Green Hydrogen

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Increasingly stringent sustainability and decarbonization objectives drive investments in adopting environmentally friendly, low, and zero-carbon fuels. Hydrogen represents a unique zero-carbon energy carrier akin to electricity. Hydrogen is hailed as a carbon-neutral fuel of the future, particularly in the form of green hydrogen.

green hydrogen production storage properties application cost carbon-neutral

1. Introduction

During the Anthropocene era, our actions have significantly shaped the earth, leading to issues such as environmental contamination, changes in weather patterns, and the extinction of numerous species. The global need for energy continues to increase, primarily due to population growth, improved quality of life, and the industrial development of emerging nations [1]. In 2019, total global primary energy provision reached 4410 million tons of oil equivalent (MTOE) [2]. The International Energy Agency (IEA) forecasts a 50% surge in worldwide energy requirements by 2030 [3]. At present, fossil fuels satisfy more than 95% of this significant energy requirement, and their utilization leads to global warming and environmental contamination. To tackle these problems, a promising approach is replacing fossil fuel-based energy sources with renewable, carbon-neutral alternatives in the energy sector [4]. One pivotal solution in the transport sector is the advancement of internal combustion engines capable of operating on environmentally friendly fuels like green hydrogen, green ammonia, or green methanol [5]. This shift can decrease the release of greenhouse gases, alleviate global warming, and confront climate change.

In sustainable energy, the pursuit of green hydrogen, green ammonia, and green methanol has emerged as a promising avenue for curbing carbon emissions. Publication trends on green fuels in the recent decade, i.e., 2013–2023, were obtained using the Scopus search tool. The results were obtained using the keywords “green ammonia,” “green hydrogen,” and “green methanol,”. Overall, the number of publications is increasing continuously, though the yearly increase is regular.

Hydrogen represents a unique zero-carbon energy carrier akin to electricity. Hydrogen is hailed as a carbon-neutral fuel of the future, particularly in the form of green hydrogen. This thriving market is presently valued at more than USD 100 billion and is expected to grow substantially, reaching an impressive USD 2.5 trillion by 2050 [6].

Hydrogen production methods vary and can include natural gas, steam, coal, biomass conversion, electrolysis powered by renewable electricity, or virtually any other energy source. Each method has its distinct carbon-emissions profile.

On a global scale, hydrogen consumption was approximately 120 million metric tons in 2020, and this is projected to increase to 530 million metric tons annually by 2050. The worldwide production is about 75 million metric tons of pure hydrogen annually, accompanied by an additional 45 million metric tons of hydrogen as part of a gas mixture [7][8].

Identifying and implementing eco-friendly hydrogen production methods is greatly hindered by the requirement for a gradual transformation of national energy systems [9]. Hydrogen-focused decarbonization involves using hydrogen in energy-intensive industrial sectors, including energy, transportation, and the chemical industry, while encouraging its adoption in local markets and everyday utilities [9]. Hydrogen is a promising energy carrier and feedstock that offers a natural-based solution for fuel consumption and its associated environmental impacts [10].

2. Color Codes of Hydrogen

The production of hydrogen fuel is possible through diverse primary energy sources. Consequently, these technologies are classified into distinct categories, denoted by different colors, which reflect the production process, the type of energy utilized, and the costs and emissions associated with hydrogen production [11]. These classifications encompass green, blue, aqua, and white hydrogen (referred to as low-carbon hydrogen) alongside gray, brown, black, yellow, turquoise, purple, pink, and red hydrogen (refer to **Table 1**).

Presently, multiple approaches have been suggested to produce hydrogen in a more environmentally friendly manner [12][13][14]. Gray hydrogen production entails fossil fuels, primarily through reforming and pyrolysis techniques, with direct CO_2 emissions, and minimal energy costs. In contrast, blue hydrogen, which involves carbon-capture utilization and storage (CCUS), has no direct CO_2 emissions but comes with additional expenses for capturing and storing CO_2 [11]. Hence, the production of green hydrogen through the electrolysis of water (H_2O) is increasingly being recognized as the primary method for future hydrogen production. Presently, hydrogen gas is derived from a variety of sources, both renewable and non-renewable [15]. Renewable sources encompass biomass conversion; water electrolysis; and harnessing wind, solar, hydro, and nuclear energy.

These various methods of hydrogen generation come with their advantages and drawbacks, varying in terms of efficiency and costs [16]. Notably, a significant portion of hydrogen gas is generated through non-renewable means, mainly using the steam reforming of methane (SRM) [17]. Electrochemical water splitting has emerged as a highly promising method for generating hydrogen energy [18]. Hydrogen produced using renewable electricity from solar, wind, biomass, geothermal, and ocean sources is commonly called renewable hydrogen [15][19].

