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Review

A Global Review of the Hydrogen Energy Eco-System

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Abstract: Climate change primarily caused by the greenhouse gases emitted as a result of the consumption of carbon-based fossil fuels is considered one of the biggest challenges that humanity has ever faced. Moreover, the Ukrainian crisis in 2022 has complicated the global energy and food status quo more than ever. The permanency of this multifaceted fragility implies the need for increased efforts to have energy independence and requires long-term solutions without fossil fuels through the use of clean, zero-carbon renewables energies. Hydrogen technologies have a strong potential to emerge as an energy eco-system in its production-storage-distribution-utilization stages, with its synergistic integration with solar-wind-hydraulic-nuclear and other zero-carbon, clean renewable energy resources, and with the existing energy infrastructure. In this paper, we provide a global review of hydrogen energy need, related policies, practices, and state of the art for hydrogen production, transportation, storage, and utilization.

Keywords: hydrogen; renewables; production; storage; utilization

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1. Introduction

Anthropogenic CO_2 emissions that cause global warming have been increasing at a worldwide scale since the end of 19th century. With a combined 66.4% of worldwide fossil fuel use and 67.8% of global fossil CO_2 emissions in 2021, China, the United States, the European Union, Japan, Russia, and India continued to lead the world in CO_2 emissions. India and Russia had the biggest relative increases in fossil CO_2 emissions among the six countries in 2021 in contrast with 2020 [1]. This situation has motivated the search for clean energy solutions. As one of the most important alternatives, hydrogen (H_2) has a long history of being used as fuel, dating back to 1806 when the first internal combustion engine (ICE) was powered by a mix of hydrogen and oxygen. With the increasing global environmental concerns, hydrogen has recently emerged as a major secondary energy source to store and transport energy produced from other sources, since it can be used without direct emissions of air pollutants or greenhouse gases. Hydrogen, as a synthetic fuel, can be produced from a variety of low-carbon sources, such as wind and solar, and can store energy efficiently with high energy content per unit mass, which further contributes to reducing the environmental impact. Developing hydrogen technologies are expected to provide a pathway to a resilient and sustainable energy eco-system by: (1) using hydrogen as an efficient energy storage and transport medium to replace carbon-based fuels; (2) storing the electricity to meet weekly or monthly imbalances in supply and demand in renewable energy (RE) systems; and (3) replacing the carbon-intensive hydrogen production methods with green ones to supply for the demand of all industries [2].

Policies have been developed at national and global levels to incentivize and support research, development and adoption to achieve the potential of hydrogen technologies. The recent geopolitical conflicts have deeply impacted global energy security, and are expected to lead to the revision of such policies. In this paper, we provide a global review of hydrogen energy need, related policies, practices, and state of the art for hydrogen production, transportation, storage, and utilization.

2. Overview of the Global Energy Landscape

After the world economy had been affected by COVID-19 pandemics, the impacts of the Russia–Ukraine conflict in 2022 on international energy supplies are causing further vital consequences. Russia is one of the largest fossil fuel producers in the world, being third in the production and exporting of crude oil; second in the production and the largest in the export of natural gas (NG); and the third in the export of coal. It is the producer of 12% of the world's oil demand, 17% of the NG demand, and 5% of the coal demand and deeply integrated into Europe's distribution networks. The European Union (EU) and United Kingdom, combined, import about 40% of the NG, about 35% of the crude oil and more than 45% of the coal from Russia [3,4]. The Russia–Ukraine conflict and sanctions have increased the interest in H_2 as a potential cost-efficient, clean, renewable, sustainable fuel for the future.

In addition to its impact on fossil fuels, the Russia–Ukraine conflict also affected the biofuel ecosystem. Russia is the world's largest exporter of wheat and the second largest exporter of sunflower oil, while Ukraine is the world's largest exporter of sunflower oil, the fourth largest exporter of maize, and the fifth largest exporter of wheat. Russia and Ukraine produce nearly 25% of the world's wheat and barley, 20% of the world's corn, and over 60% of its sunflower oil [5,6]. Rising food prices due to the conflict raised the concerns for potential famine risk and rekindled the "food versus biofuel" argument. In the US, the leading biofuels producer, 36% of total corn production was used as biofuels (blended into petroleum) in 2021. In the EU, 12 million tons of grain, including wheat and maize, is turned into ethanol—around 7% of the bloc's production [6]. It was estimated that the calories diverted to biofuel production under the current policies and future commitments are equivalent to the annual needs of 1.9 billion people [7].

The EU has developed a strategy concentrating on emission-free renewable H_2 and plans to install 40 gigawatts of green H_2 electrolyzer capacity by 2030. Germany recently started a collaboration effort with Australia to decrease the production cost of renewable H_2 and accelerate the innovation process in both countries and to minimize reliance on Russian natural gas [8]. China identified H_2 as one of the six industries of the future in its 5-year economic plan [9,10]. Japan aims at having 800,000 H_2 fuel cell vehicles (FCVs) and 900 H_2 refueling stations by 2030 [11]. South Korea has a target to supply 10% of its energy demands with H_2 by 2030, increase this rate to 30% before 2040 and make it the country's largest energy carrier by midcentury [12]. India sees H_2 as the opportunity for "quantum leap" towards energy independence by 2047 and shapes its energy policy accordingly [12]. The US Department of Energy (DoE) plans to invest $9.5B for the commercialization of innovative green H_2 production technologies with the goal of reducing the production cost by 80% within the next decade. Australia, Saudi Arabia, Morocco, United Arab Emirates and Oman have announced strategies to develop clean H_2 to diversify their energy portfolios [13].

Important developments in H_2 production, storage, distribution, and utilization have been demonstrated in recent years. As a fuel, H_2 has considerably higher energy per unit weight than other fuels such as gas, diesel, and methanol (see Figure 1) [14]. Therefore, it has an immense market potential for the transportation sector, and industry. H_2 storage is one of the key factors in the H_2 economy. RE electricity is widely stored in chemical batteries but the limited capacity, lifetime, and high cost of batteries have limited their applications. H_2 could be employed as an energy carrier, like a battery, for RE electricity. The stored H_2 can be used for electrical power production in a gas turbine or fuel cell, or mechanical power production in an ICE. Solid-state materials in standard temperature and pressure conditions (STP) are seen as a promising method of storing H_2, especially for mobile systems. In terms of H_2 utilization, the deployment of fuel cell (FC) systems opened a new window to H_2 fuel success in the transportation sector. Currently, H_2-powered engines based on proton exchange membrane (PEM) FCs are deployed worldwide.

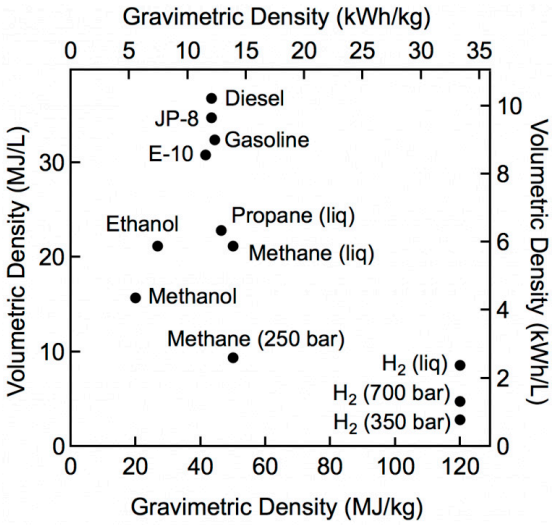


Figure 1. Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels based on lower heating values. After [14].

