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Review

Current Status and Economic Analysis of Green Hydrogen Energy Industry Chain

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Abstract: Under the background of the power system profoundly reforming, hydrogen energy from renewable energy, as an important carrier for constructing a clean, low-carbon, safe and efficient energy system, is a necessary way to realize the objectives of carbon peaking and carbon neutrality. As a strategic energy source, hydrogen plays a significant role in accelerating the clean energy transition and promoting renewable energy. However, the cost and technology are the two main constraints to green hydrogen energy development. Herein, the technological development status and economy of the whole industrial chain for green hydrogen energy "production-storage-transportation-use" are discussed and reviewed. After analysis, the electricity price and equipment cost are key factors to limiting the development of alkaline and proton exchange membrane hydrogen production technology; the quantity, scale and distance of transportation are key to controlling the costs of hydrogen storage and transportation. The application of hydrogen energy is mainly concentrated in the traditional industries. With the gradual upgrading and progress of the top-level design and technology, the application of hydrogen energy mainly including traffic transportation, industrial engineering, energy storage, power to gas and microgrid will show a diversified development trend. And the bottleneck problems and development trends of the hydrogen energy industry chain are also summarized and viewed.

Keywords: hydrogen; production; storage and transportation; application; economic analysis

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1. Introduction

As a clean and efficient secondary energy source, hydrogen energy plays an extremely important strategic role in addressing the energy crisis, climate change and environmental protection. Hydrogen energy is also an important carrier of clean energy transformation and an important part of the new power system. According to the International Energy Agency (IEA) [1], in 2022, global hydrogen use reached 9.5 billion kilograms, an increase of nearly 3% year-on-year, which is expected to exceed 11.5 billion kilograms in 2030 (Figure 1). At present, China is the largest demander of hydrogen energy, reaching 2.8 billion kilograms. The next biggest demand for hydrogen energy is in the United States and the Middle East, where the annual demand is about 1.2 billion kilograms. Europe and India are ranked fourth and fifth, respectively, and the annual demand is about 0.8 billion kilograms. These five countries or regions account for more than 70% of global hydrogen demand [2]. Recently, Germany invested 4 billion euros in green energy projects in Africa until 2030. In addition, the German government recently released a draft plan for the "Hydrogen Core Network", which plans to start transporting hydrogen in 2025, and by 2032 they will lay 9700 km of pipelines across Germany, connecting ports, industrial areas, power plants and storage facilities, with a total investment of 19.8 billion euros [3]. Such high global natural demand will lead to the solidification of strong suppliers. It is worth mentioning that Saudi Arabia as one of the future hydrogen suppliers possesses the best solar and wind energy resources on the earth. Saudi Arabia, with abundant wind resources, is expected to be the cheapest country to produce green hydrogen in the future. Meanwhile, Saudi Arabia plans to export 0.4 billion kilograms of hydrogen annually in 2030, and its photovoltaic, wind-power equipment and electrolyzer will be a huge market [4].

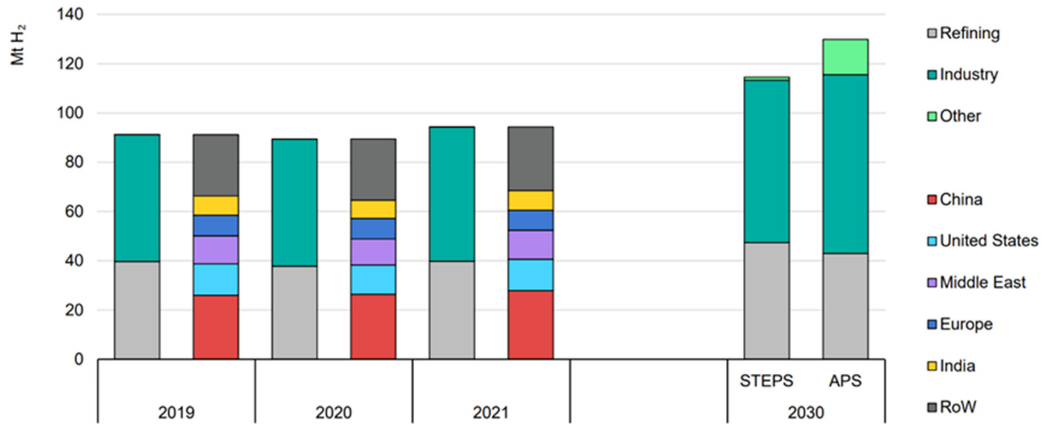

Figure 1. Hydrogen demand by sector and by region in the Stated Policies and Announced Pledges scenarios, 2019–2030 [1].

From a global perspective, hydrogen energy has become an important part of the energy system in many countries. With the strong support of the policy, the pace of development of the domestic hydrogen energy industry has accelerated significantly. At present, 3.3 billion kilograms of hydrogen per year from China, which is the world's largest producer, are produced, 99% of which is derived from fossil energy sources, contradicting the dual-carbon goal. It is globally recognized that green hydrogen as a strategic energy source is a top priority for the development of future industrial systems. The development of renewable energy hydrogen production in the early stage of industrial application will play an important role in the fields of new energy consumption, transportation and carbon emission reduction. However, the green hydrogen industry with poor economics has yet to be in the market introduction period, attributing to immature technology and incomplete business models. Recently, although the hydrogen energy industry has made certain developments, there remain bottlenecks to be broken through in the economy and technology of all industry chain of hydrogen energy "production-storage-transport-applications". Therefore, it is necessary to deepen the study of the economic "pain points" of green hydrogen and dissect the potential space for cost reduction, which provides a clear direction for the sustainable development of the green hydrogen industry.

2. Hydrogen Production

Hydrogen production methods mainly include traditional fossil fuel hydrogen production (coal, natural gas, methanol, etc.), industrial by-product hydrogen production and water electrolysis hydrogen production. Even though the hydrogen production technology of traditional fossil fuels is mature and low cost, a large amount of carbon dioxide and pollutants will be emitted in the hydrogen production process, which caused environmental pollution [5]. The technology of hydrogen production from industrial by-products is generally mature, but the cost of hydrogen production is slightly higher than that of fossil fuels. Simultaneously, the pollution of industrial by-product hydrogen production is serious, and the hydrogen purity is insufficient [6]. However, the technology of water electrolysis hydrogen production is extraordinary clean and environmentally friendly. Hydrogen produced using electrolysis of water via renewable energy sources with no carbon dioxide emissions is called "green hydrogen".

At present, alkaline water electrolysis (AWE) and proton exchange membrane (PEM) technology have been commercialized. As shown in Figure 2a, the principle of AWE technology is that H_2O at the cathode absorbs electrons to form OH^- and H_2 and then

OH^- passes through the membrane and electrolyte to release electrons to produce H_2O and O_2 at the anode [7]. Most diaphragms use a new composite diaphragm based on polyphenylene sulfide fabric to prevent gas mixing. The principle of PEM technology in Figure 2b is that H_2O releases electrons at the anode to produce O_2 and H^+, and H^+ passes through the proton exchange membrane to absorb electrons and produce H_2 at the cathode [8].

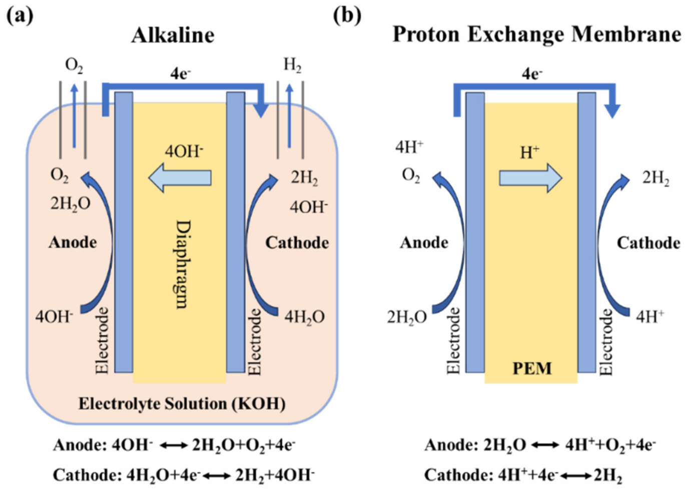

Figure 2. Commercially available electrolysis technologies of alkaline (**a**) and the proton exchange membrane (**b**).

2.1. Alkaline Water Electrolysis for Hydrogen Production

AWE hydrogen production technology as the most mature and economic technology has decades of application experience. At present, the main working conditions of alkaline electrolyzer are the working temperature of 70~90 °C and the working pressure of 1~3 MPa [9]. The electrolyte is mainly an aqueous solution of KOH or NaOH with the mass fraction of 20~30% [10]. The alkaline electrolytic cell with simple structure is safe and reliable, and life is generally 10 to 20 years.

AWE technology still suffers from high energy consumption, alkali corrosion, poor diaphragm durability and slow dynamic response in practical applications [11]. The main cost of AWE technology for hydrogen production is attributed to the use of stainless steel or nickel-based metals as electrode materials, high overpotentials and high energy consumption of the electrolyzers. In addition, the low mechanical strength and short service life of the asbestos diaphragm material in the electrolyzer easily lead to the decrease in the current efficiency, resulting in the interpenetration of hydrogen and oxygen and the decrease in hydrogen purity [12]. The cold start time of the alkaline electrolyzer is 1–2 h and the hot start time is 5–10 min, which is much higher than the start time of the PEM electrolyzer (1–5 min of cold start and 5 s of hot start) [13]. At present, it is the key for reducing costs and improving conversion rates to exploit the low-voltage and high-performance electrode and diaphragm materials.

