



Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation

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ABSTRACT

The rapid growth of the global population and industrial activities has significantly increased greenhouse gases (GHGs) emissions, with projections indicating a temperature rise of 3–6 °C by 2050. Urgent action is needed to limit global warming to 1.5 °C above pre-industrial levels. Hydrogen, with its high energy density and compatibility with renewable energy systems, presents a promising clean energy solution to mitigate GHGs emissions. Yet, its widespread adoption faces challenges such as high production costs, limited infrastructure, and an underdeveloped value chain. At present, approximately 96% of global hydrogen production relies on fossil fuels, contributing to substantial emissions, while only 4% comes from water electrolysis. Green hydrogen, produced via electrolysis with 55–80% efficiency, remains expensive at \$2.28–7.39/kg, compared to grey hydrogen at \$0.67–1.31/kg, which generates 8.5 kg CO₂ per kg of hydrogen production. Hydrogen's low density poses challenges for storage, while transportation risks and insufficient infrastructure create further obstacles. The lack of global standards and investment uncertainties further impede the development of a comprehensive hydrogen economy. This review evaluates hydrogen's potential as a sustainable energy carrier, providing insights into advancements and ongoing challenges in production, storage, and transportation. Key findings highlight the necessity of coordinated efforts to enhance storage technologies, lower production costs, and establish supportive policies, highlighting hydrogen's critical role in achieving a sustainable energy transition.

1. Introduction

In the current global energy landscape, sustainability and resilience have become vital priorities in the pursuit of a more reliable and eco-friendly future [1,2]. Hydrogen is emerging as a key player in the global effort to reach net zero emissions (NZE) by 2050 [3,4]. This clean energy carrier is especially important for reducing carbon emissions in areas that are difficult to address using alternative approaches, such as heavy industries, transportation, and heating [5,6]. The transition from carbon-intensive fuels to sustainable alternatives is motivated by the necessity to alleviate the adverse environmental effects of conventional fossil fuels such as coal, oil, and natural gas. Conventional energy sources are both limited in quantity and significant contributors to the release of CO₂ and the phenomenon of global warming [4]. It is recognized as a prospective substitute because of its distinctive characteristics. Being the least heavy and most plentiful element on earth, it can be produced within the country and combusts without pollution, releasing just water as its byproduct [7]. This feature enables it to be a compelling choice for mitigating greenhouse gases (GHGs) emissions in many

industries. The potential for low-carbon production of this has gained considerable attention, particularly with the implementation of the Energy Policy Act (EPA) of 1992, which stimulated interest in cleaner energy sources [1–4]. Hydrogen is highly efficient in fuel cell vehicles (FCVs), providing two to three times more energy per unit than gasoline [4,8]. Countries are transitioning from fossil fuels to renewable energy sources, leading to a significant transformation in the global energy model [8]. Out of these options, hydrogen is anticipated to have a significant impact since it can be manufactured on a large scale regardless of environmental circumstances, unlike solar or wind energy [8–10]. Also, hydrogen production may be scaled to fit the particular industrial infrastructure of many nations, making it a flexible solution for energy diversification and security [8].

Hydrogen has transformed from a scientific curiosity to a central element in global energy strategies over the centuries. In 1625, Jan Baptist van Helmont first observed hydrogen, and in 1776, Henry Cavendish identified it as a unique element by reacting zinc with hydrochloric acid [11]. By 1895, hydrogen was used as a lifting gas for zeppelins, although its use declined after the Hindenburg disaster in 1937 [12,13]. The 20th century saw major advancements, particularly

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transportation safety, which must be addressed to scale hydrogen technologies effectively. The interconnected clusters emphasize the need for interdisciplinary collaboration to tackle these issues holistically. For example, integrating advancements in fuel cells with renewable hydrogen production or addressing material compatibility in storage systems could unlock significant progress. Moving forward, the bibliometric insights advocate for targeted research into underexplored areas, such as lifecycle sustainability assessments, infrastructure scalability, and integration of hydrogen systems into existing energy networks. By leveraging these insights, researchers and policymakers can strategically address barriers and drive innovation toward a robust hydrogen economy.

