy system. Taking this as a starting point, this article proposes a new energy-carrying form-electric hydrogen energy system (EHS) that uses electricity and hydrogen as energy carriers and faces the consumption of a high proportion of renewable energy. This article first describes the structural framework of the electric hydrogen energy system in detail. It then reviews the existing research foundation and technical support from generation (manufacturing), storage, transmission, distribution, and utilization, and finally from economic analysis, system integration, and recent implementation paths for the electric hydrogen energy system in three aspects.

The electro-hydrogen energy system is defined as follows: using electricity and hydrogen as energy carriers (through all links of generation (manufacturing), storage, transmission, distribution, and use), with a high proportion of renewable energy consumption as the goal, it can meet the needs of human production and life. A low-carbon sustainable new energy system with multiple energy needs such as electricity, heat, cold, and hydrogen. According to different system scales, the electric-hydrogen energy system can be divided into a regional-level electric-hydrogen energy system and a cross-regional-level electric-hydrogen energy system (composed of several regional-level electric-hydrogen energy systems interconnected by a power transmission network and a hydrogen transmission network). The structure of a regional electric hydrogen energy system is shown in Figure 1.

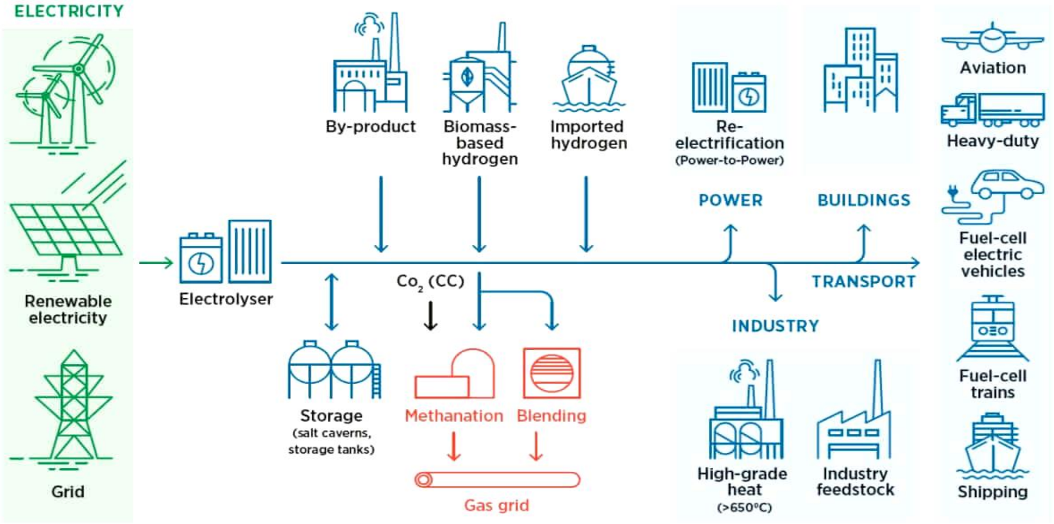


Figure 1. Structure of electricity and hydrogen energy system

Firstly, in the energy input link, based on various power generation and hydrogen production technologies, fossil energy and the regional wind, solar, hydropower, and biomass energy, and other primary renewable energy sources are converted into two types of secondary energy sources: electricity and hydrogen. The two major energy subsystems of electricity and hydrogen. The two major subsystems are coupled through the electric hydrogen production equipment and the fuel cell to realize the two-way conversion of electricity and hydrogen. While meeting the power needs of industrial, commercial, and residential users in the area, the electrical energy subsystem uses compressed air energy storage, pumped water storage, and lithium batteries to store electrical energy and uses different transmission and distribution voltage levels. The electric network and other areas carry out electric energy transmission. Due to the popularization of distributed renewable energy power generation equipment such as rooftop photovoltaics at the energy-consuming end, some power consumers have become producers and consumers in the electrical load. Demand-side response technology can strengthen terminal electrical loads, which is conducive to power generation. Safe and stable operation of the system. In addition, electricity can be converted into heat/cold energy of different grades through various electric heating/cooling equipment such as heat pumps/air conditioners to meet some of the heating needs of domestic hot water, building heating, and industrial heat in production and life in the region. Meet part of the transportation demand in the region through electric vehicles.

The hydrogen energy subsystem can store hydrogen in compressed gas, liquid, and solid forms on a large scale and carry out intra-regional distribution (mainly compressed gas trucks and low-pressure pipe networks) and out-of-region transmission (mainly compressed gas trucks) low-pressure pipe networks) through pipe networks and transportation networks. Cryogenic liquid trucks, high-pressure pipeline networks, and ships are the mainstay). On the energy consumption side, hydrogen can be used for combined heat and power generation through fuel cells or heated by gas boilers to meet part of the heat load required for production and life in the region; hydrogen can be used as hydrogen fuel cell vehicles through gaseous hydrogen refueling stations and liquid hydrogen refueling stations. The fuel for vehicles such as buses and trucks may be converted into gasoline and injected into gas stations to supply traditional fuel vehicles; in addition, hydrogen can also be directly used as industrial raw materials or converted into ammonia, methane, methanol, and other hydrocarbons for industrial production.

The electric hydrogen energy system can provide a good way to absorb intermittent renewable energy such as wind and light. Use surplus renewable energy to directly produce hydrogen, effectively solving the problems of abandoning wind and light, and hydrogen is easier to store on a large scale and long-term than electricity; electrical storage equipment and demand-side response technology in the power subsystem can absorb part of the surplus renewable Energy generation capacity; the excess electric energy in the power subsystem is converted into hydrogen energy through the hydrogen production technology. According to the requirements of the “Energy Production and Consumption Revolution Strategy (2016-2030)” announced by the National Development and Reform Commission and the National Energy Administration, by 2030, the proportion of non-fossil energy power generation in total power generation will reach 50% [4]. , The electric hydrogen energy system will begin to take shape and play an important role in the high proportion of renewable energy consumption.

This work shows the progress of hydrogen taking its place as a key factor of the future green energy society. It reviews recent developments of hydrogen technologies, their social, industrial, and environmental standing, and the stage of transitioning economies of both advanced and beginner countries. An example of the ongoing energy transition in China is considered, which is implementing a hydrogen strategy with the ambition to one day equally participates in the rapidly emerging hydrogen market. The innovation of this study is a comprehensive and detailed market study of the hydrogen industry, in which the mature technologies of hydrogen production are studied in the term of the total cost, market potential, technical future, and their current performances.

2. THEORETICAL FRAMEWORK

The electric hydrogen energy system includes the generation (manufacturing), storage, transmission, distribution, electricity, and hydrogen energy use. The following is a review of the existing relevant research foundation and technological maturity from these five links. Considering that the various existing technologies that use fossil energy for energy are very mature, the following mainly reviews related technologies for renewable energy.

2.1. Renewable energy power generation and hydrogen production technology

Renewable energy power generation mainly includes wind power, photovoltaic power, hydropower, and biomass power generation. In recent years, the installed scale of renewable energy power generation in the power system has expanded. As of the end of 2019, China's cumulative installed capacity of renewable energy power generation reached 794 GW, and renewable energy power generation accounted for 27.9% of the total power generation [6]. With renewable energy power generation technology development, its investment costs are gradually reduced, and energy conversion efficiency increases. Taking photovoltaic power generation as an example, the photoelectric conversion efficiency has increased from 8% in the 1990s to more than 20% in 2019 [16-17]. In China, the cost of photovoltaic power generation has also dropped from 5.6~15.1 yuan/(kW·h) in 2000 to 0.29~0.79 yuan/(kW·h), and it can go online at a fair price[18]. Therefore, renewable energy power generation will continue to develop rapidly in recent years. However, with the gradual increase in the installed capacity of intermittent renewable energy power generation equipment such as wind and wind, the strong uncertainty of renewable energy output and the low inertia, weak immunity, and multi-time scale response caused by power electronics will cause problems. Brings huge challenges to the operation and control of power subsystems. To achieve the high proportion of renewable energy consumption goals in the electric hydrogen energy system, it is necessary to improve renewable energy forecasting technology and research the stability analysis theory and optimized operation methods for system-related problems [19].