The equipment cost of alkaline electrolyzer is positively correlated with hydrogen production capacity. At present, the hydrogen production capacity of levels for a single alkaline electrolyzer in China ranges from dozens to 2000 Nm^3/h, with the price ranging from millions to tens of millions. The cost of hydrogen production in alkaline electrolyzers is about 30 CNY/kg, which is much higher than hydrogen production from fossil energy sources and industrial by-products. The cost of hydrogen production in alkaline electrolyzers is mainly derived from the price of electricity, which accounts for about 70% [14]. According to the calculation of Zhang et al. [15], the hydrogen production cost of alkaline electrolyzer can be calculated using factors such as electricity price, power consumption and equipment depreciation (Equation (1)):

$$HPC = EP \times UEC + (AD + AF)/TAHP + UWC \times WP, \quad (1)$$

where HPC represents hydrogen production cost, UEC is unit electricity consumption, AD represents annual depreciation, AF represents annual freight, TAHP is total annual hydrogen production, UWC represents unit water consumption and WP represents water price. As can be seen from the above equation, the cost of hydrogen production is proportional to the unit price. According to the calculation of Soochow Securities Research Institute [14], the electricity price of 0.4 CNY/kWh is equivalent to the cost of hydrogen production of 31.99 CNY/kg. When the electricity price is reduced by 0.1 CNY/kWh, the hydrogen production cost can be reduced by 5.6 CNY/kg. Therefore, in the background of the continuous decline in the price of renewable energy, the cost of AWE technology is expected to be the same as gray hydrogen. In addition, AWE technology can further achieve cost reduction and efficiency increase via extending equipment running time, reducing equipment costs and improving electrolytic efficiency.

2.2. Proton Exchange Membrane Water Electrolysis for Hydrogen Production

PEM technology with a high current density, small volume of electrolyzer, flexible operation, rapid load change and high hydrogen purity (>99.99%) plays a good match with wind power, photovoltaic and other fluctuating renewable energy [16]. However, the technology maturity of PEM with high cost is slightly lower than AWE. Compared with AWE technology, PEM electrolyzer has the following advantages [17,18]: (1) the solid electrolyte membrane enables a large pressure difference to be borne on both sides, which unidirectionally permits hydrogen ion conduction, isolates hydrogen and oxygen, and improves safety and conversion rates; (2) the thin PEM electrolyte film reduces the electrode spacing, resulting in lower voltage and energy consumption and a more compact tank structure; (3) the electrolyte is pure water, which is non-corrosive; (4) the electrolytic products are also kept clean; and (5) there is more flexible operation (load range 5~120%) [19].

The key factors to PEM technology are the cathode catalyst and proton exchange membrane. The bipolar catalysts for PEM electrolyzers are generally made of costly precious metals such as Pt, Pd and Ir [20]. The current research directions of catalysts are focused on the discovery and design of composite materials such as transition metal materials, to reduce the use of precious metals. For example, Niu et al. designed a deficient strategy for the anion vacancies of CoP_2 to accurately capture Ru atoms, which constructed a remarkable catalytic interface with Co-P and Co-Ru coordination states, improving hydrogen evolution reaction (HER) performance [21]. Zhou et al. fabricated in-plane heterostructures with P-rich NiP_2 and P-poor Ni_5P_4, where P atoms as active sites at the in-plane interfaces can regulate electronic structure and increase adsorption energy of H* and facilitate the HER process [22]. In addition, Sun et al. prepared one T-Phase Enriched P doped WS_2 nanosphere which exposed more active sites and improved the conductivity of the material [23]. At present, numerous strategies and methods have been applied to the modification of hydrogen evolution materials, and recent research reports on transition metal compounds are summarized in Table 1.

Table 1. Comparison of typical electrocatalysts derived from multiscale strategies.

Catalyst	Electrolyte	Overpotential [mV@mA cm^{-2}]	Tafel Slope [mV dec^{-1}]	Strategy	Ref.
CoS_2@1T-MoS_2	0.5 M H_2SO_4	72@10	45	Heterostructure	[24]
CeO_2/WS_2	0.5 M H_2SO_4	128@10	60	Heterostructure	[25]
Cu-FeOOH/Fe_3O_4	1.0 M KOH	129@100	11	Heterostructure	[26]
HAs@MoS_2/Ce_2S_3	0.5 M H_2SO_4	147@10	47	Heterostructure/Doping	[27]
Se-MoS_2	0.5 M H_2SO_4	100@10	49	Doping/Vacancy	[28]

Table 1. *Cont.*

Catalyst	Electrolyte	Overpotential [mV@mA cm^{-2}]	Tafel Slope [mV dec^{-1}]	Strategy	Ref.
MoS_2-60s	0.5 M H_2SO_4	131@10	48	Vacancy	[29]
VSe_2-1.8	0.5 M H_2SO_4	160@10	85	Vacancy	[30]
1rGO-2MoS_2	0.5 M H_2SO_4	197@10	41	Carbon-based	[31]
Fe-WS_2	0.5 M H_2SO_4	195@10	81	Doping	[32]
E-MoS_2-Pt-r	0.5 M H_2SO_4	38@10	29	Nano-composite	[33]
Pd-WS_2/W_3O	0.5 M H_2SO_4	54@10	70	Heterostructure/Doping	[34]
1 T-WS_2 ∣ P-5	0.5 M H_2SO_4	125@10	73.73	Doping	[23]
Ni_2P-Ru_2P/NF	1.0 M KOH	101@10	41.5	Heterostructure	[35]
CrP/NPC	0.5 M H_2SO_4	34@10	39	Carbon-based	[36]
Ga-CoP NSs	1.0 M KOH	44@10	62	Doping	[37]
NiP_2/Ni_5P_4	0.5 M H_2SO_4	30@10	30.2	Heterostructure	[22]
Fe_2P@$CoMnP_4$	1.0 M KOH	53@10	50.6	Heterostructure	[38]
Ru-SA/Pv-CoP_2	1.0 M KOH	17@10	29	Doping/Vacancy	[21]

PEM technology using perfluorosulfonic acid with the complex preparation process has long been monopolized by the corporations of the United States and Japan, such as DuPont Nafion series membrane, Dow Chemical Dow series membrane, Asahi Glass Co., Ltd. Flemion series membrane and so on [39].

PEM technology has been initially commercialized in foreign countries, but it is still in the stage of demonstration and rapid promotion and application in China. At present, the PEM technology has achieved the 10 MW level demonstration application stage, and the 100 MW level PEM electrolyzer is under development. The hydrogen production capacity of the largest single-tank PEM electrolyzer in China is 400 Nm^3/h, which is lower than the international state-of-the-art level (500 Nm^3/h) [40].

The cost of PEM electrolyzers is proportional to the hydrogen production capacity, which is much higher than that of AWE electrolyzers. At the same scale, the price of the PEM electrolyzer is about 5 to 10 times that of AWE electrolyzer due to the high cost of core components such as bipolar plates and membrane electrodes, accounting for about 53% [41]. According to the situation of the Siemens Silyzer 300 PEM electrolyzer [42], under the condition of an annual operation time of 8000 h, when the electricity price is 0.2 CNY/kWh, the cost of hydrogen production is 20.0 CNY/kg; when the electricity price is 0.1 CNY/kWh, the cost of hydrogen production can be reduced to 17.3 CNY/kg, which is close to the cost of hydrogen production from fossil fuels [43].

The cost reduction of PEM technology can be attributed to the addition of a catalyst and electricity price [44]. The first is to reduce the cost of the catalyst and electrolyzer, especially the precious metal load of the anode and cathode catalyst. The second is coupled with renewable energy, making full use of the advantage of a low price for green electricity to reduce the cost of hydrogen production.

With the technical improvement and application of PEM electrolyzer, the rapid decline of its cost in the next 5 to 10 years is an inevitable development trend.

A comparison of the technical parameters of two main hydrogen productions are shown Table 2.

Figure 3 displays the comparison of hydrogen production economy.

In addition, anion exchange membrane (AEM) technology can solve the high-cost problem of traditional hydrogen production technology using non-precious metal catalysts and titanium-free components [45]. Both AWE and AEM use an alkaline solution as the electrolyte. Compared to AWE, the main difference in the AEM electrolyte is the lower concentration which can effectively avoid the generation of salts and CO_2 from the electrolyte [46,47]. Solid oxide electrolysis cell (SOEC) is a high-temperature hydrogen production technology. Compared to existing electrolysis technologies, the high temperature of the SOEC environment can cause favorable thermodynamics and reaction kinetics. The high-temperature environment reduces the equilibrium voltage of the cell, which reduces the power demand, promoting the efficiency of energy conversion [48,49]. Therefore, the technologies such SOEC and AEM electrolysis for hydrogen production are in the early stages of commercialization and laboratory research, respectively.

Table 2. Comparison of technical parameters of two main hydrogen productions.

Main Technical and Economic Indicators	AWE for Hydrogen Production		PEM for Hydrogen Production	
	Current Level	Future Target	Current Level	Future Target
Current density/(A·cm^{-2})	0.2–0.4	<0.8	1–2	1.5–3
System efficiency/%	62–82	67–87	74–87	82–93
Electricity consumption for hydrogen production/(kWh·m^{-3})	4.5–6.5	4.3–5.7	4.5–5.5	4.1–4.8
System Power Rating/MW	150	--	10–20	100
System life/a	20–30	30	10–20	20–30
investors/ (dollars kW^{-1})	850–1500	800	2000–3000	800–1300

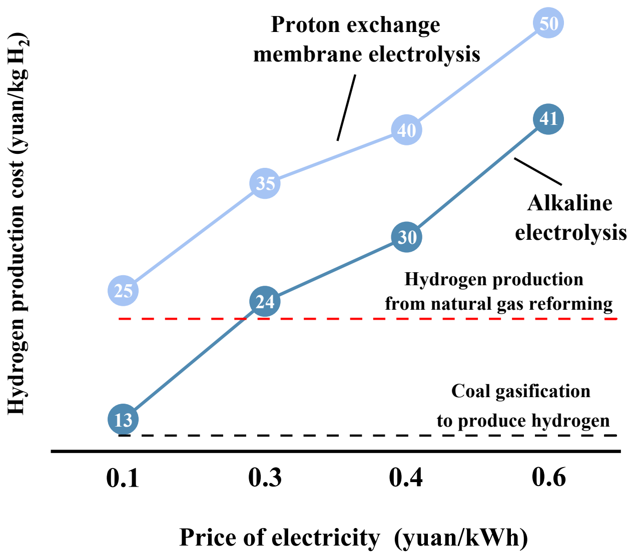

Figure 3. Comparison of hydrogen production economy.