The environmental sustainability of hydrogen production is heavily influenced by the methods used to generate it. According to Fig. 2, a significant 62% of global hydrogen production relies on natural gas without carbon capture, utilization, and storage (CCUS), while 21% comes from coal [15]. Only a small portion is produced through electrolysis, a cleaner method that can be powered by renewable energy sources like wind or solar [15,16]. This heavy dependence on fossil fuels leads to considerable carbon emissions, which challenge hydrogen's potential as a truly clean and sustainable energy carrier. Although CCUS can reduce emissions associated with fossil fuel-based hydrogen, it does not eliminate them entirely. Biomass-derived hydrogen presents challenges such as competition for land and resources, potentially impacting food production and biodiversity conservation [4].

This highlights the urgent need for cleaner and more sustainable methods of hydrogen production, such as green hydrogen, which offers a transformative approach to overcoming the environmental challenges of conventional techniques. To achieve a more sustainable and long-term hydrogen economy, it is crucial to prioritize the production of green hydrogen through renewable-powered electrolysis [17]. This requires large-scale investments in renewable energy infrastructure, advancements in carbon capture technologies, and the development of cost-effective electrolyzers to make green hydrogen more economically viable [18]. Supportive policy frameworks, including carbon pricing, subsidies, and regulatory standards, will be essential to encourage industries to adopt cleaner hydrogen production methods and overcome existing economic and technological challenges. By addressing these barriers, hydrogen can fulfill its promise as a key contributor to a sustainable energy future.

Green hydrogen, produced through water electrolysis powered by renewable energy sources like wind, solar, and hydropower, presents a novel solution to the environmental challenges posed by traditional hydrogen production methods [20]. Unlike conventional techniques, green hydrogen is entirely free of carbon emissions, making it an

environmentally friendly alternative. This clean production process positions green hydrogen as a critical component in the global transition to sustainable energy systems, supporting efforts to tackle climate change and reduce dependence on fossil fuels. The benefits of green hydrogen within the energy sector are substantial [18,20]. Its versatility as an energy carrier makes it ideal for reducing emissions in industries and sectors where direct electrification is difficult, such as heavy manufacturing, long-distance transportation, aviation, and maritime shipping. Green hydrogen also plays a vital role in addressing one of the key challenges of renewable energy: its variable nature. It enables large-scale energy storage and helps stabilize power supply and demand [18]. Its compatibility with existing energy infrastructure, including pipelines and distribution networks, further accelerates its integration and widespread use. Prioritizing hydrogen production from renewable sources has the potential to significantly minimize the environmental impact of the hydrogen economy [17]. By doing so, hydrogen can evolve into a reliable and sustainable energy solution that enhances energy security, strengthens economic resilience, and supports long-term climate objectives. As such, green hydrogen is not merely an innovative technology; it is an essential driver of a cleaner, more sustainable energy future.

Despite its immense potential, hydrogen also faces significant challenges. A fundamental difficulty arises from the fact that it is not naturally present in its pure form on earth and requires separation from hydrogen-based sources such as water or hydrocarbons [21]. The extraction process often requires significant energy inputs, leading to large expenses, especially when produced from renewable electricity using electrolysis [21]. The high cost of electrolyzers and the lack of competitive pricing relative to fossil fuels pose substantial barriers to the widespread adoption of hydrogen [4,7]. The current infrastructure for the production, transportation, and storage of hydrogen is inadequate. To attain the necessary magnitude for a net-zero economy, substantial investments are necessary to provide the essential infrastructure, including pipelines, storage facilities, and refueling stations [4]. Policy support is crucial for ensuring equitable competition in the hydrogen sector. This involves enacting measures like carbon pricing, establishing targets for renewable energy, and enforcing rules that encourage the adoption of hydrogen in various industries [4–6]. In this review article, we will explore global trends in hydrogen production, consumption, and application, alongside the technical challenges and opportunities associated with hydrogen infrastructure, particularly focusing on production, storage, and transportation.