Table 1. Summary of different types of hydrogen and their characteristics [9][11][12][14][20].

Hydrogen	Technology	Feedstock/Energy Source	Products	Emission (kg CO_2/kg H_2)	GHG Footprint	Cost (USD/kg H_2)
Black	Gasification	Coal (Bitumen)	H_2 + CO_2 Released	21.8	High	1.2–2.0
Brown	Gasification	Coal (Lignite)	H_2 + CO_2 Released	20	High	1.2–2.0
Gray	Reforming	Natural Gas	H_2 + CO_2	8.5–10.9	Medium	0.67–1.31
Blue	Reforming + CCUS	Natural Gas + CCUS Coal + CCUS	H_2 + CO_2 CCUS	1–2	Low	0.99–2.05
Turquoise	Pyrolysis	Methane	H_2 + C Solid Carbon	Solid Carbon	Solid Carbon	2.0–2.1
Yellow	Electrolysis	Water + Mixed origin Grid Energy	H_2 + O_2	0	Medium	6.06–8.81
Pink/Violet Purple	Electrolysis	Water + Nuclear Energy	H_2 + O_2	0	Minimal	2.18–5.92
Green	Electrolysis	Water + Renewable Energy	H_2 + O_2	0	Minimal	2.28–7.39
Aqua	Oxygen injection	Oil sands (Natural Bitumen)	H_2 + Carbon Oxides	Geological storage	-	0.23
White	Fracking	Naturally Occurring	H_2	0	Minimal	-
Gold	Water splitting	Water +direct solar	H_2 + O_2	0	Minimal	-

Property	Green Hydrogen
Chemical formula	H_2
Appearance	Colorless and odorless gas
Molecular Mass	2.0156 g/mol
Melting temperature	−259.2 °C
Density (20 °C)	0.0899×10^{-3} g/cm^3
Boiling point	−252.8 °C
Latent heat of vaporization	446 kJ/kg
Specific gravity	0.070

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Property	Green Hydrogen
Thermal conductivity (NTP)	0.1825 W/m-K
Specific heat (kJ/kg-K)	1.44
Octane number, RON	109–114
Cetane number, CN	3
Flash point	−253 °C
Storage pressure and temperature	0.1 MPa, 20 °C

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[illegible]essed gas storage, and chemical storage alternatives like metal hydrides, chemical hydrides, and sorbents [25]. Metal hydrides and MOFs (Metal-Organic Frameworks) are promising materials for hydrogen storage, offering efficient and reversible means for storing hydrogen as a clean energy carrier [26]. Freezing or liquefying hydrogen demands substantial energy input, primarily because hydrogen has a shallow melting point and boiling point. Consequently, solid and liquid storage options may lead to an energy loss of up to 30% due to the significant energy consumption required for hydrogen freezing or liquefaction [27]. Additionally, achieving adequate insulation for such storage can be challenging. On the other hand, compressed hydrogen gas systems offer several advantages, including low energy requirements, cost-effectiveness, quick charge and discharge cycles across a broad temperature range, even under extremely low temperatures and straightforward operation via a control valve. These systems can currently store pressurized gas within [illegible] [28].

5. Application

In the aerospace industry, hydrogen has demonstrated its capacity to serve as an outstanding energy source [29]. For green hydrogen to realize its full potential, it must be adapted for use in majorly polluting industries [29][32][33]. While the green hydrogen industry is still in its early stages, it has already seen the development of five significant applications for this renewable energy source [7][34][35][36]. It has gained considerable attention for its potential role in achieving low-carbon solutions in transportation industrial decarbonization, particularly within the oil and gas, fertilizer, fuel cell technology, petrochemical, petroleum, metal refining sectors, and also for heat supply across many nations [37].

- Hydrogen feedstocks: Green hydrogen is employed to replace conventional feedstocks, as hydrogen production can be carbon-intensive. Green hydrogen is produced using renewable energy, reducing carbon emissions associated with hydrogen production. It facilitates the integration of renewable energy sources into the power system, decreases reliance on imported fossil fuels, and reduces carbon footprint [32].
- Residential and commercial heating systems: Green hydrogen decarbonizes heating systems in residential and commercial settings, where heating contributes significantly to carbon emissions. It can be mixed with natural gas in areas with higher natural gas prices [38].
- Energy storage: Green hydrogen serves as a valuable energy storage option, although early attempts to develop hydrogen-based batteries have seen a decrease in energy efficiency compared to conventional batteries [26].
- Alternative fuel production: Green hydrogen plays a role in producing alternative fuels.
- Fuel cell vehicles: Green hydrogen is used to power these, although it has yet to gain substantial traction in the automotive market. Fuel cell electric vehicles are a transformative development in the energy and transport sector toward achieving a carbon-neutral footprint [39].