3. Hydrogen Storage and Transportation

Hydrogen storage and transportation is the intermediate link of hydrogen energy industry chain, which is the key to balancing the fluctuation of the industry chain and ensuring the security of supply. Hydrogen is flammable, explosive (explosion limit is 4% to 74.2%) and diffusible, resulting in difficulties in storage and transportation. In practical applications, the safety, efficiency and absence of leakage losses in hydrogen storage and transportation are very important, which should be considered first [50]. In general, the requirements of the hydrogen industry for storage and transportation are that the system should be safe, large capacity, low cost and easy to use. At present, the main hydrogen storage materials and technologies include high-pressure gaseous hydrogen storage, low-temperature liquid hydrogen storage, organic liquid hydrogen storage and solid hydrogen storage. The above four storage and transportation modes demonstrate their own advantages, cost differences and application occasions [51].

3.1. High-Pressure Gaseous Hydrogen Storage

Hydrogen is a reducing gas with a small molecular weight and a density of only 0.089 g/L at normal temperature and pressure. Therefore, it is extremely diffusive and reactive and prone to leakage and hydrogen embrittlement during storage and transportation [52]. Hydrogen is compressed to high pressure, typically in the range of 35–70 MPa, to increase its density and reduce the storage volume. Mechanical compression as a form of compression consumes more energy and may generate heat that must be regulated but is cheaper and easier to run [53]. The compressed hydrogen can be further stored in tanks or cylinders as fuel. The average cost for the daily storage cycle length of hydrogen stored in an above-ground compressed hydrogen gas is approximately 2.68 CNY/kg. In addition, the cost of compressed hydrogen also involves the container itself, the availability of infrastructure and the cost of production services. Generally, increasing the pressure of hydrogen storage vessels and compress hydrogen is used to improve the energy density of hydrogen storage and transportation. According to different hydrogen storage pressures, it can be divided into low-pressure gaseous hydrogen storage (≤35 MPa) and high-pressure gaseous hydrogen storage (>35 MPa) [54]. At present, the highest hydrogen storage pressure can reach 70 MPa, and hydrogen storage vessels with the storage pressure of 100 MPa are under research and development.

High-pressure gaseous hydrogen storage is currently the most common way of hydrogen energy storage and transportation. Its advantages are mature technology, simple equipment structure, and fast charging and discharging speeds of hydrogen [55]. It is the most widely used technology in hydrogen refueling stations. However, the disadvantage of this method is the low weight capacity and the safety risk of leakage and explosion. The problems of high-pressure gaseous hydrogen storage are mainly concentrated on the research of hydrogen storage vessels [56]. Furthermore, the researchers mainly focus on improving hydrogen storage pressure, designing storage and transportation pipelines, and enhancing corrosion protection and resistance to hydrogen embrittlement.

According to China's standards, the maximum working pressure limit of the long tube trailer is 20 MPa, and the mass of hydrogen transported is less than 500 kg each time. While the working pressure of 50 MPa for a hydrogen long tube trailer has been applied in the international market, the mass of hydrogen transported can reach 1000–1500 kg. Taking a 20 MPa long tube trailer (hydrogen carrying capacity of 350 kg) as an example [14], when the transport distance is 150 km, the transport cost is 8.69 CNY/kg. And when the transport distance reaches 200 km, the transport cost is upgraded to 9.56 CNY/kg. The cost is mainly ascribed to fuel consumption and labor costs, which is less room for cost reduction. If the working pressure of the long tube trailer can be increased to 50 MPa, the transportation cost is expected to greatly decrease. Therefore, high-pressure gaseous hydrogen storage is more suitable for transportation scenarios of less dosage and short distance. On the other hand, from the economic point of view, the inevitable trend to reduce costs is to increase the hydrogen storage pressure of cylinders or develop hydrogen storage tubes with higher hydrogen storage density, which is also the future development direction of high-pressure and lightweight hydrogen transportation.

3.2. Low Temperature Liquid Hydrogen Storage

The density of liquid hydrogen is about 70.8 g/L at a low temperature of −253 °C, so the density of hydrogen storage can be greatly increased via low-temperature liquefaction [50,57]. However, the complicated process, high energy consumption and volatility also limits its application [58]. In addition, the low-temperature resistance and pressure resistance causes sealing, manufacturing difficulty and high cost. The technology of the liquid hydrogen storage mainly used in aviation is not sufficiently mature. At present, the liquid hydrogen refueling stations account for about one-third of the world, mainly located in the United States, Japan and France.

The largest share of the production cost for liquid hydrogen is the cost of hydrogen procurement (58%), followed by electricity (20%) [57]. According to the electricity price of 0.3 CNY/kWh, the cost of liquid hydrogen production is about 25.3 CNY/kg using the scheme of an electrolytic water hydrogen production plant and a liquefaction plant which need to be closed to the construction of the power plant. The transportation costs of liquid hydrogen are mainly in depreciation instead of distance. In terms of transportation cost, for every 100 km increase in transportation distance, the cost of high-pressure gas hydrogen storage and transportation increases by 4.63 CNY/kg, while the liquid hydrogen is only

0.44 CNY/kg, and the balance point of the combined cost of the two modes (including production, storage and transportation) is around 200 km. Therefore, when the transportation distance exceeds 200 km, the cost advantage of liquid hydrogen is more obvious.

3.3. Organic Liquid Hydrogen Storage

Organic liquid hydrogen storage is a reversible chemical reaction. The aromatic organic compounds such as methylcyclohexane, dibenzyltoluene and decahydronaphthalene are hydrotreated and reduced to form organic compounds, which facilitates long-distance transportation [52]. When they are used on the user side, hydrogen is released via a dehydrogenation reaction. Therefore, hydrogen storage carriers with stability, safety and high hydrogen storage density can be recyclable, which is promising for long distance transportation. At present, organic liquid hydrogen storage technology is developing rapidly in Europe and Japan, which have established relevant demonstration projects [59]. However, the high cost of hydrogenation and dehydrogenation equipment is observed. In addition, the dehydrogenation process is prone to side reactions resulting in low efficiency and low hydrogen purity. Therefore, the research hotspot of organic liquid hydrogen storage is the selection of suitable hydrogen storage carriers and catalysts to improve efficiency.

The cost of organic liquid hydrogen storage can be divided into two parts: hydrogenation/dehydrogenation and transportation cost. For example, as the carriers of common organic liquid hydrogen storage systems, the cost of hydrogenation/dehydrogenation for the toluene/methylcyclohexane, benzene/cyclohexane and naphthalene/decahydronaphthalene constituted is 6.5–7.7 CNY/kg. In addition, the cost of dehydrogenation is much higher than that of hydrogenation [60]. Production costs in the hydrogenation chain are dominated by feedstock costs (about 90%), while public works in the dehydrogenation chain are the determining factor in production costs. The transportation cost of the three hydrogen storage systems ranged from 4.5 to 7.1 CNY/(kg·m). In addition, the lowest transportation cost of the naphthalene/decahydronaphthalene system is attributed to the highest hydrogen storage density [61]. Transportation costs of organic liquid hydrogen storage are less related to distance. Taking the naphthalene/decahydronaphthalene system as an example [62], when the transportation distance is 500 km, the comprehensive cost (sum of hydrogenation/dehydrogenation cost and transportation cost) is 8.86 CNY/kg, which is lower than the low-temperature liquid hydrogen storage, gaseous hydrogen storage and pipeline hydrogen transportation. Therefore, it is very competitive for the organic liquid hydrogen storage technology represented by the naphthalene/decahydronaphthalene system in scenarios with large hydrogen transport volumes, long distances and no hydrogen pipelines [63].

3.4. Solid-State Hydrogen Storage

Solid-state hydrogen storage with high hydrogen storage density, high safety, recyclability and efficient transportation equipment is a technology for storing hydrogen immobilized in a solid material [64]. However, the solid-state storage also has some shortcomings: on the one hand, the storage and release of hydrogen requires specific external conditions; on the other hand, the technology requires a high performance of solid-state hydrogen storage materials, which need to meet a series of conditions such as fast hydrogen absorption/release rate, a wide range of sources, low cost, long life, and simple process [51]. The current solid-state hydrogen storage materials are not able to meet the needs of large-scale applications. Therefore, it is the research focus to explore the innovative solid-state hydrogen storage materials with excellent performance.

At present, the metal alloys, carbon-based materials and coordination hydride materials are considered to be common solid hydrogen storage materials [65]. For example, Reza Mohassel et al. prepared the layered solids (nanostructured $GdFeO_3$ and g-C_3N_4) with hydrogen storage capacity [66]. Furthermore, the magnesium-based solid hydrogen storage materials are considered to be one of the most promising solid hydrogen storage materials. For instance, Gao et al. displayed the Ni/V_2O_3 nanoparticles for solid-state hydrogen storage in MgH_2, exhibiting more superior hydrogen absorption/desorption properties [67]. Wang et al. synthesized CrMnFeCoNi and CrFeCoNi high-entropy alloys to boost the hydrogen storage performance of MgH_2 [68].