Renewable energy hydrogen production mainly includes biomass thermochemical hydrogen production, geothermal hydrogen production, wind power hydrogen production, solar hydrogen production, and hydrogen production by electrolysis of water [20-29]. Among them, biomass thermochemical hydrogen production is to convert biomass into mixed gas (CO, CO2, CH4, H2, etc.) through high-temperature gasification and further extract H2; the principle of geothermal hydrogen production is to use geothermal energy to carry out high-temperature Hydrolysis directly produces hydrogen; solar hydrogen production includes solar power generation and water electrolysis to produce hydrogen, solar high-temperature heat collection, and decomposition of water to produce hydrogen, photobiological hydrogen production, and photocatalytic hydrogen production, etc.; hydrogen production from the electrolysis of water is a promising hydrogen production In this way, the surplus electric energy in the power subsystem can be used to electrolyze water to produce H2 and O2.

Table 1 shows the main performance comparison of alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide (SOEC) electrolysis of the three electric hydrogen generation technologies [15]. Among them, alkaline electrolysis and PEM electrolysis belong to low-temperature electrolysis technologies. The working temperature is in the range of 50-80 ℃. The single-stack power has reached the megawatt level and has been industrialized, and the system efficiency can reach up to 70%. The SOEC electrolysis, developed in recent years, is a high-temperature electrolysis technology. The operating temperature is in the range of 650 to 1,000 ℃. Therefore, the conversion efficiency of the system is improved compared with the former two. Even under the premise of making full use of industrial waste heat, Its conversion efficiency can reach more than 100%. In addition, SOEC electrolysis equipment can also reverse the reverse conversion of hydrogen energy into electrical energy [15]. This feature makes it suitable for combining hydrogen storage equipment to provide balanced power for the power subsystem, but the operating temperature is too high. It will cause material degradation and make the equipment life shorter, which is an important challenge for the future development of SOEC electrolysis equipment. The three electric hydrogen generation technologies all have high operational flexibility in terms of dynamic characteristics, and their working ranges are 10%~110%, 0%~160%, and 20%~100%, respectively. Among them, alkaline electrolysis and PEM. The dynamic response time of electrolysis is in the millisecond-second level, which can be adjusted flexibly and quickly according to renewable energy output to support the stable operation of the power subsystem. At present, there are more than 200 electricity-to-hydrogen projects built or under construction at home and abroad, with installed capacity ranging from kilowatts to megawatts. Some electricity-to-hydrogen projects are shown in Appendix A, Table A1 [30].

Table 1. Comparison of three water electrolysis technologies for hydrogen production

Technology Type	Working pressure/MPa	Working temperature/℃	Working interval/%	System efficiency/%
Alkaline electrolysis	0.10~3.00	65~85	15~115	62~73
PEM	3.00~8.00	55~85	5~165	54~61
SOEC	0.00	600~1000	25~105	73~82

2.2. Electricity/Hydrogen Energy Storage Technology

Electric energy storage can improve power quality, suppress power fluctuations of renewable energy, frequency modulation, emergency power supply, etc., and play a huge role in the operation of power systems. According to the different forms of energy storage, electrical energy storage mainly includes mechanical energy storage, electromagnetic energy storage, electrochemical energy storage, and phase change energy storage. Mechanical energy storage mainly includes pumped water storage, compressed air energy storage, flywheel energy storage, etc.; electromagnetic energy storage is subdivided into superconducting energy storage supercapacitors; electrochemical energy storage includes lithium-ion batteries, flow batteries, and Typical secondary battery systems such as sodium-sulfur batteries. Different electrical storage devices have big differences in power level, discharge time, conversion efficiency, service life, investment cost, etc. The specific parameters can be referred to [10]. Schmidt et al. took nine commonly used energy storage methods such as compressed air energy storage, pumped water storage, and lithium battery energy storage as the research objects and studied their development potential in 12 application fields such as dynamic response, seasonal storage, and congestion management [31]. The International Energy Agency pointed out that lithium-ion batteries have become the most widely used electrical energy storage equipment at present, accounting for the highest proportion of all new energy storage capacity [32]. Furthermore, compressed air energy storage, pumped water storage and hydrogen storage can play an important role in long-term energy storage [31, 33].

Hydrogen storage can be divided into two categories: physical storage and chemical storage: physical storage can be divided into low-temperature liquid hydrogen storage, high-pressure gaseous hydrogen storage, and low-temperature high-pressure storage according to different pressure and temperature hydrogen storage forms; chemical storage is mainly metal hydrogenation Hydrogen storage by chemical substances, hydrogen storage by organic liquid hydrides, and hydrogen storage by inorganic substances [34]. Appendix A Figure A1 shows the change of hydrogen density with temperature under different storage pressures [35]. It can be seen from the figure that the density of hydrogen can be increased by reducing the temperature or increasing the pressure. At present, the four most common hydrogen storage methods include 1. High-pressure gas storage (normal temperature, pressure of 70 MPa), the storage density of 39.1 kg/m3; 2. Cryogenic compression storage (temperature between 150~273 K, pressure of 50 MPa), storage density can reach 50 kg/m3; 3. Cryoprecipitation compression storage (temperature less than 150 K, pressure 35 MPa), storage density can reach more than 80 kg/m3; 4. Low-temperature liquid storage (temperature 20 K, pressure Less than 0.6 MPa), the storage density can reach more than 71.0 kg/m3. Among the above four storage methods, high-pressure gas storage is the most widely used, with a conversion efficiency of 90% to 95% (considering compression loss) [36]; cryoprecipitate compression storage and low-temperature liquid storage have the highest hydrogen storage density, with a conversion efficiency of 75%. % And 65%~75% (taking into account the liquefaction loss, theoretically 4~10 kW·h is consumed for 1 kg of hydrogen liquefied) [37]. In terms of chemical storage, hydrogen can be converted into ammonia or liquid aromatic compounds (such as benzene, toluene) for organic liquid storage, with conversion efficiencies of 82%~93% and 60%~65%, respectively [15]. Its advantages are Hydrogen energy can be transported in liquid form using existing petroleum pipelines; hydrogen can also be stored in certain metals or alloys in the form of metal hydrides, and hydrogen can be released by heating, which is a representative solid storage Hydrogen way. Appendix A Table A2 shows the comparison of the volume, weight, and density of storage devices when 3 kg of hydrogen is stored in gaseous, liquid, and solid states, respectively. From the table, it can be intuitively seen that solid-state hydrogen storage devices have more advantages than gas and liquid hydrogen storage devices. Smaller volume, but the highest quality, the lowest mass percentage [36].

The electric hydrogen energy system needs to give full play to the easier large-scale, long-term hydrogen energy storage advantages. Table A3 of Appendix A further provides a comparison of key parameters of three large-scale hydrogen energy storage technologies: pipe storage, underground storage (take salt caverns as an example), and above-ground spherical or cylindrical tank storage [38]. It can be seen from the table that the storage capacity is affected by storage volume and pressure. The underground storage capacity is the largest, and the above-ground cylindrical tank storage capacity is the smallest, and different storage methods require a certain percentage of emboldened energy. In addition, the use of existing depleted oil and gas reservoirs, underground aquifer gas storage, and salt cavern gas storage is the most economical and convenient way to realize large-scale hydrogen storage (unit investment cost is about 1.0 yuan/(kW·h) Within [39]). Among them, gas storage for depleted oil and gas reservoirs stores hydrogen by injecting hydrogen into the developed oil and gas fields, eliminating geological exploration. It has the advantages of a short construction period and low investment cost, but it has high requirements on the surrounding environment of the caprock and the reservoir. The underground aquifer gas storage is constructed under the impermeable aquifer caprock and needs to drain the water in the pores of the rock formation. The advantage lies in the structure's integrity, but the disadvantage is the higher risk of controlling the gas and water interface and the long construction period. The salt cavern gas storage is built on the salt layer and has good physical properties. It is currently the best underground hydrogen storage method. Appendix A Table A4 shows some actual hydrogen storage projects, all of which use salt caverns for large-scale hydrogen storage [40].

2.3. Electricity/Hydrogen Energy Transmission Technology

The production and utilization of energy are spatially different, and energy transmission is required to meet the energy demand of different regions. Taking the current energy supply and consumption situation in China as an example, the eastern coastal areas need to rely on the transmission of energy from the west. At present, China's power grid is very mature, and the high-speed development of UHV AC/DC transmission technology in recent years can realize high-power and long-distance power transmission. Furthermore, with the development and utilization of a high proportion of renewable energy, a new generation of power network transmission network framework is prominently manifested as a combination of renewable energy and clean energy, the combination of backbone power grids and distributed power sources, and the combination of backbone power grids with local area networks and microgrids [4].