H_2 is defined as a clean energy source but is mostly produced via the combustion of fossil fuels (grey or black-brown category). For commercial production of H_2, four methods come forward, three of which use fossil fuels: steam methane reformation, oxidation, and gasification. The fourth one is electrolysis [15]. When the electricity for H_2 production is supplied by clean electricity, (solar photovoltaics -PV-, concentrating solar power, wind, wave, hydropower, and geothermal), the produced H_2 is regarded as zero-carbon green H_2. This means cleanliness, inexhaustibility, and independence from geopolitical effects. Today, there are highly efficient electrolyzers to produce H_2 as an environmentally friendly replacement for fossil fuels in all sectors. The integrated RE H_2 system and economy is a supply chain from production to storage, transportation/distribution and utilization (Figure 2). In an established large-scale H_2 infrastructure the most featured difficulties are cost reduction and the scaling up of this chain.

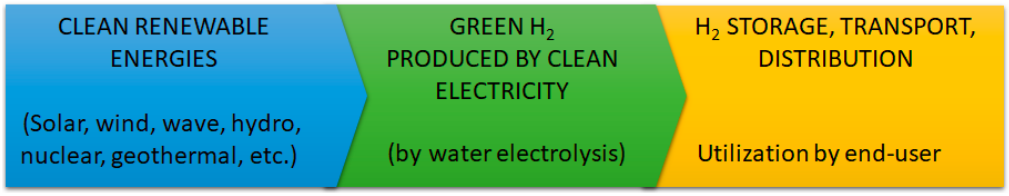


Figure 2. Integrated RE H_2 system and economy.

3. Renewable Energies

RE globally and technically promises more zero-carbon action. Hydropower and three intermittent energies, solar, wind, and tidal are resources that can forever be used to produce and store H_2 via the electrolysis of water, which is also a medium of energy storage. The global RE generation capacity has reached 2.8 TW as of 2021. Within this capacity, hydropower accounts for 1.3 TW while solar and wind powers account for 126 GW and 110 GW, respectively. The share of RE in the global electricity generation increased to 29% in 2020, up from 27% in 2019 [15]. The costs for RE continued to fall in 2021 with a 15% and 13% reduction in the cost of electricity from onshore wind and offshore wind, respectively, and a 13% reduction in the cost of solar PV generation compared to 2020, despite the rising materials and equipment costs. In 2021, about 60% of newly installed RE power had lower costs than the world's cheapest coal-fired option in the G20 countries. The benefit from RE in 2022 has been unparalleled, given the fossil-fuel price crisis: (i) in Europe, new solar and wind power added in 2021 had lifetime costs per kWh that, on average, were four to six times lower than the 2022 minimal producing expenses of fossil fuels; (ii) the additional

RE capacity developed in 2021 may globally lower the cost of producing electric power in 2022 with a minimum of 55 billion USD; and (iii) solar and wind power alone prevented the import of fossil fuels, mostly NG, in the amount of 50 billion USD in Europe during January to May 2022 [16]. As a historical turning point, the 2022 crisis showed that without RE, conditions, particularly in the developed countries, would be much more challenging for consumers, economies, and the environment. Utility-scale solar PV and wind turbines have become effectively competitive over fuel and CO_2 cost in Europe.

Solar and wind energy, with their short project lead times and relatively lower initial investment, present affordable pathways for countries to quickly reduce and eventually phase out fossil fuels while limiting the economic impact. The recent report "Renewable Power Generation Costs in 2021" published by the International Renewable Energy Agency (IRENA) states that "RE is by far the cheapest form of power today. 2022 is a stark example of just how economically viable new RE power generation has become. It frees economies from volatile fossil-fuel prices and imports, curbs energy costs and enhances market resilience. Today's situation is a devastating reminder that RE and energy saving are the future" [16].

4. Clean RE for an Integrated H_2 Energy System

H_2 is the most abundant and lightest element (2.016×10^{-3} kg/mol) in the universe, and energy-efficient fuel on the Earth (calorific or heating value). It is the richest in energy per-unit mass (140 MJ/kg), and almost three times higher than solid fuels (50 MJ/kg) (see Figure 1). It exists mainly in compounds such as water, methane, H_2S, living organisms, organic waste, etc. It is environmentally benign, since water is the only emission product at conversion to energy, and unlike electricity, it can be stored. RE H_2 produced either at a central production plant or onsite at a H_2 refueling station (HRS) could help achieve carbon-free energy economy. Despite the fact that onsite H_2 production by electrolysis typically has higher costs than production at central plants due to limited production capacity, it was shown that the at-the-pump prices end up being similar due to the additional H_2 transport cost for the case of central production. H_2 production cost constitutes the largest portion of the levelized H_2 price at the pump due to the high capital investment in both RE electricity generation and water electrolysis. As the relevant technologies advance, the at-the-pump H_2 price is estimated to fall substantially. In a 2022 study, the future at-the-pump prices of RE H_2 produced onsite at an HRS in the 26 EU countries are estimated as 11 euros/kg in 2020, decreasing to 5 euros in 2050 while the European Commission (EC) target is 1.8 euros/kg H_2 by 2030. With a 3 euro/kg H_2 subsidy for RE H_2 production, it is expected that the price targets can be reached earlier. Moreover, the subsidy can enable RE H_2 to reach an energy-based cost parity with diesel fuel (0.034 euros/MJ for H_2 compared to 0.038 euros/MJ for diesel) by 2030. Furthermore, since H_2 FCVs being more efficient, they can travel 1.3 times further compared to diesel trucks using the same amount of energy. Therefore, considering both increasing diesel prices and vehicle efficiency, the 3 euros/kg subsidy can pave the way to make H_2 cost-competitive against diesel well before 2030. Although subsidies could be a promising way to lower prices, to achieve true climate benefits, robust regulations on sourcing electric power are necessary in addition to direct financial support for RE H_2 production [17–22].

It has been shown that integrated PV-battery- H_2 systems can sustain an affordable electricity cost over the system's lifetime owing to the energy storage components. Similarly, a multi-optimization problem has been studied for integrated wind-PV energy systems for RE H_2 production to assess its exergo-economic performance and to determine the optimal operation conditions [23]. However, when the H_2 is integrated with other RE systems the overall complexity of the combined system increases the uncertainties in the power load which requires careful design to address the nonlinear characteristics and added variables [24,25].

5. H_2 Production

Though hydrogen is the most common element constituting ~70% of the universe, free hydrogen is not readily available on earth. It is typically bound into molecules such as water and hydrocarbons, particularly methane (CH_4). It can be separated from these molecules by using energy in various forms. H_2 is identified with a spectrum of colors depending on its source or production method: (1) black-brown (from coal), (2) gray (hydrocarbons without carbon capture and storage—CCS), (3) blue (hydrocarbons with CCS), (4) turquoise (pyrolysis), (5) pink (nuclear powered electricity), (6) yellow (solar energy), (7) red (high-temperature catalytic process), (8) white (naturally-occurring geological hydrogen) and (9) green (clean RE electricity) (Figure 3). Natural gas (NG), crude oil, coal, and water electrolysis processes are the most commonly used sources for H_2 production, with shares of 49, 29, 18, and 4%, respectively [26].

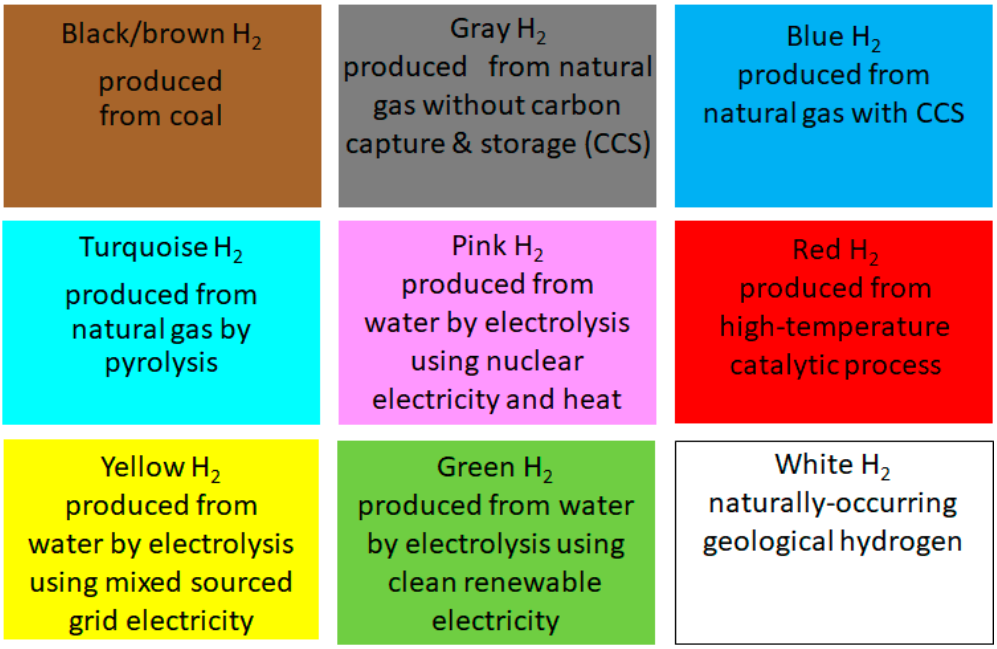


Figure 3. The spectrum of H_2 production processes.