Taking the magnesium-based solid hydrogen storage materials as an example, the current maximum hydrogen-carrying capacity of a single car is 1200 kg. China's metal solid hydrogen storage technology has not yet achieved mature commercial application, but the first demonstration project has been settled in Jining, Shandong Province [69].

When the magnesium-based solid hydrogen storage materials are used as an example [70], assuming that the amount of hydrogen transported is under the condition of 500 kg/day, when the transportation distance is greater than 500 km, the cost of solid-state storage and transportation is very advantageous, which is still slightly higher than that of low-temperature liquid storage. Therefore, the metal hydride hydrogen storage technology with moderate storage and transportation costs and more obvious safety advantages for long-distance transportation is relatively cutting-edge.

Table 3 shows the comparison of different modes of hydrogen transportation technology.

Table 3. Comparison of different modes of hydrogen transportation technology.

Hydrogen Storage and Transportation	Transport Vehicle	Specificities	Stresses (MPa)	Hydrogen-Carrying Capacity (kg/Vehicle)	Volumetric Hydrogen Storage Density (kg/m^3)	Economic Distance (km)
High-pressure gaseous	trailer	smaller scale and shorter transportation distances	20	300–400	14.5	≤150
	pipeline transport	large-scale hydrogen use with many application areas	1–4	-	3.2	≥500
low-temperature liquid	liquid hydrogen tanker	long-distance transportation and high costs	0.6	7000	64	≥200
organic liquid	tanker	limited by cost and technical issues	atmospheric	2000	40–50	≥200
solid-state	trucks	high hydrogen storage density, high transportation capacity and technical difficulties	4	300–400	50	≤150

3.5. Hydrogen Safety

Hydrogen safety is a necessary condition for hydrogen storage and transportation due to the explosion, combustion and embrittlement characteristics of hydrogen. In percentage by volume, the lower flammable limit (LFL) of hydrogen is 4.0%, and the upper flammable limit (UFL) is 77%. The minimum ignition energy of hydrogen is 0.0017 MJ. Thus, the wide flammability, low minimum ignition energy and high combustion speed also contribute to its safety. Relevant experimental and computational fluid dynamic techniques have been used to understand these risk components associated with hydrogen storage and transportation. [71] Meanwhile, hydrogen embrittlement (HE) resulting in the deterioration of metal cylinders storing hydrogen is also a safety concern. In order to reduce the HE phenomenon, the choice of materials is very important. The addition of titanium and aluminum alloys to the substrate, oxygen, nitrogen and carbide diffusion layers, electroplating technologies such as galvanizing and nickel plating, graphene and niobium coating technologies, and amorphous structural materials can reduce the penetration of hydrogen in the material and alleviate the HE problem [72,73].

4. Hydrogen Applications

As the terminal of the hydrogen industry, the promotion of the market in the hydrogen application is the main constraint on the scale of hydrogen energy development. At present, the hydrogen application is mainly concentrated in traditional industry. However, with the progressive improvement of top-level design and the upgrading and progress of industrial technology, the application of hydrogen energy will show a diversified development trend such as hydrogen energy storage, transportation, power-to-gas, and cogeneration/cooling and combined heat and power supply [74].

4.1. Transportation

Hydrogen fuel cell vehicles with a high efficiency and long range can realize genuine zero-emission and non-pollution [75], which are an ideal substitute for fuel vehicles. In addition, hydrogen fuel cell vehicles are also hailed as "the ultimate solution for new energy vehicles", which can be applied in the prospects of the medium and long range, and heavy commercial vehicles [76]. It is expected that by 2030 hydrogen fuel cell vehicles will account for 3% of global vehicle sales, and by 2050 this proportion is expected to reach 36% [77].

At present, hydrogen fuel cell vehicles have entered the market introduction stage from the technology development stage. In 2022, more than 3000 hydrogen fuel cell vehicles have been sold in China. In addition, a total of more than 13,000 hydrogen fuel cell vehicles were marketed over the years, ranking first in the global commercial vehicle fuel cell around the world. By the end of 2022, the number of fuel cell vehicles in China is 12,682, and a total of 358 hydrogen refueling stations have been built, of which 245 are in operation [78]. Furthermore, the application scenarios have also evolved from a single bus to a full range of commercial vehicles. The use of hydrogen in internal combustion engines is also developing [79]. Zhi et al. analyzed the performance of spark ignition engines using mixed fuel to add hydrogen, indicating that the engine combustion process was improved [80]. Sami et al. also found that the addition of hydrogen reduced the specific energy consumption of the brake and improved the power performance of the spark ignition engine [81]. Seongsu et al. optimized the efficiency and combustion stability based on a long-distance heavy vehicle model [82]. At the same time, the power density of fuel cell engines has been greatly improved, reaching the level of traditional internal combustion engines. Based on 70 MPa hydrogen storage technology, the vehicle is applicable to the range of conventional vehicles, including mileages (fuel fill < 5 min), the life of fuel cell (5000 h), low-temperature environment adaptability and climate adaptability. The Toyota Mirai, Hyundai iX35 and Honda Clarity hydrogen fuel cell vehicles are already in commercial production.

The main cost of hydrogen fuel cell vehicles originates from the battery and hydrogen storage system, and the rest of the cost is similar to that of electric vehicles [83]. For a 49-ton heavy truck, the cost of a fuel cell and hydrogen storage system can account for 64% [24]. In China, automotive hydrogen storage bottles are mainly 35 MPa Type III bottles, and the price of an automotive hydrogen storage system is about 5000 CNY/kg. The price of fuel cell electric stacks can now be realized for less than 2000 CNY/kW [84]. In summary, the cost of the on-board hydrogen storage system for a 49,000 kg heavy truck (40 kg H_2) is about 200 thousand CNY, and the cost of the fuel cell (130 kW) is about 260 thousand CNY. Therefore, the cost of the entire vehicle can be reduced to less than 1 million CNY, which is comparable to that of an electric heavy truck.

In addition, solid-state hydrogen storage has started relatively early in the field of transportation, and there are demonstration projects for hydrogen bicycles, two-wheelers, fuel cell forklifts and hydrogen refueling stations. Domestic enterprises such as Houpu shares are also developing vehicle solid hydrogen storage bottles, with the current titanium hydrogen storage device price of 20,000 CNY/kg and future hopes to reduce to 8000 CNY/kg via large-scale production [85].

4.2. Industrial Engineering

Industry currently has the largest share of hydrogen energy applications in China. Hydrogen is not only an energy fuel but also an important chemical and metallurgical raw material, which can be used in the synthesis of methanol, ammonia, polysilicon production, iron and steel smelting [86]. For example, in the polysilicon production process, hydrogen is used for reduction, and the hydrogen consumption can reach 0.5–1 Nm^3/kg [87].

4.2.1. Synthesis Ammonia

In the traditional Haber-Bosch process for the process ammonia synthesis, the main raw material (hydrogen) is generated from steam methane reforming, which accounts for 1–2% of global annual energy consumption and releases carbon dioxide of about 23.5 billion kilograms. However, the deep decarbonization of the ammonia synthesis process can be achieved via replacing gray hydrogen with green hydrogen [88].

Ammonia is used not only in fertilizer production as an essential element for crop growth but also as a carrier of hydrogen energy. In addition, with liquid ammonia and its high-quality hydrogen storage density (17.6%), the long-term storage, stable transportation and lower transportation costs can substitute for hydrogen transportation, further accelerating the commercialization of hydrogen energy. In addition, ammonia as a fuel has been applied in internal combustion engines [89], gas turbines [90] and fuel cells [91]. Therefore, ammonia–hydrogen linkage can break the barriers of the chemical industry and power industry, realizing the effective connection of the electric-hydrogen-ammonia industry.

With obvious economics, several companies are developing the technology of green hydrogen with the ammonia synthesis process. And there are currently more than 40 green ammonia projects worldwide. In March 2021, the solar electrolysis for hydrogen storage research and demonstration projects as the first large-scale green hydrogen project in China was constructed by Ningxia Baofeng Energy Group Corporation. On this basis, Ningxia Baofeng Energy Group Corporation initiates a project with an annual production capacity of 50 million kilograms for an ammonia production line in 2023, realizing green power, green oxygen, green hydrogen and green ammonia coupled with efficient carbon emission reduction. In order to solve the problem of renewable energy consumption, Jidian Corporation spent 6 billion CNY to build the integration demonstration project of Da'an wind–solar green hydrogen synthesized ammonia, which put forward the solution of "green hydrogen consumption of green electricity, green ammonia consumption of green hydrogen" [92].

In terms of cost, the price of green ammonia depends mainly on the price of hydrogen, which is positively correlated with the price of electricity. Therefore, the key for the scale-up of green ammonia is to produce cost-competitive hydrogen. According to the calculation of a potential silver energy chain [93], the cost of green ammonia is 3.63 CNY/kg when the electricity price is 0.2 CNY/kWh, which is close to the market price.

4.2.2. Methanol Synthesis

The synthesis and production of zero-carbon methanol using green hydrogen and carbon capture technology is a new energy technology route of realizing carbon neutrality [94]. The renewable energy sources are utilized for water electrolysis and hydrogen reduction of carbon dioxide, which is equivalent to the conversion of solar energy into stable chemical fuels, called "liquid sunlight" technology [95]. Under current technological conditions, the energy conversion efficiency of the methanol synthesis process can reach up to 75% [96].

Iceland's Carbon Recycling International built the world's first commercial methanol factory (the George Olah Renewable Methanol Factory), which is based on the recycling of green hydrogen and carbon dioxide in 2011 [97]. At the same time, Iceland's Carbon Recycling International also utilized producing hydrogen and carbon dioxide from geothermal energy to synthesize renewable methanol, reaching 4 million kilograms of methanol productivity in 2014.