At present, hydrogen energy is mainly transmitted in three ways: compressed-gas trucks, cryogenic liquid trucks, and pipeline transmission. Appendix A Table A5 gives the comparison of key indicators of these three transmission methods [38]. It can be seen from the table that pipeline transmission has advantages in transmission capacity, transmission efficiency, and transmission distance and can use its storage characteristics for hydrogen storage. However, its disadvantage is that the investment cost is high, so it is suitable for medium and long-term development. Transmission to long-distance and high-demand areas; although the transmission capacity of compressed gas trucks is small, it is more flexible than other methods. It is suitable for transmitting hydrogen to short-distance and low-demand areas, such as those scattered throughout the city. The distribution of hydrogen energy at hydrogen refueling stations is suitable for near-term development; low-temperature liquid trucks are somewhere between the two in terms of transmission capacity and efficiency and can simultaneously undertake the duties of large-capacity long-distance hydrogen energy transmission and hydrogen supply to liquid hydrogen refueling stations. Ferries to transport low-temperature liquid hydrogen can achieve a single hydrogen output of tens of thousands of tons, especially suitable for transnational transportation and suitable for medium and long-term development. It should be pointed out that in addition to technical challenges, hydrogen transmission also requires huge investment costs in infrastructure. For example, hydrogen pipelines must be made of strong sealing and high-quality stainless steel due to hydrogen energy's special physical and chemical properties, making the investment cost of hydrogen pipelines two higher than natural gas pipelines under the same pipe diameter. Times [41]. Therefore, the form of end-use hydrogen, the cost of hydrogen transmission, and the future market demand will be the key to deciding which hydrogen transmission method to choose.

Considering that the hydrogen energy transmission network is still immature, many scholars pointed out that mixing hydrogen directly into natural gas or injecting it into natural gas pipelines for transmission after methanation can be regarded as a transitional means to develop an electric hydrogen energy system. The European research team has given that the volume ratio of hydrogen-mixed natural gas can reach 10% [42]; the literature [43] pointed out that 17% of the hydrogen-mixed ratio will not cause any problems, but in practical applications, more from a safety perspective Set out to control it within 5%. Because the density of hydrogen is very low, about 1/8 of the density of natural gas, to meet the energy demand, the pressure of hydrogen pipelines is much higher than that of natural gas. For example, a natural gas pipeline operating at 0.4 MPa needs a compressor to compress it to high pressure of 1 to 2 MPa when used for hydrogen transmission, so the transmission loss of the pipeline is relatively higher [15]. In addition, hydrogen is very volatile, and the polymer materials used to make natural gas pipelines have high porosity and are not suitable for use as hydrogen pipeline materials. At present, expensive low-carbon steel is used to manufacture most of the hydrogen transmission pipelines. If relatively inexpensive materials can be developed to manufacture hydrogen transmission pipelines, it will help accelerate hydrogen energy transmission and distribution pipeline networks.

2.4. Electricity/Hydrogen Energy Utilization Technology

Compared with traditional fossil energy, electricity has the advantages of cleanliness, safety, and convenience and has been used in all aspects of human life. The "China Energy and Power Development Outlook 2019" issued by State Grid Energy Research Institute Co., Ltd. [44] predicts that by 2050, electric energy will account for more than 50% of terminal energy consumption. In the electric hydrogen energy system, the proportion of electric energy in the final energy consumption can be further increased.

In the hydrogen energy utilization link, hydrogen energy can meet different energy needs such as electricity production, thermal energy supply, and transportation through various fuel cell technologies. Table 2 shows five typical types of Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Solid Oxide Fuel Cell (SOFC), and Molten Carbonate Fuel Cell (MCFC). The working characteristics of fuel cells [13]. PEMFC and AFC have fast start and stop speeds and are most suitable for hydrogen fuel cell vehicles and as backup power generation in the power system; PAFC, MCFC, and SOFC have high operating temperatures and are suitable for distributed power generation and cogeneration. In terms of conversion efficiency, the electric conversion efficiency of PEMFC, AFC, MCFC, and SOFC is about 60%, while the efficiency of PAFC, MCFC, and SOFC can reach 85% when working with cogeneration [45]. The rapid development of fuel cell technology has led to a significant drop in investment costs in recent years. It has dropped from 2,000 to 16,000 yuan/kW in the early 20th century to 1,000 to 1,400 yuan/kW in 2020 [13]. In 2030, it will reach 410~1,030 yuan/kW (AFC), 280 yuan/kW (PEMFC) and 560 yuan/kW (SOFC) [39].

Table 2. Comparison of different fuel cell technologies

Technology	Operating temperature/℃	Capacity/kW	Application field
PEMFC	<125	<280	Backup power/mobile power/traffic/distributed power generation
AFC	<110	10~110	Backup power/traffic
PAFC	155~210	50~1100	Distributed Power Generation/Combined Heat and Power
MCFC	610~710	<1100	Distributed Power Generation/Combined Heat and Power
SOFC	510~1050	5~3100	Distributed Power Generation/Combined Heat and Power

With the development of hydrogen fuel cell technology, hydrogen can be used as fuel for various types of vehicles such as small cars, buses, medium and large trucks, and airplanes, and it has huge application potential in the transportation field. The hydrogen refueling station is an important terminal supply facility for the development of hydrogen fuel cell vehicles, which can be divided into input-type hydrogen refueling stations according to energy sources (hydrogen energy comes from the hydrogen transmission network, and the core equipment is compressors, hydrogen storage containers, and hydrogen refueling machines) and Self-sufficient hydrogen refueling station (in addition to the above three core equipment, it also includes electrical hydrogen production equipment) [14]. In addition, hydrogen refueling stations can also be divided into gaseous hydrogen refueling stations and liquid hydrogen refueling stations according to hydrogen storage. At present, gaseous hydrogen refueling stations mainly supply hydrogen at two high-pressure types of 35 MPa and 70 MPa, while liquid hydrogen refueling stations are the same. Compared with gaseous hydrogen refueling stations, the hydrogen supply is larger, suitable for larger-scale hydrogen refueling needs. However, as the pressure of the hydrogen refueling station is higher than that of the existing gas refueling station (25 MPa), the safety requirements for the hydrogen refueling station are higher. For example, the pressure resistance level of the hydrogen refueling machine needs to be greatly improved. “Technical Specification for Hydrogen Refueling Station” [46] The fire hazard level of the hydrogen refueling station is classified as Class A.

Hydrogen can also be used as an industrial raw material in the chemical industry. For example, it can be converted into ammonia through the Haber synthetic ammonia reaction, which can be used to make ammonia, nitrogen fertilizer, compound fertilizer, ammonium salt, soda ash, etc.; it can be reacted with CO2 to synthesize methane and methanol for the production of acetylene, hydrocyanic acid, formaldehyde, and methyl alcohol. Amines and olefins can also synthesize gasoline by reacting with CO to ignite internal combustion engine fuel. It needs to be pointed out that compared with the traditional coal chemical method, the cost per kilowatt-hour of the hydrogen mentioned above production + hydrogen-to-X method is less than 0.14 yuan/(kW·h) to have cost advantages in the above-mentioned industrial fields [29], that is, rely on the power system There is a large amount of surplus electric energy. As for the electricity-hydrogen energy system that is oriented to a high proportion of renewable energy as described in this article, as the proportion of renewable energy power generation gradually increases, combined with the gradual improvement of the hydrogen energy supply chain, hydrogen is expected to be a raw material for those mentioned above related industrial fields. Thus, substituting traditional fossil energy sources to achieve low-carbon or even zero-carbon emissions in the chemical industry.