5.1. Black-Brown and Gray H_2 Production

By far the most widely used H_2 production method is the steam reforming of natural gas, also known as steam methane reformation (SMR). This is one of the cheapest H_2 production technologies in terms of operation and production costs [27], and is also renowned for its high efficiency operation [28]. Steam and natural gas are heated together up to ~900 °C at high pressure in the presence of a nickel-based catalyst. The process yields a mixture of carbon monoxide (CO) and H_2 known as syngas which is further treated in the water–gas shift reaction to produce more hydrogen and carbon dioxide. The H_2 produced by this method is named gray H_2. However, it has serious downsides, for instance: (1) as an endothermic reaction it requires huge amount of heat supply at extremely high temperature; (2) generating heat to produce extra steam (exceeds the stoichiometric requirement by two to three times) which is required for the curving of deactivation events like coking and moving the equilibrium position of the reaction more in the direction of the H_2 generation, and (3) complex extraction of H_2 from a combination of other outcomes (CO, CO_2, CH_4, and H_2O) by employing pressure swing adsorption (PSA, separates gases in a mixture of gases to obtain a high degree of purity) and water–gas shift reactors [29]. In a similar process called gasification, steam and oxygen are used to break molecular bonds in black coal or lignite (brown coal) to produce syngas consisting of CO, H_2, CO_2, CH_4, and water vapor. These processes also result in substantial CO_2, which must be captured and stored (CCS). To address these limitations, a carbon-efficient process concept was developed that

converts captured CO_2 to CO_2 in two steps. It prevents direct contact between O_2 and CH_4, lowering safety risks. The external energy demand is reduced by coupling endothermic and exothermic reactions, and the operating temperature to produce H_2 is reduced by more than 150 K when compared to conventional CH_4 reforming. Iron, nickel, and calcium oxides are used in this process as solid intermediates, which operates between 923 and 998 K. By simultaneously delivering steam and methane to the materials in a fixed bed, an H_2-rich stream is created in the first phase, and a CO-rich stream is created in the second step by renewing the materials with a combination that is like air. H_2 concentrations of over 65 mol% and CO_2 conversion rates of over 80% were reached in proof-of-concept tests. According to cyclical experiments, carbon deposition is reduced, and the ratio of generated H_2 to CO is around 2. Experimental findings demonstrate that the process idea enables conventional methane reforming for the generation of syngas to avoid the limitations of thermodynamic equilibrium [29].

Biomass is another source of feedstock for H_2 production. As gasification is a well-established and commercially available technology, it is commonly applied to biomass like coal. The oxidation eventually results in a combination of CO, H_2, CO_2, CH_4, N_2, and higher hydrocarbons gases [30]. After the creation of syngas H_2/CO_2 a WGS reactor is used for H_2 production with high temperature [30]. It is really hard to obtain pure H_2 as biomass produces large amounts of tar even with high temperature operation due to higher hydrocarbons. The efficiency of the biomass ranges from 35–50% [31]. The moisture contents in biomass limit the efficiency of this process as it needs to be vaporized. Gasification of biomass for H_2 production are not yet commercially established due to high operation costs and the complicated process for cleaning the H_2 from tar.

Approximately 6% of the globally extracted NG and 2% of the globally extracted coal are used for H_2 production. Over 95% of current H_2 production (black-brown and grey) leading over 2% of global annual CO_2 emissions by 2020 is by steam reforming of NG, its partial oxidation, and coal gasification; very little of it is green. Producing H_2 in pure form for industry is energy intensive. The global demand for H_2 is for its utilization in chemical production (40%), oil refineries (33%), metallurgical industries (3%), and the rest is used in synthetic fuel and petrochemical production, semiconductor and glass manufacturing, welding processes, powering FCVs, and in the food industries [32,33].

5.2. Blue H_2 Production

H_2 produced from NG processing coupled with CCS is referred to as blue H_2 being carbon neutral. Blue H_2 production is predicted to reach 80 million metric tons by 2050 [34]. The climate change impact of H_2 produced from fossil fuels coupled with CCS is still debated, especially in regard to the leakage risks of indefinite long-term storage of methane gas [35]. H_2 produced using fossil-fuel feedstock causes greenhouse gas (GHG) emissions, even when CCS is used. These emissions could be substantial, and the cost of CCS is higher than frequently assumed. The percentages of GHG releases and those of CCS during blue H_2 production process determine the impacts of blue H_2 on the climate and the competitiveness of blue H_2 regarding global environment seems to depend on high CCS and negligible GHG releases. However, according to a research analysis the positive effects of blue H_2 production in terms of GHG emissions and climate change are insignificant and the use of blue H_2 seems challenging to justify on climate grounds [36]. Establishing H_2 supply chains on the basis of fossil fuels, as many national strategies forecast, may be incompatible with decarbonization goals [18]. Therefore, developing advanced supply chains in combination with high CCS capture rates is vital for blue H_2 to be a sustainable option for an actual net zero hydrogen economy [37].

In a study of optimizing blue hydrogen production for future energy systems, a northern European perspective based on Germany was investigated [38]. Blue routes provide significant benefits in the hydrogen industry but limited gains in the electricity sector. Systems using CCS (CO2 Capture and Storage) become significantly less expensive than those depending just on renewables in an energy system of the future when vast amounts

of carbon-free fuels are required for usage in sectors like long-distance transportation and industrial. Another conclusion is that paths that allow CCS would prioritize carbon-free fuels above electrification. The study found that when conventional CCS technology were used, system costs decreased by 29% and CO_2 emissions decreased by 106% (biomass's negative emission), with hydrogen generated for less than the cost of power. With the possibility for integrated power cycles that enable variable power and hydrogen generation, advanced blue hydrogen technologies might provide an extra 12% decrease in system costs with extra negative emissions because of extremely high CO_2 capture metrics. Since handling the intermittent hydrogen fluxes resulting from such an operational strategy proved to be expensive, scenarios with lower variable renewable energy shares proved to be more cost-effective. Originally, these concepts were created to better integrate higher shares of wind and solar energy [38].

5.3. Turquoise H_2 Production

Like gray and blue H_2, turquoise H_2 also uses methane as a feedstock, but the process is driven by heat produced with electricity rather than through the combustion of fossil fuels. In the process called pyrolysis, hydrogen is separated from methane (i.e., NG) in one step via flow through a molten metal catalyst in a bubble column at higher temperatures (1065 °C). This pyrolysis process is an endothermic reaction where two molecules of H_2 in gaseous form and one molecule of carbon in solid form is produced from one molecule of methane. This reaction is advantageous over methane reforming as it can be performed in near ambient pressure. Theoretically, this reaction produces a larger amount of solid carbon than H_2 with the ratio of 1 to 3 in favor of carbon. However, there is no GHG-free methane reform process. Industrial quality solid carbon can be used as manufacturing feedstock, for example for carbon-fiber production or landfilled which are simpler than capturing and sequestering CO_2. Since it is not released into the atmosphere and does not pollute groundwater in landfills, turquoise H_2 may contribute to low-carbon H_2 production in the future. Pyrolysis has not been fully commercialized yet for H_2 production. There are variants of the process that are being developed including thermal, plasma, and catalytic decomposition. The required process temperature for thermal, plasma, and catalytic decomposition are over 1000 °C, over 2000 °C, and below 1000 °C. Plasma processes realized on industrial scale are still being further developed. The other processes are at an early stage of development [39].