The cost of zero-carbon methanol also mainly depends on the price of green hydrogen, that is, the price of green electricity. When the electricity price is 0.2 CNY/kWh, the cost of zero-carbon methanol is about 2.6 CNY/kg [98]. For every 0.1 CNY/kWh reduction in electricity price, the methanol cost can be reduced by 0.5 CNY/kg. When the electricity price is lower than 0.15 CNY/kWh, zero-carbon methanol initially has market competitiveness.

4.3. Energy Storage

In recent years, renewable energy generation has been growing rapidly. However, the fluctuations of renewable energy sources such as wind and solar also brings a severe shock to the reliability and security of the power grid. The traditional physical, electrochemical and thermal energy storage methods can only store energy for a short period of time [99], while hydrogen energy storage not only enables inter-seasonal and inter-geographical energy storage, but also has a capacity of up to a 100 GW level [100]. Therefore, hydrogen energy storage can provide a solution to the problem of long-term and cross-season power balance in the new power system, realizing the optimal allocation of energy across regions and seasons. In terms of new energy consumption, hydrogen energy storage can be used to solve the intermittency and uncertainty problems of renewable energy [101].

Hydrogen storage is already commercially available in major developed countries around the world, with nine projects in operation by November 2021, all located in the European Union [100]. Among them, the Audi E-gas project in Germany, which was built in 2013, utilizes the abundant wind and solar energy resources in Werlte to convert excess energy into storable and moveable methane gas via the process of electrolysis of water and methanation, which can be connected to the natural gas network or combusted to generate electricity for the Internet as needed [102]. The project solves the problem of long-term storage of renewable energy using the caching capacity of the natural gas network.

The projects of hydrogen energy storage in China are still in the early stage of commercialization. According to incomplete statistics, as of June 2022, there are currently 17 projects of hydrogen energy storage in China. The Anhui Lu'an Megawatt-level hydrogen comprehensive utilization demonstration project invested by the State Grid is the first megawatt-level hydrogen energy storage power station in China, with 723,000 m^3 of hydrogen and 1.278 million kilowatts of hydrogen power generation. This project uses 1 MW PEM electrolysis hydrogen production and waste heat utilization technology, where different types of distributed energy, such as hydrogen storage, fuel cells, distributed photovoltaic, wind power, combined cold and heat supply, and controllable load are aggregated into virtual microgrids, realizing real-time perception and scientific scheduling of microgrid operating state [103]. Another regional integrated energy system application model is the United Kingdom's Kirkwall town hydrogen ecological community. Due to its relatively remote location, the town uses abandoned wind and tidal power generation to produce hydrogen and then via fuel cells provides power for cars and ships and achieves cogeneration [104].

The cost of hydrogen energy storage has been approaching the cost of electrochemical energy storage, but it is still high relative to pumped hydro storage. As the capacity of hydrogen energy storage increases and continues to scale, the cost is expected to be lower than electrochemical energy storage [105].

Hydrogen storage is expected to further improve economics via peak-to-valley arbitrage. According to the data of China's grid proxy tariffs in April 2023, there have been 22 regions with the difference in peak–valley electricity tariffs exceeding 0.7 CNY/kWh, of which the maximum peak-valley electricity tariff difference in Zhejiang Province has reached 1.28 CNY/kWh. According to estimates, when the peak-valley electricity price difference reaches 0.7 CNY/kWh, the yield of energy storage can reach 10% [106].

4.4. Power-to-Gas

Power-to-Gas (P2G) technology converts electricity generated from renewable sources into gas fuels and methane. P2G technology mainly includes two processes: the first process is the reaction of electrolytic water to produce hydrogen, and the second reaction is the combination of hydrogen and carbon dioxide to produce methane gas under high temperature and pressure. Therefore, P2G technology can be coupled with carbon capture, which is also currently regarded as one of the important ways to deeply decarbonize the power sector [107].

There are two main application scenarios of P2G technology [108]: The first applied scenarios are specific regions or China's energy allocation in order to improve grid stability and security and reduce the problem of wind and light abandonment. The second applied scenarios are the energy chain of industrial, small power facilities or other distributed devices to enhance benefits. In both application scenarios, P2G technology is introduced to maximize energy utilization and reduce harmful gas emissions. In the case of Jupiter 1000 in France, GRTgaz uses green hydrogen from surplus wind power and carbon dioxide captured using steel mills to synthesize methane, which is injected into natural gas pipelines or used as fuel for ships.

Compared with hydrogen, methane synthesized via P2G technology with higher overall conversion efficiency is safer and more convenient in transportation and storage. In addition, the transmission loss of the natural gas pipeline network is only one-quarter of that of transmission lines [109]. Therefore, the synthesized methane has a broader prospect. However, the high investment cost is still the main bottleneck to restrict the development of P2G technology. At present, the cost of P2G projects mainly originates from power consumption and carbon dioxide. Therefore, the utilization of abandoned wind and light for power generation and technological innovation of the carbon capture system are the ways to realize cost reduction and commercialization of P2G technology [110]. In addition, the full utilization of by-products of P2G technology (such as oxygen and waste heat) can further improve the economy [111].

4.5. Microgrid

Microgrid with the core of combined cooling, heating and power (CCHP) and combined heating and power (CHP) is a kind of collaborative planning system for energy production, supply, storage and consumption using distributed power sources [112]. Via the synergistic energy supply of multiple devices such as electrolyzers and hydrogen fuel cells, the hydrogen energy system as an energy storage link can participate in microgrid operation, which improves energy utilization [113].

For example, the China Huadian Corporation LTD's research project of renewable energy hydrogen production, large-scale energy storage and comprehensive utilization technology of hydrogen energy has completed research and demonstration of distributed cooling, heating and power triple-supply technology via utilizing solid-state hydrogen storage and hydrogen fuel cells. The project has created the first cooling, heating and power triple-supply system for hydrogen fuel cells in China, which realizes the use of hydrogen to generate electricity from fuel cells, utilizes the heat from the power pile, completes low-temperature waste heat refrigeration, achieves the graded utilization of energy and extends the application scenarios of fuel cells. Based on the operation, it is found that the system efficiency of CCHP is 41.6% and that of CHP is 45.5%, which is better in terms of energy efficiency.

Currently, the unit investment of a 10–50 MW distributed CCHP system is about 4000–4500 CNY/kW [114], while the cost of a small-scale hydrogen fuel cell CHP system (kilowatt-scale) is more than 2 CNY/kWh, which is still an improvement in terms of economy.

5. Summary and Outlook

5.1. Conclusions

The relationship between electricity production and consumption is revolutionized, and the substitution of electricity and hydrogen contributes to whole-society carbon neutrality. In summary, the technological development status and economy of the whole industrial chain of “production-storage-transport-use” of green hydrogen energy are discussed and reviewed. The principles and characteristics of hydrogen production technologies such as AWE, PEM, AEM and SOEC are first described in detail. In addition, electricity prices and equipment costs are the most important economic costs of AWE and PEM hydrogen production technologies. Then, the technologies of hydrogen transport and storage are also described. The quantity, scale and distance are the keys to controlling the costs of hydrogen storage and transportation. Finally, in terms of hydrogen energy applications, with the gradual upgrading and progress of top-level design and technology, hydrogen energy applications based on transportation, industrial engineering, energy storage, electricity to gas and microgrids will show a diversified development trend.

5.2. Outlook

At present, there are still many challenges in the large-scale commercial application of hydrogen energy. In terms of hydrogen production, the use of green electricity from renewable energy sources such as water, wind and solar energy to produce green hydrogen is an inevitable requirement for effective cost reduction and efficiency increasing and environmental protection and sustainable development. With the continuous breakthrough and large-scale application of the key technology for hydrogen production via electrolytic water, the cost of hydrogen production will be greatly reduced. In terms of hydrogen storage and transportation, although the technology of pressurized compression hydrogen storage, liquefied hydrogen storage, metal hydride hydrogen storage and organic compound hydrogen storage have all achieved considerable progress, the counterbalance between unit hydrogen density, safety and cost has not yet been resolved. Therefore, there is still a certain gap between this and large-scale commercialization and application. In terms of hydrogen utilization, hydrogen energy application scenarios show a diversified trend. Hydrogen energy as the pivot of the energy Internet can be deeply coupled with carbon capture technology, connecting renewable energy with the power grid, gas network, heat network and transportation network, which accelerates the process of energy transition. Based on the commercial value of green hydrogen, the commercialization of the whole industrial chain will be driven by diversified and large-scale hydrogen energy demonstration applications in the future.