In addition, the safety of hydrogen energy has always been the focus of attention, which has restricted the popularization and utilization of hydrogen energy on the energy-consuming side to a certain extent. Appendix A Table A6 comprehensively compares the safety of three-terminal fuels, hydrogen, methane, and gasoline, from more than ten indicators such as gas toxicity, density, diffusion performance, and ignition temperature [38]. It can be seen from Table A6 that the characteristics of low density, high diffusivity, and high calorific value of hydrogen make it safer than conventional fuels such as natural gas and gasoline. In contrast, low ignition energy, low ignition temperature, higher explosion energy, and higher flame radiation rate make hydrogen more dangerous than other fuels. The overall safety of hydrogen energy is better than that of methane and gasoline. Literature [47] further pointed out that the extremely low density of hydrogen energy allows it to quickly diffuse out of the leak, which reduces the risk of fire or explosion; in addition, because the flame of hydrogen combustion does not contain soot emits very little heat radiation. , The impact on the surrounding environment is small. However, due to the immaturity of existing hydrogen energy-related technologies, explosion problems occur from time to time [48], restricting the development of hydrogen energy to a certain extent. Therefore, more standardized technical standards should be formulated in the development of hydrogen energy. The “Blue Book of Infrastructure Development of China’s Hydrogen Energy Industry (2018)” [14] gives China’s current national standards for hydrogen energy technology, which is the foundation for China’s hydrogen energy industry. Guide the development of the facility.

3. METHODOLOGY

As shown in Figure 2, the hydrogen energy industry involves a huge industry chain covering hydrogen production, storage, transportation, and terminal applications [17]. Hydrogen can be processed to meet different demands. To meet the hydrogen fuel standard, the hydrogen must be purified after preparation. During the hydrogen production process, a large amount of carbon dioxide is emitted. Therefore, purification costs and carbon trading costs are also part of the total cost of hydrogen.

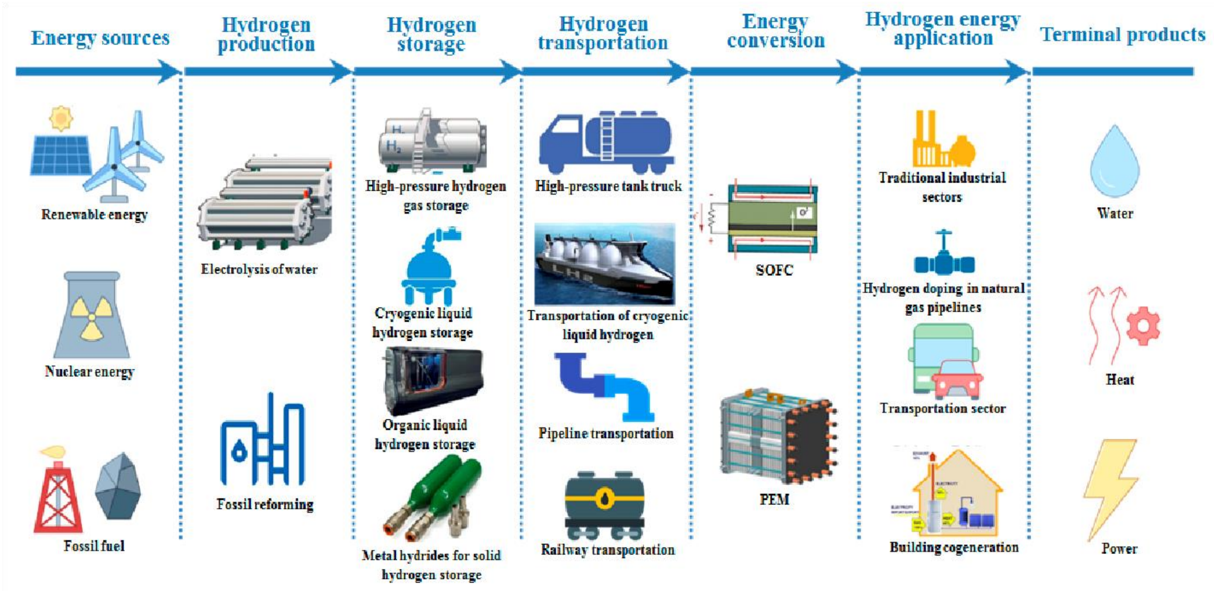


Figure 2. Schematic diagram of the hydrogen industry chain.

According to the survey, the current demand for hydrogen in transportation far exceeds the supply, while the storage time and storage scale are small [18]. Therefore, the storage cost of hydrogen was not studied as an independent factor in this paper. Instead, the storage cost during transportation was included in the transportation cost for analysis. Therefore, the cost of hydrogen is mainly affected by its production cost, transportation cost, purification cost, and carbon trading cost, as shown in Equation (1) [19–24].

$$C = I1,m + D1,t + W1,r + M1,i, (1)$$

Where C is the hydrogen fuel cost, $I_{1,m}$ is the hydrogen production cost, $D_{1,t}$ is the purification cost, $W_{1,r}$ is the carbon trading cost, and $M_{1,i}$ is the hydrogen transportation cost. The specific expression of Equation (1) is as follows:

$$\begin{cases} I_{1,m} = I_{1,p} + \left(1 + k_m + \frac{1}{n_m}\right) I_{1,a} + I_{1,f} + I_{1,ot} \\ W_{1,r} = W_{1,p} + \left(1 + k_r + \frac{1}{n_r}\right) W_{1,a} + W_{1,ot} \\ M_{1,i} = \varphi_i M_{1,e} \\ D_{1,t} = S_{1,0} + \lambda_l L_{1,0} \end{cases} \quad (2)$$

where $I_{1,p}$, $W_{1,p}$ is the labor cost, $I_{1,a}$,$W_{1,a}$ is the fixed production cost (one-time investment), related to the project scale $I_{1,ot}$, $W_{1,ot}$ represents the supplementary materials and other expenses, k_m, k_r is the maintenance cost coefficient, nm, nr is the operating life of the equipment, $I_{1,f}$ is the raw material cost, related to the hydrogen production process, involving coal, natural gas, electricity, water, etc., $M_{1,e}$ is the carbon trading price, ϕ_i is the carbon emission coefficient, $S_{1,0}$ is the hydrogen compression cost [25], $L_{1,0}$ is the cost of transportation equipment, and λ_l is the distance cost coefficient. The innovation of this method is a systematic view of market analysis and considering the end-to-end approach to estimate the costs. Also, implementing this method helps researchers to be able to consider different aspects of supply-chain in their studies.

4. RESULTS AND DISCUSSION

4.1. Economic and Technical Analysis

From the perspective of energy consumption, hydrogen can be used as a raw material for industrial enterprises such as synthetic ammonia plants and oil refineries, and it can also meet people’s transportation needs through hydrogen fuel cell vehicles. When hydrogen is used as a terminal energy source, its price competitiveness is analyzed: In industrial applications, taking synthetic ammonia as an example, hydrogen can be converted into ammonia through the Haber ammonia synthesis reaction. Considering that the conversion efficiency of the reaction is 70%, 1 kg is synthesized ammonia requires 0.25 kg of hydrogen and 1.05 kg of nitrogen. If the price of synthetic ammonia is 3 yuan/kg and the price of raw nitrogen is 0.65 yuan/kg, the price of raw hydrogen must be less than 9.4 yuan/kg to achieve profitability; in transportation, hydrogen Fuel cell vehicles can travel 106.2 km per kg of hydrogen [49], while traditional fuel-fuel vehicles can only travel 13.9 km per kg of gasoline [48]. The mass ratio of gasoline to hydrogen is 7.65:1 under the same travel demand.

When gasoline is 7-10 yuan/kg, the corresponding hydrogen price is 53.5-76.5 yuan/kg. From the above analysis, it can be seen that the price competitiveness of hydrogen in different application fields is significantly different. Considering the supply side, define the Levelized cost (LCOH) of hydrogen production by electrolysis as LCOH. Its calculation equation is:

$$L_{COH} = \frac{c_{inv}^{P2h} C^{P2h} + \sum_{n=1}^{N} \frac{\left(c_{O\&m}^{P2h} C^{P2h} + 8760 c^{elec} p^{elec}\right)^2}{(1+r)^n}}{\sum_{n=1}^{N} \frac{365H}{(1+r)^n}} \qquad (3)$$

Where: c_{inv}^{P2h}, $c_{O\&m}^{P2h}$ and c^{elec}, C^{P2h}, P^{elec} And H are the rated input power, purchasing power, and daily hydrogen production capacity of the electrolytic cell of the electric hydrogen production system, respectively; n is the lifespan of the system; r is the interest rate; the meanings and values of other relevant economic and technical parameters are shown in Appendix A, Table A7.