5.4. Pink H_2 Production

In a global zero-carbon energy system, nuclear-produced H_2 has a potential place. In this alternative method, H_2 can be produced by steam of which heat source is nuclear power plant. Nuclear energy can be used, as a source of electricity and heat, to produce H_2 efficiently and with little to no CO_2 emissions.

The nuclear alternative has had the challenge of high cost in the past, but that is now changing in the midst of a global energy crisis causing significant price hikes for fossil fuels as well as making global supplies less secure [40]. Nuclear power is the second largest low-carbon source of electricity after hydropower, supplying 10% of the world's electricity. However, nuclear power generating capacity will need to more than double to achieve net zero by 2050 [41].

Light water reactor technology presents great potential for H_2 production. The reactors reach an operating temperature of ~300 °C, while district heating and seawater desalination processes require ~150 °C. Numerous district heating systems have been in operation for decades. This heat could also be utilized for the production of fresh water, H_2 or other products in cogeneration (simultaneous production of electricity, heat and heat-derivative product) [41,42]. Electricity and heat produced at temperature levels of 300 °C in small modular reactors can be used in solid-oxide electrolyzer cells (SOEC). Six small modular reactors with a total capacity of 300 MW can meet the annual H_2 demand of a mid-sized ammonia plant (73,000 tons of H_2/year) [43]. In the longer term, advanced nuclear reactors

will be able to provide the higher temperatures required for industrial processes such as steel and cement production, as well as H_2 production by thermochemical water splitting (with some reactor designs having coolant outlet temperatures of 800–1000 °C). A single 1000 MW nuclear power reactor could produce more than 200,000 tons of H_2 each year to fuel more than 400,000 FCVs or more than 16,000 long haul FC trucks [44]. In the near future, small-to medium-sized reactors can be dedicated, on an industrial scale, to making H_2, which also takes away the cost of storage and transportation. Moreover, using base-load surplus of nuclear or any RE power grid H_2 can be produced for the local market by a mix of electrolysis and thermal processes. Nuclear power, by its potential for further development, can be a part of efforts to achieve global climate targets, and it is a sufficiently experimented alternative which can stimulate clean H_2 production preferences.

5.5. Green H_2 Production

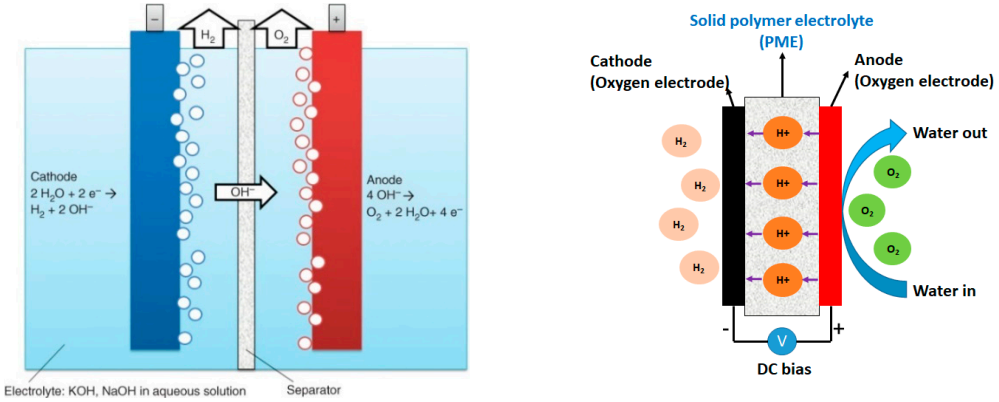
H_2 produced by water electrolysis using electricity from clean RE, namely, the green H_2, promises to help meet global energy demand while contributing to climate action goals, and represents the most promising energy carrier for the zero-carbon economy. Falling RE energy prices coupled with the declining cost of electrolyzers and increased efficiency due to technology advancements have increased the commercial feasibility of green H_2 production. Assuming these costs continue to fall, green H_2 can be produced for \$0.70–\$1.60/kg by 2050, a price range competitive with NG [45].

In 2003, the European Commission (EC) suggested that the EU should attain a H_2-based economy in 2050 and estimated that 35% of newly produced vehicles will be fueled by zero-carbon H_2 in 2040 [46]. This strategy updated in 2022 aims to ensure low-carbon H_2 technologies be able to be deployed at large scale to cover all hard-to-decarbonize sectors. Projects varying from 20 MW to above 100 MW are being developed with the current H_2 costs of 5–8 €/kg. The EC launched a call for a 100 MW electrolyzer to scale up manufacturing facilities to multi-GW per annum, to attain the goal of 1.5 \$/kg of green H_2 by 2025 provided that low-cost RE power is ensured. In this way, it is believed that green H_2 production cost parity (or even superiority) with fossil- fuels could be achieved as early as 2025. Deploying zero-emission H_2 vehicles (heavy-duty FC H_2 buses, trucks, and trains) is an essential part of EU's H_2 policy. They will require a very reliable, high-capacity HRS capable of delivering several tons each day. The regulation requires one HRS available every 150 km along the Trans-European Transport Network and in every urban node by 2030. In order to fully unleash the potential of H_2 technologies and establish them as a mainstream means of decarbonization in all transportation modes, cost reduction, increased performance and lifetime, sustainability, recycling, and eco-design in transport FC system components and vehicles are needed [47]. Another H_2 -hub plan approved by the EC in July 2022 allocates €5.4 billion to support 41 technology development projects. A small hub near Hamburg, Germany, is already under construction, and a larger hub is being built at the Port of Rotterdam in Netherlands. Portugal will produce green H_2 using wind power and transport it into the Port of Rotterdam. Spain houses Europe's largest green H_2 facility with a 100 MW solar farm. In USA, the Intermountain Power Project will also have a 220 MW electrolysis system based on PV generators to produce H_2 on site, along with the facilities to store up to 300 GW hours of the gas in underground salt domes [48]. Studies on China's potential of green H_2 production showed that the efficiency of the H_2 production from wind power is significantly higher than that from solar power. These efficiencies and green H_2 production in each province of China are expected to significantly increase by 2030 [49]. In a recent study in Sweden the feasibility of producing green H_2 using electrolysis with RE electricity in HRS was investigated. With hourly solar radiation and wind speed data, and electricity price, simulations were used to assess the cost components of H_2 production. The study revealed that integrating the electricity grid in green H_2 production was important, wind speed was critical for cost reduction, whereas solar radiation had less influence. Further, a combination of solar and wind could provide

better performance in an off-grid scenario. The most encouraging finding was the cost, which was competitive with reported costs in other EU countries [50].

In addition to the currently existing technologies, efficient and direct conversion of sunlight through a photocatalytic process to split ocean water without use of electricity can pave the way to a clean production route. A unique, CdS/ZnTHPP binary nanocomposite was recently created and employed as a reliable photocatalyst for the generation of H_2 in the presence of artificial sunlight which is all solid state. It demonstrated a conversion rate of almost ten times greater than that of pure CdS nanorods, the data showed that this nanosystem had remarkable photocatalytic activity. This innovation may lead to further improvement toward high-efficient photocatalytic green H_2 productions for real applications [51].