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Nomenclature

Acronyms and Parameters	**Full Title**
AWE	Alkaline water electrolysis
PEM	Proton exchange membrane
CNY	China Yuan
HPC	Hydrogen production cost
UEC	Unit electricity consumption
AD	Annual depreciation
AF	Annual freight
TAHP	Total annual hydrogen production
UWC	Unit water consumption
WP	Water price

HER	Hydrogen evolution reaction
SOEC	Solid oxide electrolysis cell
AEM	Anion exchange membrane
LFL	Lower flammable limit
UFT	Upper flammable limit
HE	Hydrogen embrittlement
P2G	Power to Gas
CCHP	Combined cooling heating and power
CHP	Combined heating and power

References

1. International Energy Agency. Global Hydrogen Review 2022 [R/OL]. Available online: https://www.iea.org/reports/global-hydrogen-review-2022 (accessed on 1 September 2022).
2. Zhang, W. The Progress and Economic Analysis of Hydrogen Production Technology. *Pet. Petrochem. Today* **2022**, *30*, 31–36.
3. Germany Pledges to Invest 4 Billion Euros in Green Energy Projects in Africa [R/OL]. Available online: https://apnews.com/article/germany-g20-compact-africa-green-energy-investment-dfd9e54ee108758bc22a8ce8e842a910 (accessed on 21 November 2023).
4. Jiang, H.; Xu, X.; Liu, Z.; Zhang, R.; Hu, X. Energy transition and hydrogen development prospects in Saudi Arabia. *Energy Storage Sci. Technol.* **2022**, *11*, 2354–2365.
5. Li, S.; Shi, Y.; Cai, N. Progress in hydrogen production from fossil fuels and renewable energy sources for the green energy revolution. *J. Tsinghua Univ. (Sci. Technol.)* **2022**, *62*, 655–662.
6. Zou, C.; Li, J.; Zhang, X.; Jin, X.; Xiong, B.; Yu, H.; Liu, X.; Wang, S.; Li, Y.; Zhang, L.; et al. Industrial status, technological progress, challenges and prospects of hydrogen energy. *Nat. Gas Ind.* **2022**, *42*, 1–20. [CrossRef]
7. Han, L. Nanoporous Metal-Based Hybrid Electrodes as Highly Efficient Electrocatalysts for Alkaline Hydrogen Evolution Reaction. Ph.D. Thesis, Jilin University, Changchun, China, 2020.
8. Zhang, L. Study on the Electrocatalytic Hydrogen Evolution Performance of Transition Metal Dichalcogenides and Phosphides Heterojunctions. Ph.D. Thesis, Changchun University of Technology, Changchun, China, 2023.
9. Liu, W.; Wan, Y.M.; Xiong, Y.L.; Tao, Z.J.; Zhu, Y.B. Key Technology of Water Electrolysis and Levelized Cost of Hydrogen Analysis under Carbon Neutral Vision. *Trans. China Electrotech. Soc.* **2022**, *37*, 2888–2896.
10. Song, Z. Development of Polysulfone Membrane for Alkaline Water Electrolyzer. Master's. Thesis, Hunan University, Changsha, China, 2018.
11. Johan, C.E.; Anders, A.F.; Kasper, T.T.; Gastón, O.L. Affordable Green Hydrogen from Alkaline Water Electrolysis: Key Research Needs from an Industrial Perspective. *ACS Energy Lett.* **2023**, *8*, 1502–1509.
12. Anh, L.H.; Sivakumar, B.; Aaron, H.; George, T.; Atheer, A.; Klaudia, W.; Chong, L.; Gerhard, F.S.; Gordon, G.W. High-performing catalysts for energy-efficient commercial alkaline water electrolysis. *Sustain. Energy Fuels* **2023**, *7*, 31–60.
13. CNY, T.; Wan, Z.; Wang, J.; Zhang, D.; Jiang, D. The Day-Ahead Output Plan of Hydrogen Production System Considering the Start-Stop Characteristics of Electrolytic Cell. *Electr. Power* **2022**, *55*, 101–109.
14. Soochow Securities Research Institute. Hydrogen Energy Series Research II: Industry Chain Economy Measurement and Cost Reduction Outlook. [R/OL]. Available online: https://pdf.dfcfw.com/pdf/H3_AP202205081564384333_1.pdf?1652088458000.pdf (accessed on 8 May 2022).
15. Zhang, X.; Wang, K.; Fan, X.; Zheng, L. Cost analysis on hydrogen production via water electrolysis. *Mod. Chem. Ind.* **2021**, *41*, 7–11.
16. Mostafa, E. Hydrogen production by water electrolysis technologies: A review. *Results Eng.* **2023**, *20*, 101426.
17. Shiva, K.S.; Aleksey, N.; Himabindu, V.; Hankwon, L. Experimental and simulation of PEM water electrolyser with Pd/PN-CNPs electrodes for hydrogen evolution reaction: Performance assessment and validation. *Appl. Energy* **2023**, *348*, 121565.
18. Mehrnaz, M.N.; Pouria, A.; Ehsan, H. Comparative optimization study of three novel integrated hydrogen production systems with SOEC, PEM, and alkaline electrolyzer. *Fuel* **2023**, *336*, 126835.
19. Babar, P.T.; Pawar, B.S.; Lokhande, A.C.; Gang, M.G.; Jang, J.S.; Suryawanshi, M.P.; Pawar, S.M.; Kim, J.H. Annealing temperature dependent catalytic water oxidation activity of iron oxyhydroxide thin films. *J. Energy Chem.* **2017**, *26*, 757–761. [CrossRef]
20. Bishnupad, M.; Piyali, B.; Bikash, K.J. An overview on advances in design and development of materials for electrochemical generation of hydrogen and oxygen. *Mater. Today Energy* **2022**, *23*, 100902.
21. Niu, S.; Fang, Y.; Rao, D.; Liang, G.; Li, S.; Cai, J.; Liu, B.; Li, J.; Wang, G. Reversing the Nucleophilicity of Active Sites in CoP_2 Enables Exceptional Hydrogen Evolution Catalysis. *Small* **2022**, *18*, 2106870. [CrossRef]
22. Zhou, Q.; Liao, L.; Bian, Q.; Yu, F.; Li, D.; Zeng, J.; Zhang, L.; Wang, H.; Tang, D.; Zhou, H.; et al. Engineering In-Plane Nickel Phosphide Heterointerfaces with Interfacial sp H-P Hybridization for Highly Efficient and Durable Hydrogen Evolution at 2 A cm^{-2}. *Small* **2022**, *18*, 2105642. [CrossRef]
23. Sun, L.; Cao, M.; Jing, Z.; Cheng, Z.; Zheng, D.; Xu, H.; Zhou, Q.; Lin, J. 1 T-Phase Enriched P doped WS_2 nanosphere for highly efficient electrochemical hydrogen evolution reaction. *Chem. Eng. J.* **2022**, *429*, 132187. [CrossRef]
24. Liu, Z.; Wang, K.; Li, Y.; CNY, S.; Huang, G.; Li, X.; Li, N. Activation engineering on metallic 1T-MoS_2 by constructing In-plane heterostructure for efficient hydrogen generation. *Appl. Catal. B Environ.* **2022**, *300*, 120696. [CrossRef]