Without loss of generality, assume that the daily hydrogen production capacity of the electrolytic hydrogen production system is 1 kg; both Cp2h and P_{elec} must be 2.26 kW. Figure 2 shows the electrolytic hydrogen production when the electricity price is between 0.1 and 0.8 yuan/(kW·h).

cost. In addition, assuming that the investment price of the coal gasification hydrogen production system is 19,000 yuan/(kW·h), and the conversion efficiency is 60%, based on the coal price of 0.76 yuan/kg, Figure 3 further shows that the carbon emission costs are respectively 0, The cost of hydrogen production from coal gasification at 50, 100, and 200 yuan/t is used as a comparison (as shown by the four dashed lines in the figure).

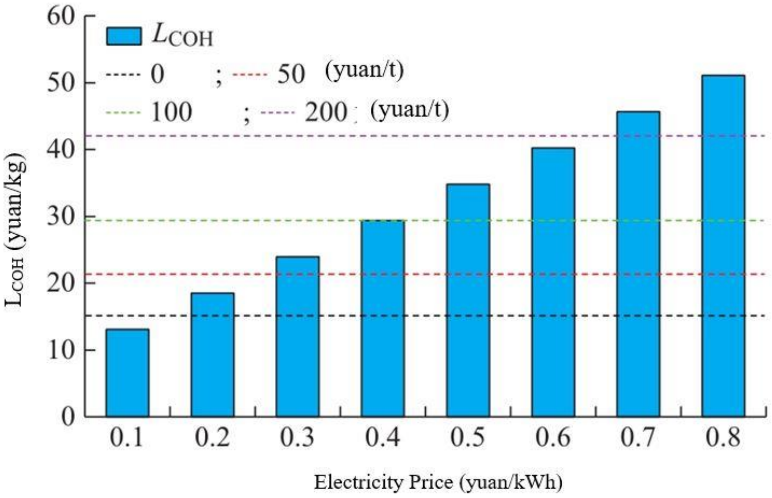


Figure 3. LCOH with different electricity prices

It can be seen from the figure that the cost of hydrogen production by electrolysis is greatly affected by the price of electricity. Only when the electricity purchase price reaches 0.1 yuan/(kW·h) will the cost of hydrogen production by electrolysis be lower than that of hydrogen production by coal gasification. In addition, considering that the cost of carbon emissions will increase the cost of hydrogen production from coal gasification, the cost of carbon emissions of 100 yuan/t will make the cost of hydrogen production from coal reach 30 yuan/kg, which is equivalent to 0.4 yuan/(kW·h) for electricity purchase. Therefore, the cost of electrolysis hydrogen production under the price is the same. In China, hydrogen is mainly derived from coal, and the price of hydrogen produced from coal without considering the cost of carbon emissions is 10-15 yuan/kg. Therefore, if you want to realize the application of electrolytic hydrogen in the industry, you need to significantly reduce the price of electricity or increase carbon emissions. In addition, with the development of renewable energy power generation technology, the cost of power generation has gradually decreased (the cost per kilowatt-hour of photovoltaic power generation can be as low as 0.3 yuan/(kW·h) or less [18]), combined with its increase in the proportion of power generation (2030 Strive to achieve 50% of non-fossil energy power generation), which is bound further to reduce the cost of hydrogen production by electrolysis. In terms of energy storage, Figure 3 shows the comparison between electricity storage and hydrogen storage in terms of storage time, storage scale, and energy conversion efficiency [40, 48].

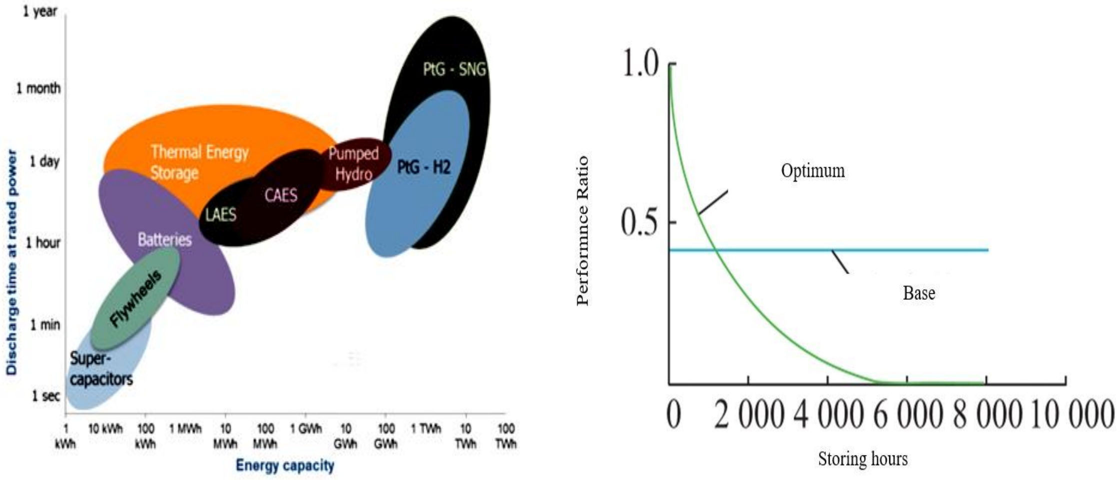


Figure 4. Comparison of electrical storage and hydrogen storage characteristics

It can be seen from Figure 4(left) that hydrogen storage is much larger than the commonly used compressed air energy storage and pumped water storage in terms of storage time and storage capacity [40]. In terms of storage costs, literature [31] shows that in inter-seasonal energy storage, the Levelized storage cost (LCOS) of hydrogen storage can drop from USD 3.6/(kW·h) in 2015 to USD 1.2 in 2050. /(KW·h), while the LCOS drop space of compressed air energy storage and pumped water storage is very small (both maintained at about 3.2 US dollars/kWh). Therefore, when the penetration rate of renewable energy is high enough, a large amount of surplus renewable energy power generation must be converted into hydrogen for long-term storage to make up for renewable energy output such as wind and solar different seasons. Figure 4(right) shows the energy conversion efficiency of hydrogen storage and electricity storage (the ratio of energy output to energy input) over time [31]. It can be seen from the figure that the initial efficiency of electric storage equipment is higher, but it varies with time. Therefore, as the storage time increases, its efficiency gradually decreases. However, hydrogen storage does not have its energy loss problem (except for liquid storage), and its conversion efficiency is unchanged. In addition, if we further consider the direct and efficient use of hydrogen energy, such as combined heat and power, the energy conversion efficiency can be further improved. Therefore, as the proportion of renewable energy in primary energy gradually increases, hydrogen will play an important role in energy storage.

4.2. System integration technology

The core goal of the electric hydrogen energy system is to achieve a high proportion of renewable energy consumption, and the key difference between the system characteristics and the existing renewable energy power system and integrated energy system is that it fully taps the hydrogen energy in energy generation (production, storage, transportation, distribution, utilization, etc. The previous article has comprehensively reviewed the maturity of hydrogen energy-related technologies. The following will analyze the problems of constructing an electric hydrogen energy system from a system perspective.

4.2.1 Business Model

The electric hydrogen energy system promotes the grid auxiliary service market, the carbon trading market, and the hydrogen energy market. For example, the hydrogen energy subsystem can provide auxiliary services such as frequency modulation, black start, network congestion management, and backup power generation for the power subsystem, which promotes the economic benefits of the hydrogen energy subsystem while improving the safety of the power subsystem and the consumption of renewable energy. Proportion. In addition, a large amount of surplus renewable energy power generation is conducive to reducing the cost of hydrogen production by electrolysis. Furthermore, as the carbon trading market gradually matures, it will further enhance the competitiveness of hydrogen production by electrolysis in the hydrogen energy market. Finally, hydrogen fuel cells, hydrogen storage technology, and electrolysis hydrogen production technology will further release the market’s demand for hydrogen energy and deepen the acceptance of new energy in the electricity market, thereby deepening the coupling degree of the electricity-hydrogen energy market. Therefore, exploring new business development models that include multiple energy coupling markets such as electricity, hydrogen energy, and carbon trading is necessary.

4.2.2 Planning and construction

In the planning and design of the electric and hydrogen energy system, full consideration should be given to the resource endowments and the current status of energy use in different regions of China, combined with the advantages of China’s power grid in energy transmission, to carry out coordinated planning for the power subsystem and the hydrogen energy subsystem, and formulate compliance The regional development of the electric hydrogen energy system planning scheme encourages the effective development of the hydrogen energy subsystem from the multidimensional perspectives of safety, economy, and environmental protection. In addition, considering the stable hydrogen energy demand in the existing industrial enterprises (refineries, synthetic ammonia plants) in cities, the large-scale utilization of electrolytic hydrogen can be ensured, and a typical architecture and integration plan for urban/regional hydrogen energy systems is urgently needed. Research.