The inherent production intermittency of RE sources makes operation of energy systems with large RE components reliably and securely quite challenging. In an energy system with 100% RE the infrastructures for carbon-free H_2 production by electrolysis, and storage and/or transportation can overcome the intermittency of RE. The commercial production of H_2 by electrolysis of water can achieve efficiency up to 81%. Less than 0.1% of H_2 production globally comes from water electrolysis today, and the H_2 produced by this means is mostly used in markets where high-purity H_2 is necessary (electronics and polysilicon), but electrolysis, as an energy-intensive process for H_2 production, is still confronting challenges [52–57]. Electrolysis can be classified into three types: (i) alkaline (AWE), (ii) proton-exchange membrane (PEM), and iii) solid-oxide steam (SOSE). H_2 production by AWE is well established technology up to the megawatt range for commercial level (Figure 4a).



(**a**) (**b**)

Figure 4. (**a**) H_2 generation from alkaline electrolyzer. Reproduced with permission from [58], John Wiley and Sons, 2022; and (**b**) schematics of PEM water electrolyzer (Solid polymer electrolyte membrane is the same as proton exchange membrane).

PEM electrolyzers have the ability to deliver on-site and on-demand H_2 at very high purity and carbon-free (Figure 4b). Solid polymer electrolyte membrane used in electrolyzer is the same as proton exchange membrane. They use pure water, and therefore do not need to deal with the recovery and recycling of the potassium hydroxide electrolyte solution that is necessary with AWE. They are also relatively small and more appealing than AWE in dense urban areas. They can produce and store highly compressed H_2 at HRS and provide frequency reserves.

SOSE process is a promising technology with high scalability, high application flexibility, pure H_2 production, enhanced reaction kinetics at higher temperatures with low capital costs, and high degree of electrical efficiency [59]. It requires a heat source because steam is the electrolysis medium. A SOSE's heat source options include nuclear power plants, solar thermal systems, and geothermal energy. In contrast to AWE and PEM, an SOSE has the ability to function in reverse mode as an FC, turning H_2 back to electric power. As a result,

it might work in conjunction with H_2 storage facilities to offer stabilizing benefits to the grid. Managing the material degradation brought on by the extreme operation temperatures is one of the major drawbacks that the SOSE electrolyzers are facing [2]. As a way to generate oxygen for both human nourishment and liquid oxygen rocket fuel, MIT demonstrated an SOSE system in the Mars Oxygen ISRU Experiment on the Perseverance rover in 2014. In April 2021, NASA claimed it has produced, 4–5 g of oxygen on Mars from CO_2 in the Mars atmosphere using SOSE [60].

Today's total global H_2 production of 70 Mt would require 617 million m^3 water if it all is produced by electrolysis. It corresponds to 1.3% of the water consumption of the global energy sector [2]. However, in some regions, there may be discordance between localities of suitable water resources and those of RE sources, and this may pose a serious obstacle to H_2 production. To address this challenge, H_2 production from the air can offer a solution. Freshwater may be collected from the environment employing a hygroscopic electrolyte driven by solar or wind with a current density up to 574 mA cm^{-2} and a consistent quality at a Faradaic efficiency of 95%. This direct air electrolysis (DAE) can work in arid environments with a relative humidity (RH) of 4%, overcoming water supply challenges and producing green H_2 sustainably. There are 12.9 trillion tons of water in air at any moment. Even in the Sahel desert, the average RH is about 20%, and at Uluru desert (Australia) is 21%. DAE systems may be expanded to readily create H_2 in far-flung, dry, and dispersed regions [61]. In coastal locations, seawater could replace other sources. Reverse osmosis for desalination has little effect on the overall expenditures of water electrolysis, raising total H_2 generation costs by \$0.01–0.02/kg H_2 with an electricity requirement of 3–4 kWh/m^3 of water [62]. However, seawater causes corrosion and chlorine byproducts. Future research can make this method more feasible and at a lower cost. In electrolysis, the solar-powered system can be improved by applying magnetic, ultrasonic, pulsating electric or light energy fields [63]. It is known that these applications enhance the efficiency of electrolysis. Further studies are needed to use the physicochemical and kinetic properties of water for this innovative approach to be developed.

Recently, semiconductor-based photocatalysis and photoelectrochemical water splitting have emerged as novel and promising techniques for solar hydrogen production. In these methods, a semiconductor material is exposed to light to generate electron–hole pairs which undergo redox reactions resulting hydrogen production. The basic principle of these two processes is the same. As the first step, the semiconductor material absorbs photons from the sunlight. In the second step, an electron-hole pair is generated and is separated. After that, the created positive and negative charges are transported with the help of the catalysts. Finally, surface chemical reactions take place [64]. However, there are some dissimilarities between photocatalysis and photoelectrochemical processes. The semiconductor material in photocatalysis is in a powder form whereas it is in a thin film form for photoelectrochemical processes. The charge transfer path is relatively shorter in photocatalytic system them in photoelectrochemical system. Considering everything, the photoelectrochemical system has the upper hand over the photocatalytic system in terms of cost and efficiency as well [65]. One of the major challenges in photocatalysis is the recombination of photo-generated charge carriers before they reach the surface for the reduction and oxidation reactions, which reduces the quantum efficiency [66]. It was shown that introduction of heterojunction materials could substantially improve conversion efficiency. For example, $Ag/WO_3/Bi_2WO_6$ heterojunction yielded improved conversion rate by up to 250% and 190% compared to pristine Bi_2WO_6 and WO_3/Bi_2WO_6 samples, respectively. The improvement was attributed to the increased separation efficiency of the photogenerated electrons and holes as well as the improved visible-light absorption, both provided by the heterojunction [67]. Studies have shown that using noble materials such as Ru, Rh, and Ta in the photoactive semiconductor provides excellent photocatalytic performances [68–72], but to commercialize this technology, these noble materials should be replaced by more common materials. More studies, such as increasing active surface area using nanotechnology [73–79], light trapping [80–82], Z- scheme photocatalyst [83–87], are

required to overcome the current challenges and enhance the efficiency of this technology for commercial use.

Plasmonic nanomaterials can attain frequency-tunable localized-surface plasmon resonances (LSPR) at which the surface electric field is substantially intensified promoting the photocatalytic kinetics reaction rate [88,89]. Plasmonic nanostructures of noble metals (Rh, Ru, Ag, Pd, Pt, and Au) with different photocatalyst materials including TiO_2, NiO, GaN:ZnO, have been demonstrated for effective H_2 production through water splitting [90–94]. Although there has been considerable advancement in heterojunction photocatalysts, there are serious challenges that need to be addressed to achieve throughput heterojunction photocatalysts at the industrial scale for functional and cost-competitive applications. Moreover, the structure, morphology, porosity, surface conditions, contact interface, and crystallinity of substances need to be accurately controlled to attain high-efficiency heterojunction photocatalysts [66].

Another important scheme for H_2 production is power-to-gas (P2G) technology. It uses the surplus renewable electric energy to produce H_2 mainly alkaline electrolysis, proton-exchange membrane (PEM) electrolysis, and solid-oxide electrolysis cells (SOECs) [95]. The produced H_2 gas can be directly feed into the H_2 fuel cells for electric vehicle use or other H_2 infrastructures [96]. Alternatively, the H_2 can be fed into an NG infrastructure which displaces it and helps to reduce carbon emissions [97]. P2G can also be used to improve the conversion rate of CO_2 to biomethane through microbial methanation [98,99]. The overall efficiency for the H_2 production in the power-to-gas method is around 60% which is still lower than its competitive storage technologies [100]. However, recent studies have promised 70–80% efficiency using reversible and pressurized reversible solid-oxide cell technologies [101,102]. With the expected improvements, P2G technology is considered to be a promising transition to greener energy and effective use of surplus electricity.

RE and green H_2 sources are important for the development of a zero-carbon energy eco-system. To achieve this goal, technologies such as electrolysis, photocatalysis, photo-electrochemical water splitting, and nuclear-based H_2 production are being developed, as shown in Table 1. However, methane reforming is still the most commonly used commercially available H_2 production technology. It is attractive due to its high efficiency and low-cost operation. Low-carbon emission technologies such as pyrolysis and nuclear-based H_2 production are almost ready to be commercially used. However, studies are ongoing to develop technologies where fossil-fuel independent sources (water, sunlight, etc.) are being used. They still suffer from low efficiency, but more work is being done to take these technologies to the level of commercial use.