25. Chen, H.; Hu, M.; Jing, P.; Liu, B.; Gao, R.; Zhang, J. Constructing heterostructure of CeO_2/WS_2 to enhance catalytic activity and stability toward hydrogen generation. *J. Power Sources* **2022**, *521*, 230948. [CrossRef]
26. Yang, C.; Zhong, W.; Shen, K.; Zhang, Q.; Zhao, R.; Xiang, H.; Wu, J.; Li, X.; Yang, N. Electrochemically Reconstructed Cu-FeOOH/Fe_3O_4 Catalyst for Efficient Hydrogen Evolution in Alkaline Media. *Adv. Energy Mater.* **2022**, *12*, 2200077. [CrossRef]
27. Yu, D.; Zhang, F.; Zhang, Y.; Tian, M.; Lin, H.; Guo, W.; Qu, F. Constructing Heteroatom-Doped Transition-Metal Sulfide Heterostructures for Hydrogen Evolution Reaction. *ACS Appl. Energy Mater.* **2023**, *6*, 6348–6356. [CrossRef]
28. Jiang, L.; Zhou, Q.; Li, J.; Xia, Y.; Li, H.; Li, Y. Engineering Isolated S Vacancies over 2D MoS_2 Basal Planes for Catalytic Hydrogen Evolution. *ACS Appl. Nano Mater.* **2022**, *5*, 3521–3530. [CrossRef]
29. Wang, X.; Zhang, Y.; Si, H.; Zhang, Q.; Wu, J.; Gao, L.; Wei, X.; Sun, Y.; Liao, Q.; Zhang, Z.; et al. Single-Atom Vacancy Defect to Trigger High-Efficiency Hydrogen Evolution of MoS_2. *J. Am. Chem. Soc.* **2020**, *142*, 4298–4308. [CrossRef]
30. Fu, J.; Ali, R.; Mu, C.; Liu, Y.; Mahmood, N.; Lau, W.; Jian, X. Large-scale preparation of 2D VSe_2 through a defect-engineering approach for efficient hydrogen evolution reaction. *Chem. Eng. J.* **2021**, *411*, 128494. [CrossRef]
31. Joyner, J.; Oliveira, E.F.; Yamaguchi, H.; Kato, K.; Vinod, S.; Galvao, D.S.; Salpekar, D.; Roy, S.; Martinez, U.; Tiwary, C.S.; et al. Graphene Supported MoS_2 Structures with High Defect Density for an Efficient HER Electrocatalysts. *ACS Appl. Mater. Interfaces* **2020**, *12*, 12629–12638. [CrossRef]
32. Kang, M.; Lin, C.; Yang, H.; Guo, Y.; Liu, L.; Xue, T.; Liu, Y.; Gong, Y.; Zhao, Z.; Zhai, T.; et al. Proximity Enhanced Hydrogen Evolution Reactivity of Substitutional Doped Monolayer WS_2. *ACS Appl. Mater. Interfaces* **2021**, *13*, 19406–19413. [CrossRef] [PubMed]
33. Li, Y.; Wang, S.; Hu, Y.; Zhou, X.; Zhang, M.; Jia, X.; Yang, Y.; Lin, B.; Chen, G. Highly dispersed Pt nanoparticles on 2D MoS_2 nanosheets for efficient and stable hydrogen evolution reaction. *J. Mater. Chem. A* **2022**, *10*, 5273–5279. [CrossRef]
34. Rui, Y.; Zhang, S.; Shi, X.; Zhang, X.; Wang, R.; Li, X. Chemically Activating Tungsten Disulfide via Structural and Electronic Engineering Strategy for Upgrading the Hydrogen Evolution Reaction. *ACS Appl. Mater. Interfaces* **2021**, *13*, 49793–49801. [CrossRef]
35. Yang, S.; Zhu, J.; Chen, X.; Huang, M.; Cai, S.; Han, J.; Li, J. Self-supported bimetallic phosphides with artificial heterointerfaces for enhanced electrochemical water splitting. *Appl. Catal. B Environ.* **2022**, *304*, 120914. [CrossRef]
36. Sarkar, B.; Parui, A.; Das, D.; Singh, A.K.; Nanda, K.K. Interfacial Electron Transfer Strategy to Improve the Hydrogen Evolution Catalysis of CrP Heterostructure. *Small* **2022**, *18*, 2106139. [CrossRef]
37. Zhang, Y.; Hui, Z.; Zhou, H.; Zai, S.; Wen, Z.; Li, J.; Yang, C.; Jiang, Q. Ga doping enables superior alkaline hydrogen evolution reaction performances of CoP. *Chem. Eng. J.* **2022**, *429*, 132012. [CrossRef]
38. Zhao, Y.; Zhao, S.; Chen, J.; Zhou, Y.; Zhao, P.; Dai, R.; Zhou, W.; Yang, P.; Zhang, H.; Chen, A. Interface engineering of Fe_2P@$CoMnP_4$ heterostructured nanoarrays for efficient and stable overall water splitting. *J. Colloid Interface Sci.* **2023**, *633*, 897–906. [CrossRef]
39. Safronova, E.Y.; Lysova, A.A.; Voropaeva, D.Y.; Yaroslavtsev, A.B. Approaches to the Modification of Perfluorosulfonic Acid Membranes. *Membranes* **2023**, *13*, 721. [CrossRef] [PubMed]
40. Ge, S.; Bai, J.; Ding, Y.; Wen, J.; Li, X. Development status and prospect of hydrogen production technology by renewable energy and its main equipment. *J. TaiCNY Univ. Technol.* **2023**. Available online: https://link.cnki.net/urlid/14.1220.N.20231222.1128.002 (accessed on 22 December 2023).
41. IRENA. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020.
42. Hu, D. *SIEMENS Energy Power-to-X Solution*; 2021 Renewable Energy Hydrogen Forum: Shanghai, China, 2021.
43. Wang, P. Study on Economy of Green Hydrogen Industry Based on Levelized Cost. *Green Pet. Petrochem.* **2023**, *8*, 1–9.
44. Zhao, X.; Li, G.; Sun, X.; Song, J.; Liang, D.; Xu, G.; Deng, Z. Key Technology and Application Progress of Hydrogen Production by Electrolysis Under Peaking Carbon Dioxide Emissions and Carbon Neutrality Targets. *J. Glob. Energy Interconnect.* **2021**, *4*, 436–446.
45. Gul, E.; Baldinelli, G.; Farooqui, A.; Bartocci, P.; Shamim, T. AEM-electrolyzer based hydrogen integrated renewable energy system optimisation model for distributed communities. *Energy Convers. Manag.* **2023**, *285*, 117025. [CrossRef]
46. Zainal, B.S.; Ker, P.J.; Mohamed, H.; Ong, H.C.; Fattah, I.M.R.; Rahman, S.M.A.; Nghiem, L.D.; Mahlia, T.M.I. Recent advancement and assessment of green hydrogen production technologies. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113941. [CrossRef]
47. Guo, X.; Zhu, H.; Zhang, S. Overview of electrolyser and hydrogen production power supply from industrial perspective. *Int. J. Hydrogen Energy* **2024**, *49*, 1048–1059. [CrossRef]
48. Wolf, S.E.; Winterhalder, F.E.; Vibhu, V.; Haart, L.G.J.; Guillon, O.; Eichel, R.; Menzler, N.H. Solid oxide electrolysis cells-current material development and industrial application. *J. Mater. Chem. A* **2023**, *11*, 17977–18028. [CrossRef]
49. Meng, X.; Gu, A.; Zeng, J.; Chen, M.; Zhou, J.; Liu, B.; Mao, Z. Advantages and challenges of China's participation in international hydrogen trade. *Int. J. Hydrogen Energy* **2024**, *52*, 1356–1368. [CrossRef]
50. Gao, J.; Mi, Y.; Zhou, Y.; Zhou, H.; Xu, Q. Recent developments in new hydrogen storage materials. *Chem. Ind. Eng. Prog.* **2021**, *40*, 2962–2971.
51. Yin, Z.; Ma, Q.; Hao, J.; Yang, G.; Lei, Y. Key Technologies and Prospect Analysis of Hydrogen Energy Storage and Transportation. *Liaoning Chem. Ind.* **2021**, *50*, 1480–1482+1487. [CrossRef]

52. Xue, J.; Yu, P.; Zhang, Y.; Liu, H.; Che, D. Review on advances of dehydrogenation reactor for hydrogen storage system using liquid organic hydrogen carrier. *Therm. Power Gener.* **2022**, *51*, 1–10.
53. Ibrahim, A.; Paskevicius, M.; Buckley, C.E. Chemical compression and transport of hydrogen using sodium borohydride. *Sustain. Energy Fuels* **2023**, *7*, 1196–1203. [CrossRef]
54. Cai, Y.; Xu, J. *Hydrogen Storage Technologies and Materials*; Chemical Industry Publishers: Beijing, China, 2018.
55. Wang, X.; Li, B.; Jin, X.; Han, B.; Shu, C. Ultimate pressure-bearing capacity of Type III onboard high-pressure hydrogen storage tanks under typical accident scenarios. *J. Energy Storage* **2023**, *63*, 107135. [CrossRef]
56. Bosu, S.; Rajamohan, N. Recent advancements in hydrogen storage—Comparative review on methods, operating conditions and challenges. *Int. J. Hydrogen Energy* **2024**, *52*, 352–370. [CrossRef]
57. Li, J.; Wang, X.; Guo, Y. The significance of hydrogen energy development and the current status of hydrogen storage technology. *Chem. Eng. Equip.* **2023**, *312*, 205–206.
58. Zhang, Z.; Xie, H. Hydrogen Energy Utilization—Status and Analysis of Liquid Hydrogen Production, Storage and Transportation Technologies. *Renew. Energy* **2023**, 1–8. [CrossRef]
59. Song, B. Current Status and Trends of Foreign Hydrogen Storage Technology. *CFHI Technol.* **2023**, *212*, 61–63.
60. Ma, X. T Techno-Economic Analysis of Liquid Organic Hydrogen Carrier and Pt/Al_2O_3 Catalytic Dehydrogenation Performance Study. Ph.D. Thesis, East China University of Science and Technology, Shanghai, China, 2021.
61. Ma, X.; Li, Z.; Xiao, Z.; Li, P. Techno-economic analysis and comparison of liquid organic hydrogen carrier system. *Mod. Chem. Ind.* **2022**, *42*, 202–205+210.
62. Si, W.; Yu, D. How Low Can the Cost of Hydrogen Go? Storage and Transportation [R/OL]. Available online: https://www.sohu.com/a/334833486_354900 (accessed on 19 August 2019).
63. Song, P.; Hou, J.; Mu, X.; Wang, X. Screening and application scenarios of liquid organic hydrogen carrier systems. *Nat. Gas Chem. Ind.* **2021**, *46*, 1–5+33.
64. Muduli, R.C.; Kale, P. Silicon nanostructures for solid-state hydrogen storage: A review. *Int. J. Hydrogen Energy* **2023**, *48*, 1401–1439. [CrossRef]
65. Zhang, X.; Jiang, L.; Ye, J.; Wu, Y.; Guo, X.; Li, Z.; Li, H. Research progress of solid-state hydrogen storage technology. *Acta Energiae Solaris Sin.* **2022**, *43*, 345–354.
66. Mohassel, R.; Shabani-Nooshabadi, M.; Salavati-Niasari, M. Effect of g-C_3N_4 amount on green synthesized $GdFeO_3$/g-C_3N_4 nanocomposites as promising compounds for solid-state hydrogen storage. *Int. J. Hydrogen Energy* **2023**, *48*, 6586–6596. [CrossRef]
67. Gao, D.; Zhang, L.; Song, M.; Wu, F.; Wang, J.; Zhao, H.; Li, H. Interfacial engineering of nickel/vanadium based two-dimensional layered double hydroxide for solid-state hydrogen storage in MgH_2. *Int. J. Hydrogen Energy* **2023**, *48*, 9390–9400. [CrossRef]
68. Wang, L.; Zhang, L.; Lu, X.; Wu, F.; Sun, X.; Zhao, H.; Li, Q. Surprising cocktail effect in high entropy alloys on catalyzing magnesium hydride for solid-state hydrogen storage. *Chem. Eng. J.* **2023**, *465*, 142766. [CrossRef]
69. DT New Energy. Research and Development of Hydrogen Storage and Transportation Technology and Cost Analysis. [R/OL]. Available online: https://mp.weixin.qq.com/s?__biz=MzU5MzY1MzQ2NA==&mid=2247504183&idx=1&sn=ebed31bd93aeab3d59988d1741d8ebb7&chksm=fe0faa80c97823965e9f2bc60f751a8a5562697c36ed96914adbedc7cf42d818e16a2fbfed3c (accessed on 30 April 2022).
70. Ding, L.; Tang, T.; Wang, Y. Research progress and development trend of hydrogen storage and transportation technology. *Nat. Gas Chem. Ind.* **2022**, *47*, 35–40.
71. Abohamzeh, E.; Salehi, F.; Sheikholeslami, M.; Abbassi, R.; Khan, F. Review of hydrogen safety during storage, transmission, and applications processes. *J. Loss Prev. Process Ind.* **2021**, *72*, 104569. [CrossRef]
72. Włodarczyk, P.P.; Włodarczyk, B. Effect of hydrogen and absence of passive layer on corrosive properties of aluminum alloys. *Materials* **2020**, *13*, 1580. [CrossRef]
73. Włodarczyk, P.P.; Włodarczyk, B. Influence of hydrogen on shortening the operational reliability time of aluminum alloy construction. *Instal* **2013**, *12*, 32–34.
74. Shahverdian, M.H.; Sohani, A.; Pedram, M.Z.; Sayyaadi, H. An optimal strategy for application of photovoltaic-wind turbine with PEMEC-PEMFC hydrogen storage system based on techno-economic, environmental, and availability indicators. *J. Clean. Prod.* **2023**, *384*, 135499. [CrossRef]
75. Tollefson, J. Hydrogen vehicles: Fuel of the future? *Nature* **2010**, *464*, 1262. [CrossRef]
76. Zhang, L.; Xie, N.; Cao, T.; Hu, M.; Jiang, N. Application of Hydrogen Energy in Transportation and Cost Analysis of Fuel Cell Vehicles. *Green Pet. Petrochem.* **2022**, *7*, 1–5+30.
77. Chang, H.; Wan, Z.; Zheng, Y.; Chen, X.; Shu, S.; Tu, Z.; Chan, S. Energy analysis of a hybrid PEMFC–solar energy residential micro-CCHP system combined with an organic Rankine cycle and vapor compression cycle. *Energy Convers Manag.* **2017**, *142*, 374–384. [CrossRef]
78. What in the World Is Happening with Hydrogen? [R/OL]. Available online: https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-plenary-global-context.pdf (accessed on 25 August 2021).
79. Le, T.T.; Sharma, P.; Bora, B.J.; Tran, V.D.; Truong, T.H.; Le, H.C.; Nguyen, P.Q.P. Fueling the future: A comprehensive review of hydrogen energy systems and their challenges. *Int. J. Hydrogen Energy* **2024**, *54*, 791–816. [CrossRef]