4.2.3 Safe operation

Considering the differences between the two heterogeneous energy flows of electricity and hydrogen, the electro-hydrogen energy system differs greatly in many aspects, such as equipment operation, network transmission, and energy use characteristics. For example, the power subsystem needs to meet the requirements of real-time balance of supply and demand, which has extremely high requirements for the safe and stable operation of the system; while the hydrogen energy subsystem does not need to meet the real-time balance of supply and demand, and is involved in all aspects of production, transmission, distribution, and use. All have a certain hydrogen storage capacity and high flexibility. Therefore, how to use the flexible resources of the hydrogen energy subsystem through coupling equipment to achieve a high proportion of renewable energy consumption in the power subsystem under the premise of ensuring the safe and stable operation of the system is the key and difficult point of constructing an electric hydrogen energy system.

4.2.4 Core equipment

Taking electric-hydrogen coupling equipment as an example, electric-hydrogen production equipment can convert electric energy into hydrogen energy. The future electric-hydrogen energy system needs to meet the technical requirements of high conversion efficiency, fast dynamic response, wide working range, and large-scale equipment. At present, there is no electric hydrogen production equipment that can meet the above requirements at the same time; hydrogen fuel cell, as the core equipment for the conversion of hydrogen energy to electric energy, still has a lot of room for improvement in equipment life and conversion efficiency, but it is difficult in terms of capacity level and system scale. Match the power generation volume required by the power subsystem. Therefore, it is necessary to improve related technologies in terms of equipment scale, capacity level, and conversion efficiency.

4.3. Recent implementation path

Since 2006, the Chinese government has issued a series of related policies and formulated a hydrogen energy development route suitable for China’s national conditions. For details, see Appendix A, Figure A2 [30]. This article believes that electric and hydrogen energy systems should fully combine the price advantages of traditional fossil energy and the efficient use of renewable energy. Therefore, under the current situation, it is advisable to carry out the construction of the electric and hydrogen energy system from the following implementation paths. Establish large-scale electric hydrogen production plants in surplus renewable energy power generation areas to convert surplus electric energy into hydrogen to solve the “three wastes” problem. The hydrogen produced can be transmitted through the existing natural gas network, or synthetic ammonia can be synthesized according to local conditions. Methanol and other related industrial materials. At present, some domestic energy and power companies have used surplus renewable energy to develop and demonstrate hydrogen production from electricity [41], which is conducive to the coupling of the electricity-hydrogen energy system on the energy supply side.

The investment and construction of various distributed renewable energy power generation are beneficial to reduce the coal consumption and greenhouse gas emissions of the upper-level large power grid. The surplus electricity can be converted into hydrogen energy through hydrogen production, avoiding the traditional power grid distributed power generation. Problems such as over-voltage and power reverse transmission [48]. Hydrogen energy can be used in many forms. Synthetic ammonia can be considered industrial materials, and synthetic methane can be used as gas or synthetic gasoline for transportation, etc. With the development of hydrogen fuel cell technology, it can be directly used for people’s clothing, food, housing, and transportation in the medium and long term. All aspects. This is conducive to the coupling of the electric hydrogen energy system on the energy consumption side.

The advantages of fuel cells in terms of efficiency and environmental protection have been recognized, and the price and durability of their equipment are the main challenges in commercialization. Taking the application of fuel cells in the transportation field as an example, the US Department of Energy has given PEMFC’s short-term and long-term goals for the durability of 5000 h and 8000 h when PEMFC is applied to light vehicles, while the current durability of PEMFC for vehicles is only is 2500~3000 h [41]. Therefore, it is necessary to increase the R&D and utilization of fuel cell technology to realize the large-scale application of hydrogen energy in the transportation field.

Consider that the cost of hydrogen production from coal in China is currently the lowest, and the relevant technology is very mature. Therefore, under the premise of ensuring the clean utilization of coal, coal to produce hydrogen will promote the industry chain of hydrogen energy-related transmission and distribution, storage, utilization, and other related technologies. Furthermore, with the gradual increase in the proportion of renewable energy power generation and the gradual maturity of the carbon trading market [44-48], hydrogen production by electrolysis will gradually become price-competitive in the process of hydrogen energy production, and subsidies for the purchase of electricity for hydrogen production by electrolysis can further reduce the electrolysis production cost of hydrogen.

5. CONCLUSION

This paper analyses the market potential for electricity-hydrogen applications. The electric hydrogen energy system is a new energy system that uses electricity and hydrogen as the core energy carriers and can achieve a high percentage or even a 100% renewable energy supply. So far, the research on the key technologies of the electric-hydrogen energy system has achieved initial results, and the introduction of relevant policies has also laid a good foundation for the further development of the electric-hydrogen energy system. The core quantitative indicators to measure the development maturity of the electric hydrogen energy system include 1. The proportion of renewable energy in primary energy consumption; 2.The proportion of electricity and hydrogen energy in the final energy consumption; 3.The degree to which the allocation capacity of hydrogen production, hydrogen storage, and hydrogen transmission infrastructure match the corresponding power infrastructure. In the future, the construction of the electric and hydrogen energy system should be gradually carried out. Soon, it is advisable to rely on the price advantage of fossil energy to develop the relevant infrastructure in the hydrogen energy subsystem and integrate the hydrogen energy industry chain; in the medium and long term, consider using the mature hydrogen energy industry chain to promote the consumption of a high proportion of renewable energy, and then gradually realize renewable energy. Energy hydrogen production is an alternative to traditional fossil energy hydrogen production methods. The electric hydrogen energy system mentioned in this article explores the future energy system form of human society, which is conducive to solving the problem of a high proportion of renewable energy consumption and is expected to improve the production and lifestyle of human beings. The most important findings of this paper were: (1) determining the most important drivers of the hydrogen industry; (2) Market potential evaluation of the hydrogen industry; (3) Frameworking the hydrogen market and determining its challenges and opportunities; (4) Recommending strategies to improve the hydrogen industry.

Appendixes

Table A1. Large-scale hydrogen production projects in global

project name	country	Construction time	Equipment capacity (MW)	Hydrogen production capacity (nm^3 H_2/hour)
CUTE, Stockholm (ALK)	Sweden	2003-2006	0.4	60
ELYGRID (ALK)	EU	2011-2014	3.5	760
Commercial Plant Svartsengi	Iceland	2011-present	6	1200
RH2 WKA (ALK)	Germany	2012-2015	1	200
INGRID (ALK)	Italy	2012-2016	1.152	240
H2FUTURE (PWM)	Australia	2017-2021	6	1250
Zero Impact Production (ZIP)	USA	2017-present	2.5	450
Hebei-China (ALK)	China	2017-present	4	400
Guangdong Synergy Hydrogen Co., Ltd. Project (PEM)	China	2017-present	3	625
Nordic Blue Crude (SOEC)	Norway	2020-present	20	>5500