Table 1. Summary of H_2 production technologies.

H_2 Production Technology	Sources	Efficiency	Advantages	Carbon Emission Status
Steam methane reforming (SMR)	Natural gas, Hydrocarbons	70–85%	Cheap, high efficiency, established technology	CO_2 emission
Coal gasification	Hydrocarbons	60–70%	Abundance of source material, established technology	CO_2 emission
Biomass gasification	Biomass	35–50%	Renewable technology	CO_2 emission
Pyrolysis	Natural gas, Hydrocarbons	78–90%	Low carbon emission, efficient	Solid C byproduct
Nuclear produced H_2	Steam	-	Low carbon emission, no fossil-fuel required	No CO_2 emission
Electrolysis: AKL	Water	70%	Safe, long lifetime, cheaper	No CO_2 emission
Electrolysis: PEM	Water	60%	Low maintenance cost, small, recycling of electrolyte is not required	No CO_2 emission
Electrolysis: SOSE	Steam	-	Flexible application, scalability, pure H_2, reverse mode operation	No CO_2 emission
Photocatalytic and photoelectrochemical	Water and sunlight	~5%	Electricity independent, self-sufficient	No CO_2 emission

6. H_2 Storage

Although H_2 has the highest energy per mass density (about 120 MJ/kg) among all fuels, its low mass density at STP results in low energy per volume density, which necessities the development of sophisticated storage methods (Figure 2) [62]. Storage is a vital issue for the safety, transportation, and utilization aspects of an H_2 energy system in stationary, mobile, and off-grid applications. A typical H_2-based off-grid system comprises an electrolyzer, a pressurized tank and a FC (to produce electricity from H_2 in intermittency periods of REs). An example of this approach was built in the Froan islands (Norway) which well represents typical insular microgrid environments.

Studies show that energy storage devices are the key elements to reduce the dependency on fossil fuels. Due to its affordable prolonged storage capabilities, H_2 storage is particularly necessary in off-grid locations to increase the RE penetration, since it prevents the battery and RE technologies becoming bulky or overpriced. The levelized cost of energy (LCOE) for the most affordable option, which contains batteries and H_2, is 0.41 €/kWh. This number is around 35% less expensive than the system's LCOE if it just used batteries to store energy [103].

H_2 can be stored either by physical-based methods or material-based methods (Figure 5) [104–108].

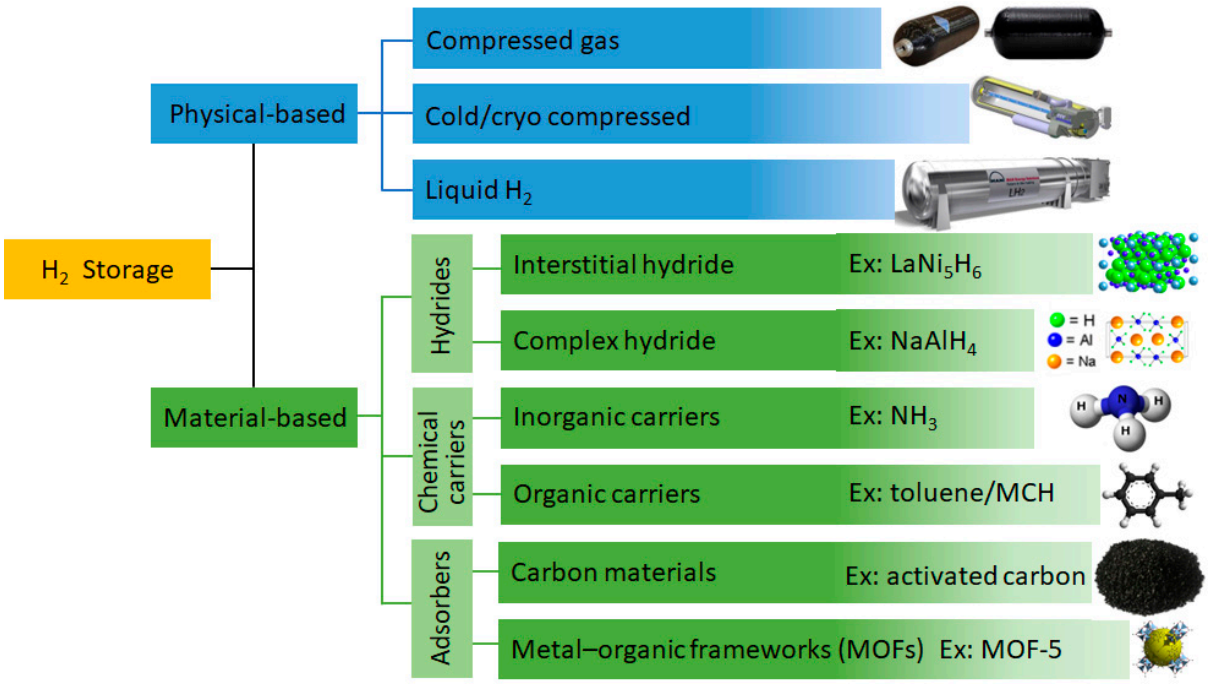


Figure 5. Overview of H_2 storage technologies.

6.1. Physical-Based H_2 Storage

Pressurized H_2 gas is the most established H_2 storage method for H_2 applications. Since the mass density of H_2 is very low (0.089 kg/m^3), its storage necessitates high pressure or extremely low temperatures [58]. The current FC applications require pressurization of H_2 at the 35–70 mPa level. It was estimated that pressuring would affect 11–13% of the hydrogen energy content negatively [109]. The conventional pressurized H_2 storage tanks for commercial applications are made using steel and aluminum materials.

For long-term or large-quantity storage needs, large underground geological formations, such as salt caverns, can be used for compressed H_2. Such natural structures are exceptionally impermeable even under high pressures and effectively prevent leakage. A remarkable recent example for underground storage is the HyUnder project in Romania, which is aimed at the storage of enough H_2 in salt caverns for potential use in the transportation sector and chemical manufacturing [62]. Storage of H_2 in underground salt

caverns is a highly scalable and adaptable method. It is much more efficient compared to compressed air energy storage option because hydrogen has a higher energy density. Numerical studies demonstrated that these storage systems could provide emergency backup power for almost seven times longer (57.7 days) than a compressed-air energy system (8.7 days) [110].

Its volumetric mass and energy densities allow H_2 to be stored and transported in liquid form in super-insulated containers especially as a way of transmission of large amounts to far points for short term storages to avoid boil-off loss issues. It is an important bridge between rich renewable energy sources and end-users. Liquid H_2 has the density of 71 g/L at its boiling point of −253 °C, which is approximately 1.8 times the density of H_2 pressurized up to 70 mPa at 15 °C. Due to its low boiling temperature, liquid H_2 technology requires cooling down to very cryogenic temperatures (−253 °C) which consume about 30% of its total energy content. Since they are more compact and lighter, cryogenic pressure vessels are considered to be safer than compressed H_2 vessels. Liquid H_2 storage systems are generally used within a short time (automotive, and air and space applications) [111–113].

6.2. Material-Based H_2 Storage

In general, an ideal solid-state H_2 storage material should be able to absorb a high weight percentage and a high volume of H_2, and possess high H_2 absorption and desorption speeds at—or close to—STP. It should be inexpensive, resistant to poisoning by trace impurities, have good thermal conductivity in charged and uncharged conditions, require low energy for preparation, be safe and reusable on exposure to air, and have the ability to be regenerated and be readily recycled [54]. The most promising solid-state storage systems for both mobile and stationary applications are material-based. Some of the featured ones among material-based storage techniques are metal hydrides, chemical carriers, and adsorbents.