80. Tian, Z.; Wang, Y.; Zhen, X.; Liu, D. Numerical comparative analysis on performance and emission characteristics of methanol/hydrogen, ethanol/hydrogen and butanol/hydrogen blends fuels under lean burn conditions in SI engine. *Fuel* **2022**, *313*, 123012. [CrossRef]
81. Sami, M.M.E.A.; Carlos, R.P.B.; Gabriel, L.R.S.; Renan, S.L.; Edvaldo, S.C.; Paulo, E.V.M. Analysis of performance parameters of an ethanol fueled spark ignition engine operating with hydrogen enrichment. *Int. J. Hydrogen Energy* **2020**, *45*, 5588–5606.
82. Kim, S.; Kim, J. Feasibility assessment of hydrogen-rich syngas spark-ignition engine for heavy-duty long-distance vehicle application. *Energy Convers. Manag.* **2022**, *252*, 115048. [CrossRef]
83. Xu, S.; Yu, B. Current Development and Prospect of Hydrogen Energy Technology in China. *J. Beijing Inst. Technol.* **2021**, *23*, 1–12.
84. Wang, J.; Hu, C. Analysis of the development status and trend of China's hydrogen fuel cell special-purpose vehicles. *Spec. Purp. Veh.* **2021**, *287*, 51–55.
85. Special Research Report on Solid State Hydrogen Storage. [R/OL]. Available online: https://finance.sina.com.cn/esg/2023-04-07/doc-imypnmqt2018912.shtml (accessed on 7 April 2023).
86. Ramachandran, R.; Menon, R.K. An overview of industrial uses of hydrogen. *Int. J. Hydrogen Energy* **1998**, *23*, 593–598. [CrossRef]
87. Zhang, Z.; Jiang, G.; Yang, Y.; Yan, D. The Analysis and Optimization solution of Hydrogen consumption in Polysilicon Production. *World Nonferrous Met.* **2017**, *2*, 32–33.
88. Humphreys, J.; Lan, R.; Tao, S. Development and Recent Progress on Ammonia Synthesis Catalysts for Haber–Bosch Process. *Adv. Energy Sustain. Res.* **2021**, *2*, 2000043. [CrossRef]
89. Reiter, A.J.; Kong, S.C. Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. *Fuel* **2011**, *90*, 87–97. [CrossRef]
90. Xiao, H.; Valera-Medina, A.; Bowen, P.J. Study on premixed combustion characteristics of co-firing ammonia/methane fuels. *Energy* **2017**, *140*, 125–135. [CrossRef]
91. Chen, R.; Zheng, S.; Lin, Z.; Liu, Y.; Wang, Z. Performance Study of Direct Ammonia Fuel Cell Based on PtIr/C Anode Electrocatalyst. *Acta Chim. Sin.* **2021**, *79*, 11286–11292. [CrossRef]
92. Li, J. *Status and Trends of Green Power-Green Hydrogen-Green Ammonia Integration*; Progress Report on Carbon Neutrality in China; Social Science Literature Publishing House: Beijing, China, 2022; pp. 110–122.
93. Orange Club. New Trends in the Hydrogen Industry: Will the Ammonia Era Arrive? [EB/OL]. Available online: https://www.ofweek.com/hydro-gen/2022-01/ART-180827-8420-30547720_2.html (accessed on 26 January 2022).
94. Xu, G.; Xue, X.; Zhang, Z.; Wu, Z.; Liang, S.; Chen, H.; Lei, J. A New Carbon Neutral Energy Technology Route Based on Electrolytic Water to Hydrogen and Methanol Synthesis. *Proc. CSEE* **2023**, *43*, 191–201.
95. Chen, J. "Liquid Sunshine Methanol" could be the mainstay of emission reductions- Interview with Li Can, Academician of Chinese Academy of Sciences, Researcher of Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Director of National Laboratory of Clean Energy (Preparation). *China Petrochem. Ind. Obs.* **2020**, *275*, 12–14.
96. Battaglia, P.; Buffo, G.; Ferrero, D.; Santarelli, M.; Lanzini, A. Methanol synthesis through CO_2 capture and hydrogenation: Thermal integration, energy performance and techno-economic assessment. *J. CO_2 Util.* **2021**, *44*, 101407. [CrossRef]
97. Pengxiang, S.O.; Bo, Z.H.; Cenyu, Y.A.; Le, W.A.; Yi, J.I.; Shihui, Y.A. An assessment of the use of fuel chemicals synthesized from captured carbon dioxide for renewable electricity storage. *Energy Storage Sci. Technol.* **2016**, *5*, 78–84.
98. Hydrogen Energy Committee of China Energy Conservation Association. Green Methanol-One of the Most Important Downstream Applications of Green Hydrogen. [EB/OL]. Available online: http://www.heic.org.cn/newshow.asp?id=786 (accessed on 12 July 2022).
99. Ji, L.; Zhao, Y.; Wang, F.; Song, J.; Li, L.; Song, X.; Pan, Y. Current situation of hydrogen energy technology and hydrogen energy storage applied in power generation. *Met. Funct. Mater.* **2019**, *26*, 23–31.
100. Xu, C.; Liu, J. Hydrogen Energy Storage in China's New-Type Power System: Application Value, Challenges, and Prospects. *Chin. Acad. Eng.* **2022**, *24*, 89–99. [CrossRef]
101. Mehrjerdi, H.; Iqbal, A.; Rakhshani, E.; Torres, J.R. Daily-seasonal operation in net-zero energy building powered by hybrid renewable energies and hydrogen storage systems. *Energy Convers Manag.* **2019**, *201*, 112156. [CrossRef]
102. Audi, A.G. Audi e-Gas-Project Life Cycle Assessment. [EB/OL]. Available online: https://www.audi.com/en/company/sustainability/downloads-and-contact/documents-and-policies.html (accessed on 3 February 2014).
103. Jiang, D.; Jia, Y.; Lu, Q.; Hong, B.; Shen, R.; Zhang, Y. Application Prospect of Hydrogen Energy in Integrated Energy Systems. *Electr. Power* **2020**, *53*, 135–142.
104. Zhang, H. Key Technologies and Development Prospect of Hydrogen Energy Storage System. *J. Shandong Electr. Power Coll.* **2021**, *24*, 8–12.
105. Liu, C.; Xu, Y.; Zhang, J.; Hu, S.; Yue, F.; Ding, J.; Chen, H. Research progress in economic study of energy storage. *Energy Storage Sci. Technol.* **2017**, *6*, 1084–1093.
106. Unicorn Intelligence Center. In-Depth Report on Electrochemical Energy Storage. [R/OL]. Available online: https://xueqiu.com/1048969405/194802324 (accessed on 19 August 2021).
107. Yang, J.; Xie, L.; Song, X.; Li, J.; Zhang, P.; Bian, Y. Collaborative Operation Method of Carbon Capture-P2G Based on Renewable Energy. *New Energy* **2022**, *50*, 70–78.
108. Valerie, E.; Tesfaldet, G. A Review of Projected Power-to-Gas Deployment Scenarios. *Energies* **2018**, *11*, 1824.

109. Zakeri, B.; Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renew. Sustain. Energy Rev.* **2015**, *42*, 569–596. [CrossRef]
110. Xue, Y. Power to Gas Technology of Renewable Energy and Its Life Cycle Assessment. Master's Thesis, Southeast University, Nanjing, China, 2021.
111. Tichler, R.; Lehner, M.; Horst, S.; Koppe, M. *Power-to-Gas: Technology and Business Models*; Springer International Publishing: Cham, Switzerland, 2014.
112. Pei, Y. Optimal Operation of Combined Cooling, Heating and Power Micro-Energy Grid with Hydrogen Energy. Master's Thesis, Taiyuan University of Technology, Taiyuan, China, 2020.
113. Shao, Z.; Yi, B. Developing Trend and Present Status of Hydrogen Energy and Fuel Cell Development. *Bull. Chin. Acad. Sci.* **2019**, *34*, 469–477.
114. Hua, B.; Gong, J. Techno-economic Analysis on Combined Cold Heat and Power & Dsiteibuten Energy System. *Nat. Gas Ind.* **2007**, *7*, 118–120+146.

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