4. Properties and Characteristics

Hydrogen, when used as a fuel or as an energy storage medium, has a negligible adverse environmental impact [27]. Moreover, hydrogen is the lightest and most abundant element in the universe, comprising 75% of all matter by mass and an impressive 90% when considering the number of atoms [29]. Hydrogen boasts an exceptional trait as an energy carrier: an impressively high energy density ranging from 120 to 140 megajoules per kilogram (MJ/kg), double that of typical solid fuels [30]. The combination of hydrogen and oxygen releases the highest energy per unit of fuel weight [31]. The heat energy generated from hydrogen combustion is approximately 142.26 kilojoules per gram (kJ/g). In contrast, petroleum yields a heat energy of 35.15–43.10 kJ/g, and wood produces about 17.57 kJ/g [30]. It is important to highlight that although hydrogen has [illegible] and lower ignition energy than gasoline and methane, it also possesses lower explosion energy. Additionally, hydrogen demonstrates lower toxicity levels than gasoline and methane when utilized as a fuel, leading to fewer toxic emissions post-combustion. With a higher ignition temperature and lower flame emissivity, hydrogen is collectively acknowledged as a safer fuel than gasoline and methane. Refer to **Table 2** for a breakdown of some of the physical properties of green hydrogen.

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2. Industrial sector: Green hydrogen is increasingly finding applications in various industrial sectors, notably in the chemical industry for ammonia and fertilizer production, the petrochemical sector for manufacturing petroleum products, and the steel industry, where it is being employed to mitigate its environmental impact. This gas enables changes in industrial processes to make them more environmentally friendly, particularly in response to the ecological challenges faced by the European steel industry. Additionally, ongoing sustainable initiatives aim to substitute natural gas networks with green hydrogen networks for household use, providing households with cleaner sources of electricity and heat while minimizing pollutant emissions [40].

6. Cost Analysis

Recent studies suggest that the cost of renewable hydrogen production will need to be halved to be economically competitive with hydrogen produced using fossil fuels [41]. Green hydrogen cost depends on several factors, such as the location (easy/difficult access to green electricity), the production method (e.g., Alkaline Water Electrolyzer (AWE), Proton Exchange Membrane (PEM), Solid Oxide Electrolyzer Cell (SOEC), Anion Exchange Membrane Electrolysis (AEM)); plant capacity and lifetime of the plant; electrolysis efficiency; renewable energy costs; electrolyzer capital costs; operation and maintenance costs; scaling and capacity utilization; infrastructure and transportation; and government incentives, etc. [42]. The current cost range of green hydrogen is about USD 2.28–USD 7.39/kg H_2 produced [14][43]. To decrease the high cost of the electrolysis process, it is necessary to find ideal materials to produce electrolytic cells and establish a large-scale electrolysis supply chain [44].

In the present scenario, improvements in electrolyzer efficiency have led to lower electricity consumption, reducing the cost of hydrogen production. Falling renewable energy prices substantially impact the cost of green hydrogen. As renewable energy costs decrease, green hydrogen becomes more competitive [45]. As electrolyzer manufacturing scales up and technology advances, capital costs are declining. This trend is expected to continue. Proper maintenance and operational practices can help control ongoing costs and maximize equipment lifespan. Large-scale production facilities tend to have lower production costs per hydrogen unit [46]. Efficient use of capacity is essential to cost optimization. It is vital to provide government support and incentives, such as subsidies and tax credits, which can significantly reduce the cost of green hydrogen. The advances in research in this area will result in a reduction in production costs. The price of green hydrogen for commercial use is expected to be reduced by 2030 [7][8].

7. Pros and Cons of Green Hydrogen

Green hydrogen, produced through renewable methods, is a promising solution for transitioning to a sustainable-energy landscape. Its primary advantage lies in its potential to significantly reduce greenhouse gas emissions, offering a clean alternative for various industries, particularly transportation and heavy manufacturing. The versatility of green hydrogen in energy storage and its capability to be a key player in decarbonizing industrial sectors make it a frontrunner in carbon-neutrality goals. However, challenges include high production costs, the

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need for extensive infrastructure development, and the energy-intensive nature of its production process. **Table 3** highlights the pros and cons of green hydrogen.

Table 3. Pros and cons of green H_2 [11][47][48][49].

Pros	Cons
• Eco-friendly power	• Elevated production costs
• Versatile energy carrier	• Infrastructure establishment
• Efficient energy storage solution	• Technical hurdles
• Generates job opportunities	• Competition from other green fuels
• Utilizing excess renewable energy	• Secondary energy carrier
• Decarbonize industries	• Economically not feasible

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