Metal hydrides are produced by the reaction of H_2 with different metals, making solid-state storage under moderate temperature and pressure possible. Hence, they have a unique safety advantage compared to liquid and gaseous storage systems. In metal hydride tanks, H_2 molecules bond into metal typically at 3–30 atm pressure, which is much lower than the one in compressed gas tanks. Recently, hydrides of light metals such as Al, Mg, Li, Na, and B have been studied for solid-state storage materials for H_2. They present great potential for high safety, volumetric energy density, low-pressure equipment, reversibility of hydration/dehydration, and have low energy requirements. They function like a 'sponge' for absorbing and 'squeezing out' H_2 by small changes in temperature and pressure [114,115]. Aluminum hydride (AlH_3) is a covalently bonded tri-hydride with a high volumetric (148 $kg.m^{-3}$) and gravimetric (10.1 wt%) hydrogen capacity. It offers some significant technical difficulties since it is often created by reacting Al with H_2 at extremely high hydrogen pressure, yet it decomposes quickly into Al and H_2 at relatively low temperatures, demonstrating good hydrogen desorption kinetics at room temperature. AlH_2 is thus one of the most promising possibilities for materials for high-capacity hydrogen storage. For hydrogen storage, its synthesis, regeneration, dehydrogenation thermodynamics and kinetics, and techniques for enhancing reversibility are all promising [116]. High percentage of H_2 retention is the most important factor for mobile utilizations. Complex hydrides have a greater capability of absorption than intermetallic ones, especially $Mg(BH_4)_2$ with its high rate of 14.8 wt.% [104]. A particular member of the metal borohydrides, the nanoporous hydride γ-$Mg(BH_4)_2$ demonstrated the capability of storing 17.4 wt.% H_2 at 105 bar and −143 °C [117]. The H_2 storage density of magnesium hydride (6.5H atoms/cm^3) is higher than H_2 gas (0.99H atoms/cm^3) or liquid H_2 (4.2H atoms/cm^3) proving that H_2 storage in metal hydride is volume-efficient and safe for onboard applications [62,118–120].

However, metal hydrides have not yet met all the requirements of H_2 energy systems. The challenges that need to be addressed include high weight and low H_2 storage capacity

of low-temperature metal hydrides, and slow kinetics and undesirable high operation temperatures for lightweight metal hydrides with higher H_2 storage capacities [58,62]. Metal hydride tanks can be easily used in stationary applications. In the future, it will be possible to develop lighter materials to incorporate them in mobile applications, and to realize the cost reduction of all H_2 storage materials.

Chemical H_2 carriers include organic hydrocarbon liquids and inorganic materials such as ammonia and ammonia borane [121]. Liquid-phase hydrogen carriers offer the advantage of using existing petrochemical infrastructure for production, storage, and delivery, e.g., storage tanks and tanker trucks. However, to assess their feasibility more accurately toxicity, material compatibility, lifecycle cost and emission characteristics should be considered.

Hydrogen carriers can be broadly classified as one-way and two-way carriers. One-way carriers include NH_3 with a hydrogen content of 109 g/L and 17.6 wt.% and methanol with a hydrogen content of 99 g/L and 12.6 wt.% at 15 °C and 10 bar. These carriers release byproduct gases, such as CO_2 and N_2, in addition to H_2, which would necessitate separation and purification steps for practical applications. Technically, one-way carriers can be regenerated from the products. For example, ammonia can be regenerated from N_2 and H_2 through the Haber–Bosch process [104,122]. The use of carbon-based one-way carriers such as methanol and formic acid results in the emission of CO_2, which requires the integration of CCS modules into the decomposition system.

Two-way carriers, on the other hand, form a byproduct that can be used for regeneration after hydrogen is released. A perfect two-way carrier must be rehydrated for reuse effectively and affordably. For instance, toluene can be hydrogenated to create methylcyclohexane, which can then be dehydrogenated to extract and store the hydrogen. Through catalytic formate/bicarbonate reaction mechanism, formate salts are another possible two-way carrier that may produce and collect hydrogen at appropriate pressures and temperatures. They can be utilized as solids or as aqueous media. H_2 storage in organic compounds was not thought to be viable as low-temperature and reversible hydrogen extraction processes are usually regarded as impractical. However, the development of new and efficient catalytic processes can potentially change this assumption [104,123].

In general, chemical carriers have the advantages of relatively dense H_2 storage and transport at near-ambient temperatures and pressures. Moreover, it is possible to continuous high-pressure (>120 mPa) H_2 production by the selective decomposition of certain chemical carriers with very low level of carbon monoxide release. As the pressure is enough to feed FCVs (70 mPa) without any compression system, it can substantially reduce the H_2 infrastructure costs [124].

Nanostorage based on adsorption processes is one of the promising solutions, particularly for mobile systems. Weight and size restrictions for onboard applications require H_2 to be stored in small and light vessels, which are supposed to have high gravimetric and volumetric storage capacities. Adsorption to porous and high surface area nanomaterials like carbon nanotubes, metal organic frameworks, activated carbon, spherical carbon fullerenes and metal-decorated carbons are very promising for H_2 storage in onboard systems.

Nanomaterials have increased the surface area, shorter diffusion lengths and multiplied grain boundary atoms benefiting thermal-mechanical stability and H_2 sorption kinetics. For example, the magnesium hydride + mischmetal nanostructured composite provides decreased grain sizes, an increased free and porous surface, micro-strains and defects. These defects facilitate the diffusion of H_2 into the nanostructure by decreasing the diffusion activation energy [125]. Nanomaterials can also be produced by constricting the active material within porous scaffold hosts such as carbon-based materials, zeolites, metal–organic frameworks, and mesoporous silicas and oxides. These hosts are light, have a very large surface space (to facilitate higher contents), extremely porous, are non-reactive, cheap, abundant, and have a suitable purity. The large surface areas of carbon-based materials (nanorods, nanofibers, nanowires, nanotubes, and nanoribbons) that improve

bulk adsorption/desorption temperature, physisorption kinetics, surface interactions, and H_2 dissociation have attracted attention [62].

In addition to carbon-based nanostructures, there are other nanostructures offering strong potential for H_2 storage. Boron fullerenes and boron nitride nanostructures are two prominent families of these materials, with similar geometries to carbon nanostructures but with different properties [126]. Studies on calcium-decorated boron fullerenes using density functional theory revealed that the decorating calcium atoms can attract five H_2 molecules each. With favorable binding energies of 0.12–0.40 eV/H_2, a B80 system adorned with 12 calcium atoms exhibited a gravimetric density of 8.2 wt% hydrogen. Similarly, a boron nanotube decorated with Ca showed hydrogen storage capacity of 7.6 weight percent with binding energies of 0.10–0.30 eV/H_2. Most notably, ambient environmental conditions were suitable for the adsorption and desorption of these H_2 molecules [127].

Different H_2 storage technologies are summarized in Table 2, along with their key parameters and important applications.

Table 2. Comparison among different H_2 storage technologies.

H_2 Storage Technologies	Temperature	Pressure	Storage Capacity	Applications	Merits	Demerits	Ref.
Pressurized H_2 tanks	Low	High	0.99H atoms/cm^3	Short term supply and storage for commercial use	Established H_2 storage facility	Heavy metal tanks; storage density not great	[58,109]
Underground salt caverns	Low	High	10 kg/m^3	Long term storage and emergency backup	High density energy storage	Not suitable for mobile use or transportation	[62,110]
Liquid H_2	Cryogenic	Extremely high	71 g/L	Transportation, automotive, air, and space	Large amount transport, lighter, compact, safer	Energy loss for cooling	[111–113]
Metal hydrides	Moderate	Moderate (3–30 atm)	6.5H atoms/cm^3	Onboard applications	Safe, high storage density, volume efficient, reversibility	High weight and low storage capacity at low temperature	[114,115, 117–120]
Chemical carriers	Near ambient	Near ambient (~10 atm)	(99–109) g/L	Easy Transportation and suitable for FCV use	Relatively dense storage capacity, no need for extra compression system	By products (N_2, CO_2), need CCS unit (for one way carrier).	[121–124]
Nano absorbers	Ambient	Ambient	7.6–8.2 wt.%	Compatible for weight and size restricted onboard systems	Bulk absorption/desorption, good storage capacity, low diffusion activation and binding energy	Not suitable for mass storage	[62,126,127]

7. H_2 Distribution

To distribute H_2 produced in remote RE-rich points to dense population regions or electricity generation plants, a wide infrastructure and a grid of distribution and H_2 refueling stations are required. This depends on many parameters, such as distance, amount of H_2, large scale storage possibilities, and final use. It should be noted that in some cases, insular environments compel and allow for producing and utilizing low-cost H_2. Worldwide established NG infrastructure and pipelines have the flexibility to be converted to H_2 transmission systems. In this scenario "fugitive emissions of H_2 infrastructures, similar to those of NG" are possible [109].