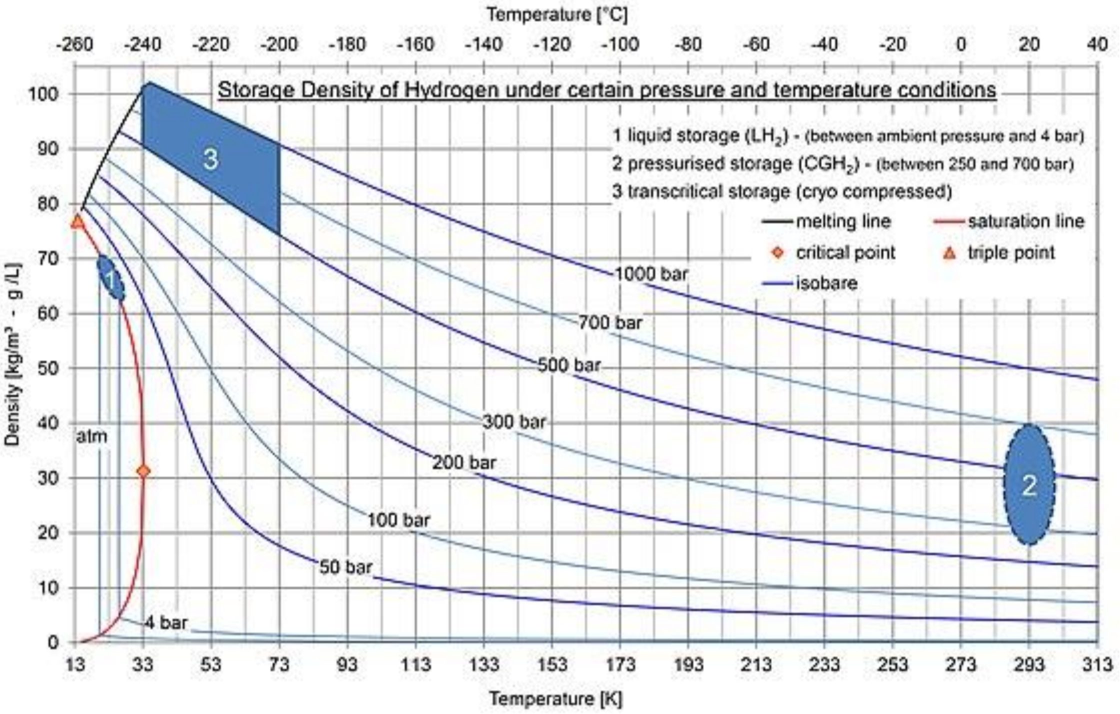


Figure A1. Hydrogen density versus temperature for several storage pressures[35]

Table A2. Comparison of three hydrogen storage technologies[36]

Storage type	Compressed gas	Liquid	Solid (metal hydride)
Volume/L	100	90	55
Weight/kg	50	40	215
Density/Wt.% H2	6	7.5	1.4

Table A3. Comparison of three large scale hydrogen storage technologies[38]

Large-scale hydrogen storage	Underground storage	Buried pipe section	Above cylindrical ground tank
Assumed volume/m3	500 000	6 800	110
Pressure range/MPa	6~18	2~7	2~5
Hydrogen storage range/(MW·h)	80 000~200 000	370~1 200	6.5~16
Net usable quantity/(MW·h)	125 000	850	9.0
Energy density/W·h/l	250	125	85
Equipment life/a	30	50	20

Table A4. Large-scale hydrogen storage projects in global

Location	country	Types of	Volume (m^3)	Depth (m)	Pressure (MPa)	Capacity (GWh)
Teesside-UK	UK	Salt cave	3*150000	370	4.5	24.4
Chevron, Texas-USA	USA	Salt cave	580000	850-1150	7-13.5	83.3

Table A5. Comparison of three hydrogen transmission technologies[38]

Hydrogen transmission method	pipeline	Cryogenic liquid truck	Compressed gas truck
Transmission capacity	100 t/h	4 t/vehicle	0.4 t/vehicle
Transmission distance	far	far	near
Transmission energy	Compressor energy consumption	Transportation fuel	Transportation fuel
cost of investment	\$20~1 million/km	\$300,000~400,000/vehicle	\$300,000/vehicle
Variable costs	\$0.03/kg	\$0.3~0.5/kg	\$0.5~2.0/kg
Total unit cost	\$0.1~1.0/kg/100 km	\$0.3~0.5/kg/100 km	\$0.5~2.0/kg/100 km
effectiveness	99.2%/100 km	99%/100 km	94%/100 km

Table A6. Safety ranking of fuels[38]

characteristic toxicity	Fuel grade		
	gasoline	Methane	hydrogen
Toxic gas emissions such as CO and SOx	3	2	1
density	3	2	1
Diffusion coefficient	3	2	1
Specific heat capacity	3	2	1
Ignition boundary	3	2	1
Ignition energy	1	2	3
Ignition temperature	2	1	3
Burning temperature	3	2	1
Explosion energy	3	1	2
Flame radiance	3	2	1
total	3	2	1
Safety factor	30	20	16
characteristic	0.53	0.80	1.00

Note: 1-safe; 2-more safe, 3-unsafe.

Table A7. Parameters of power to hydrogen

Parameter	**Numerical value**
c_{p2hinv}	12000 ¥/kW[44]
$c_{p2ho\&m}$	500 ¥/(kW·a)[44]
lifespan	20 years [44]
Conversion efficiency	61.3%[44]
interest rate	2%

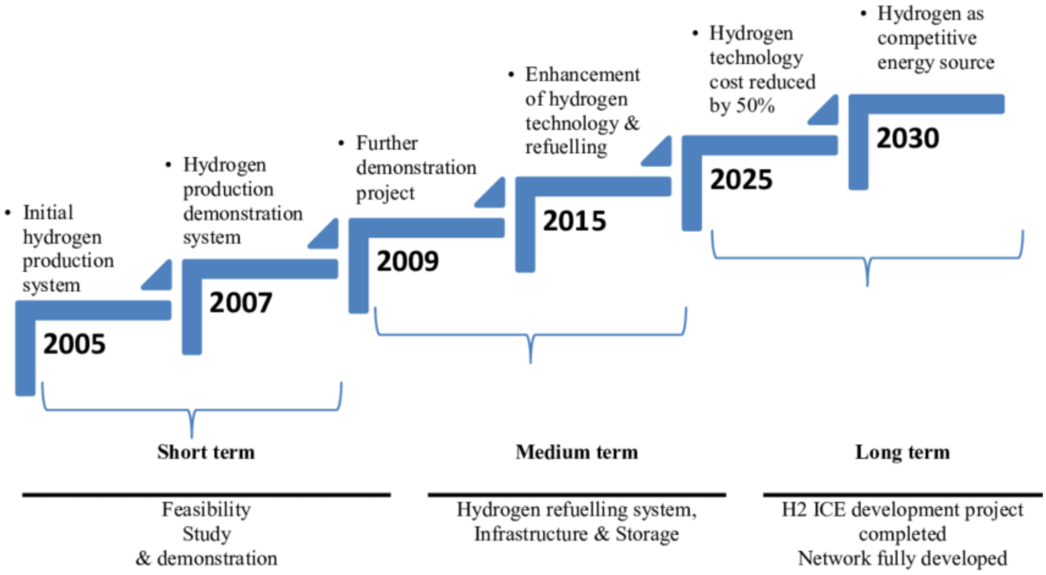


Figure A2. Roadmap of hydrogen energy development in China

Acknowledgment

The author thank the Amirkabir University of Technology for their kind supports.

Declaration of Ethical Standards

The paper's author declare that nothing necessary for achieving the paper requires ethical committee and/or legal-special permissions.

Credit author statement

Nima Norouzi: Conceptualization, Methodology, Validation, Formal analysis, Writing, Review & Editing

REFERENCES

[1]. Sun, H., Guo, Q. “Pan Z. Energy internet: concept, architecture and frontier outlook”, *Automation of Electric Power Systems* 2015;39(19):1-8.

[2]. Haiyang, J. Ershun, D.， Guiping, Z. “Review and prospect of seasonal energy storage for power system with high proportion of renewable energy”, *Automation of Electric Power Systems* 2020; 44(19):194-207.

[3]. Jingwei, Y.， Ning, Z.， Yi, W. “Multi-energy system towards renewable energy accommodation： review and prospect”, *Automation of Electric Power Systems* 2018；42（4）∶11-24.

[4]. Xiaoxin, Z.， Shuyong, C.， Zongxiang, L. “Technology features of the new generation power system in China”， *Proceedings of the CSEE* 2018; 38 （7）∶1893-1904.

[5]. Zhou, K., Yang, S., Shao, Z. “Energy internet: the business perspective”, *Applied Energy* 2016;178:212-22.

[6]. Wang, K., Yu, J., Yu, Y., Qian, Y., Zeng, D., Guo, S., Xiang, Y., Wu, J. “A survey on energy internet: Architecture, approach, and emerging technologies”, *IEEE Systems Journal* 2017;12(3):2403-16.

[7]. Ziegler, M.S., Mueller, J.M., Pereira, G.D., Song, J., Ferrara, M., Chiang, Y.M., Trancik, J.E. “Storage requirements and costs of shaping renewable energy toward grid decarbonization”, *Joule* 2019;3(9):2134-53.

[8]. Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A.S., Barbosa, L.D., Breyer, C. “Radical transformation pathway towards sustainable electricity via evolutionary steps”, *Nature communications* 2019;10(1):1-6.

[9]. Albertus, P., Manser, J.S., Litzelman, S. “Long-duration electricity storage applications, economics, and technologies”, *Joule* 2020;4(1):21-32.