Injecting H_2 into the NG distribution networks is technically feasible. Based on the individual network and/or location, mixes of H_2 up to 20% by volume may be feasible without the need for infrastructure conversion, according to the EU's H_2 agenda. To assess the feasibility of using high-pressure pipelines for H_2 transmission at a broader scale, the impact of H_2 depending on the materials that are utilized, and the pressure levels, need to be investigated further. The goals of the HyDeploy (UK) and Hyblend (US) programs are to comprehend how greater H_2 concentrations could affect various gas grid components as well as the potential effects on piping and pipeline materials [47]. Some existing pipelines already have properties to meet requirements to be used for H_2 distribution. For example, a 12 km pipeline formerly used for transporting NG in the Netherlands has been transformed for transportation of 100% H_2 in 2018. The NorthH_2 project in the same country aims to

produce and distribute 800,000 tons of H_2 through the NG infrastructure. Another sign of the growing momentum for repurposing NG pipelines in Europe is the European H_2 Backbone (EHB) effort. To repurpose a 39,700 km H_2 pipeline system that is expanding in 21 nations, the EHB now engages 23 gas infrastructure corporations from 21 countries [47]. Results of these initiatives and pilot projects are expected to build a strong knowledge base to develop larger scale H_2 distribution infrastructure in the near future.

8. H_2 Utilization

In line with the worldwide efforts and developments aiming to attain climate goals on the one hand, and an international energy crisis on the other hand, almost all industries and transport sectors evaluate H_2 alternatives more seriously than in the past and tend to establish their H_2 utilization systems. The H_2 gas turbine is one such system, albeit with some challenges. After different reconversion technologies were evaluated, there is now an H_2 gas turbine technology which runs on 100% green H_2 and makes it possible to convert conventional NG turbines to those of H_2. Moreover, H_2 gas turbines may have a synergistic benefit from the existing H_2 infrastructures built for other industrial applications, such as those in the transportation sector and in fossil-fuel steel production.

As a part of its 2050 greenhouse gas-neutral status goal, Germany plans to feed all H_2 gas turbines with 100% green H_2 generated by electrolysis. The plan's modeling showed that H_2-fueled gas turbines can be competitive under severe CO_2 emission caps (as in the modeling for the years 2040 and 2050) and under conditions where variable RE power is widely used [128,129]. In fact, the town of Lingen in northern Germany will soon have a 34 MW H_2 gas turbine power station that runs on 100% green H_2, offering a carbon-free solution to electricity generation on an industrial scale, with an efficiency of 40.3% [130].

On the other hand, H_2 gas turbines come with their own challenges. Hydrogen flame propagation velocity is up to seven times higher than NG, which may lead to flame instability, undesirable pressure fluctuations, and mechanical stress on the parts of the combustor, all of which require careful design optimization. Moreover, H_2 burns at a higher temperature compared to NG, which results in up to three times more nitrogen oxides (NO_x) than NG. Being a toxic air pollutant, NO_x needs to be reduced/eliminated through careful turbine design and integrated capturing systems.

In another field of H_2 utilization, FCs convert H_2 into electricity with an efficiency more than twice, the efficiency of ICEs. H_2 FCs engines operate in transportation with an efficiency of up to 65%, compared to 25% for conventional petroleum car engines. The overall efficiency of FCs even exceeds 85% when the generated heat is used in combined heat and power systems. This offers an enormous advantage for FCs, considering that the typical efficiency of a modern coal-fired power plant is ~45% [2,52]. In 2018, Germany started the world's first H_2 FC powered commercial train service that can run for about 1000 km on a single tank of hydrogen, similar to the range of diesel trains [131].

9. Global Zero-Carbon Green H_2 Economy

In 2022, about 80% of global energy demand is met by oil, NG, and coal. The energy sector is responsible for about three-quarters of GHG emissions, with electricity generation alone accounting for 40% of it. Another 60% or so is emitted by fossils fuels used in industry, transportation, and heating [37,132]. The research shows that a safe future below 1.5 °C global warming requires the world to cut 30 gigatons of GHG emissions annually by 2030 [133]. Within this effort, H_2 is particularly appealing for the energy sector due to its broad usage area. It may serve as an alternative engine fuel, a means of generating and storing electricity and heat. The heating applications already constitute the third largest consumer of H_2 today [34].

The global climate goals require significant levels of new investment to successfully commercialize and scale a global green H_2 industry. It is estimated that global annual investments of between US $20 to $25 billion are needed for a total investment of about $280 billion by 2030 to provide up to 18% of the world's energy demand with H_2 by 2050 [15].

Given the already available industrial infrastructure and compatible distribution networks, for H_2, it is not a feedstock and technology problem, but a cost and time problem. H_2 gives the possibility to develop multiple alternatives both in its integration with RE in terms of production, and in its post-production processes, provided that its storage and distribution network costs are subsidized for a while [37].

10. Conclusions

Current climate action plans of governments are crucial to achieve the Paris Agreement target (for which, in November 2022 a commitment was repeated to keep the plans alive at the COP27 in Sharm El Sheikh, Egypt) of holding global average temperature increase to a maximum of 1.5 °C. There are some pushbacks from energy companies regarding a reduction in fossil-fuel production. A clean and sustainable alternative is needed to combat the idea that the climate is no longer a priority. As a clean, renewable energy carrier, H_2 produced via electrolysis, photocatalysis, and photoelectrochemical splitting of ubiquitously available water of which electricity comes from clean REs (wind, solar, wave, tidal energies, and hydro, and geothermal power plants) is the most promising synthetic fuel in the transition period to zero carbon. Although electrolytic H_2 alone cannot meet the demand of H_2 for the world, at least in the upcoming years, green H_2 can compensate for the mismatch between production of and the demand for RE. Today, H_2 is already used in almost all types of vehicles and industry. It can be used in power plants to generate electricity. FCs can substitute conventional engines. Green H_2 systems present a considerable integration capability with the existing industrial use of H_2 infrastructure, as well as with clean RE energy sources and fossil-fuel infrastructures. RE sources used in clean electricity production are vital for H_2 sustainability in addition to their other uses. Their intermittency from spatiotemporal instabilities can be balanced by storage in the form of H_2 produced by clean energy through electrolysis. Such an integrated H_2 eco-system and economy require a cost-effective, large-scale H_2 infrastructure. The rapidly decreasing cost of electricity generated from REs further encourages investment in the widespread production and utilization of green H_2 by the middle of the 21st century. Leading up to that, low carbon emission H_2 generation processes such as nuclear-produced H_2, pyrolysis, and steam reforming with CCS using fossil-fuel as the source will play a vital role in the upcoming years. These processes have the ability to keep carbon emissions in check, in some cases (nuclear) producing almost zero-carbon emissions. These technologies will help meet the demand of H_2 in the transition period while green H_2 generation technologies mature to meet global demand. Today, for H_2, it is not a question of competitiveness but a global will and determination to invest more in electrolyzers, clean REs and other infrastructure components in the face of global climate change.

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