[10]. Jianlin, L., Huimeng, M., Dong, H. “Present development condition and trends of energy storage technology in the integration of distributed renewable energy”, *Transactions of China Electrotechnical Society* 2016;31(14):1-10.

[11]. Maggio, G., Nicita, A., Squadrito, G. “How the hydrogen production from RES could change energy and fuel markets: A review of recent literature”, *International Journal of Hydrogen Energy* 2019;44(23):11371-84.

[12]. Xin, C.， Jinsong, Z.， Donghua, L. “Development and future prospect of the hydrogen fuel cell vehicle at home and abroad”, *Automotive Engineering* 2019; （4） ： 8-10.

[13]. Chongqing, K.， Liangzhong, Y. “Key scientific issues and theoretical research framework for power systems with high proportion of renewable energy”, *Automation of Electric Power Systems* 2017；41 （9） ： 2-11.

[14]. Kırtay, E. “Recent advances in production of hydrogen from biomass”, *Energy conversion and management* 2011;52(4):1778-89.

[15]. Sambusiti, C., Bellucci, M., Zabaniotou, A., Beneduce, L., Monlau, F. “Algae as promising feedstocks for fermentative biohydrogen production according to a biorefinery approach: a comprehensive review”, *Renewable and Sustainable Energy Reviews* 2015;44:20-36.

[16]. Kang, K., Azargohar, R., Dalai, A., K., Wang, H. “Hydrogen production from lignin, cellulose and waste biomass via supercritical water gasification: Catalyst activity and process optimization study”, *Energy Conversion and Management* 2016;117:528-37.

[17]. Yasin, N., H., Mumtaz, T., Hassan, M., A. "Food waste and food processing waste for biohydrogen production: a review", *Journal of Environmental Management* 2013;130:375-85.

[18]. Balta, M., T., Dincer, I., Hepbasli, A. "Potential methods for geothermal-based hydrogen production", *International Journal of Hydrogen Energy* 2010;35(10):4949-61.

[19]. Honnery, D., Moriarty, P. "Estimating global hydrogen production from wind", *International Journal of Hydrogen Energy* 2009;34(2):727-36.

[20]. Turner, J., Sverdrup, G., Mann, M., K., Maness, P., C., Kroposki, B., Ghirardi, M., Evans, R., J., Blake, D. "Renewable hydrogen production", *International Journal of Energy Research* 2008;32(5):379-407.

[21]. Bak, T., Nowotny, J., Rekas, M., Sorrell, C., C. "Photo-electrochemical hydrogen generation from water using solar energy: Materials-related aspects", *International Journal of Hydrogen Energy* 2002;27(10):991-1022.

[22]. Saxena, R., C., Seal, D., Kumar, S., Goyal, H.B. "Thermo-chemical routes for hydrogen rich gas from biomass: a review", *Renewable and Sustainable Energy Reviews* 2008;12(7):1909-27.

[23]. Jiarong, L.， Jin, L.， Jinyu, X. "Technical and energy consumption comparison of power-to-chemicals（P2X） technologies for renewable energy integration", *Journal of Global Energy Interconnection* 2020；3(1)：86-96.

[24]. Winebrake, J., J., Creswick, B., P. "The future of hydrogen fueling systems for transportation: an application of perspective-based scenario analysis using the analytic hierarchy process", *Technological Forecasting and Social Change* 2003;70(4):359-84.

[25]. Schmidt, O., Melchior, S., Hawkes, A., Staffell, I. "Projecting the future levelized cost of electricity storage technologies", *Joule* 2019;3(1):81-100.

[26]. Hwangbo, S., Lee, I., B., Han, J. "Mathematical model to optimize design of integrated utility supply network and future global hydrogen supply network under demand uncertainty", *Applied Energy* 2017;195:257-67.

[27]. Guerra, O.J., Zhang, J., Eichman, J., Denholm, P., Kurtz, J., Hodge, B., M. "The value of seasonal energy storage technologies for the integration of wind and solar power", *Energy & Environmental Science* 2020;13(7):1909-22.

[28]. Preuster, P., Alekseev, A., Wasserscheid, P. "Hydrogen storage technologies for future energy systems", *Annual Review of Chemical and Biomolecular Engineering* 2017;8:445-71.

[29]. Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., Villafáfila-Robles, R. "A review of energy storage technologies for wind power applications", *Renewable and Sustainable Energy Reviews* 2012;16(4):2154-71.

[30]. Liu, J., Chen, X., Cao, S., Yang, H. "Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings", *Energy Conversion and Management* 2019;187:103-21.

[31]. Yanxing, Z., Maoqiong, G., Yuan, Z., Xueqiang, D., Jun, S. "Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen", *International Journal of Hydrogen Energy* 2019;44(31):16833-40.

[32]. Singh, S., Jain, S., Venkateswaran, P., S., Tiwari, A., K., Nouni, M., R., Pandey, J., K., Goel, S. "Hydrogen: A sustainable fuel for future of the transport sector", *Renewable and Sustainable Energy Reviews* 2015;51:623-33.

[33]. McPherson, M., Johnson, N., Strubegger, M. “The role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions”, *Applied Energy* 2018;216:649-61.

[34]. Ozarslan, A. “Large-scale hydrogen energy storage in salt caverns”, *International Journal of Hydrogen Energy* 2012;37(19):14265-77.

[35]. Ball, M., Wietschel, M. “The future of hydrogen–opportunities and challenges”, *International Journal of Hydrogen Energy* 2009;34(2):615-27.

[36]. Yang, Z., J., Gao, C., W., Zhao, M. “Review of coupled system between power and natural gas network”, *Autom. Electr. Power Syst.* 2018;42:21-31.

[37]. Tabkhi, F., Azzaro-Pantel, C., Pibouleau, L., Domenech, S. “A mathematical framework for modelling and evaluating natural gas pipeline networks under hydrogen injection”, *International Journal of Hydrogen Energy* 2008;33(21):6222-31.

[38]. Qing-bo, Z., H. “State Grid Contributes to the Development of Clean Energy”, *Electric Power Technologic Economics* 2009;5.

[39]. Shulga, R., N., Putilova, I., V. “Multi-agent direct current systems using renewable energy sources and hydrogen fuel cells”, *International Journal of Hydrogen Energy* 2020;45(11):6982-93.

[40]. Qian, J., Y., Li, X., J., Gao, Z., X., Jin, Z., J. “A numerical study of unintended hydrogen release in a hydrogen refueling station”, *International Journal of Hydrogen Energy* 2020;45(38):20142-52.

[41]. Sharma, S., Ghoshal, S.K. “Hydrogen the future transportation fuel: From production to applications”, *Renewable and Sustainable Energy Reviews* 2015;43:1151-8.

[42]. Kobayashi, T., Nagai, H., Chino, M., Kawamura, H. “Source term estimation of atmospheric release due to the Fukushima Dai-ichi Nuclear Power Plant accident by atmospheric and oceanic dispersion simulations: Fukushima NPP Accident Related”, *Journal of Nuclear Science and Technology* 2013;50(3):255-64.

[43]. Guerra, O., J., Eichman, J., Kurtz, J., Hodge, B.M. “Cost competitiveness of electrolytic hydrogen”, *Joule* 2019;3(10):2425-43.

[44]. Gabrielli, P., Poluzzi, A., Kramer, G., J., Spiers, C., Mazzotti, M., Gazzani, M. “Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage”, *Renewable and Sustainable Energy Reviews* 2020;121:109629.

[45]. Utgikar, V., Thiesen, T. “Life cycle assessment of high temperature electrolysis for hydrogen production via nuclear energy”, *International Journal of Hydrogen Energy* 2006;31(7):939-44.

[46]. Sheng, W., Wu, M., Ji, Y., Kou, L., Pan, J., Shi, H., Niu, G., Wang, Z. “Key techniques and engineering practice of distributed renewable generation clusters integration”, In *Proceedings of the CSEE* 2019; 39(8): 2175-2186.

[47]. Badwal, S., P., Giddey, S., Munnings, C. “Hydrogen production via solid electrolytic routes”, *Wiley Interdisciplinary Reviews: Energy and Environment* 2013;2(5):473-87.

[48]. Peng, X., Adams, P., D., Liu, J. “China’s new growth pattern and its effect on energy demand and greenhouse gas emissions”, *Global Energy Interconnection* 2018;1(4):428-42.