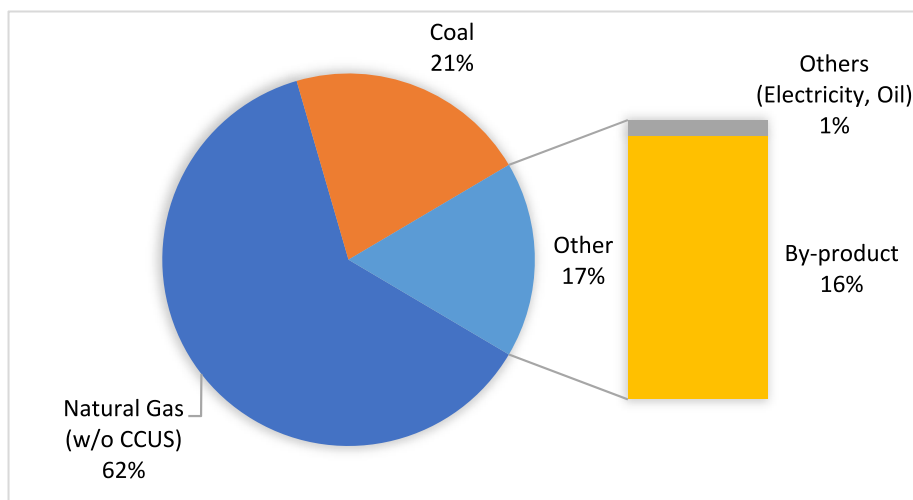


Fig. 2. Global hydrogen production from different sources [19].

2. Global trends in hydrogen production, consumption, and application

2.1. Global trends and policy

Countries across the globe are integrating hydrogen into their energy strategies as a key component of their efforts to meet NZEs targets. Nations like Germany, Japan, and South Korea are leading the charge, each with distinct approaches to hydrogen production, infrastructure, and technology, which are aligned with broader sustainability goals [22].

Germany's "National Hydrogen Strategy" focuses on using green hydrogen to decarbonize industrial sectors and reduce emissions in transportation. The strategy emphasizes building a comprehensive hydrogen infrastructure, including storage and refueling stations, and prioritizes research and innovation to reduce hydrogen production costs, particularly via renewable energy sources. Germany is fostering international collaborations to build a global hydrogen economy [23]. Japan's "Basic Hydrogen Strategy" aims to establish hydrogen as a central element in its energy transition by focusing on hydrogen-powered transport, including fuel cell vehicles. Japan's emphasis on creating a robust hydrogen infrastructure includes the development of domestic hydrogen production and international hydrogen trade networks with countries like Australia, facilitating a hydrogen supply chain. Japan has also significantly invested in hydrogen fuel cells for both industrial and residential applications [24]. South Korea's "Hydrogen Economy Roadmap" outlines a vision to become a global leader in hydrogen technology by focusing on scaling up hydrogen production through electrolysis and enhancing fuel cell technology. South Korea's ambitious goals also include deploying hydrogen-powered vehicles and setting up a nationwide network of refueling stations. The roadmap demonstrates the country's dedication to building a sustainable hydrogen economy with a focus on renewable and low-carbon hydrogen production [25].

The strategies of these countries offer valuable lessons in the importance of comprehensive, long-term policy frameworks, the need for significant government and private sector investment, and the benefits of international cooperation. A strong regulatory environment and targeted incentives are key to overcoming challenges like high infrastructure costs and technological limitations, facilitating a transition to hydrogen as a viable, sustainable energy source. By studying these nations, other countries can develop strategies to accelerate their own

hydrogen adoption and make meaningful progress toward meeting global climate targets.

2.2. Trends in global hydrogen production and consumption

The increasing importance of hydrogen as a sustainable energy source is reflected in the evolving patterns of global production and consumption. The IEA report highlights key trends in hydrogen generation from 2019 to 2024, as depicted in Fig. 3. Fossil fuels remain the predominant source of hydrogen, with production rising from 68 Mt (Million tonnes) in 2019 to 84 Mt in 2024 [15,16,26]. This growth illustrates the ongoing reliance on conventional fossil fuel-based methods, particularly natural gas, which are well-established and cost-effective despite their environmental drawbacks. On the other hand, hydrogen production from renewable sources, which includes by-product hydrogen, has shown limited growth over the same period. Production levels from renewable sources have remained relatively constant, fluctuating between 16 Mt and 18 Mt from 2019 to 2024 [15,16,26]. This slow increase points to the challenges associated with scaling up green hydrogen production, despite its potential to reduce carbon emissions and promote a more sustainable energy future.

Global hydrogen consumption has been steadily increasing, as shown in Fig. 4, rising from 86 Mt in 2019 to an estimated 100 Mt in 2024. This

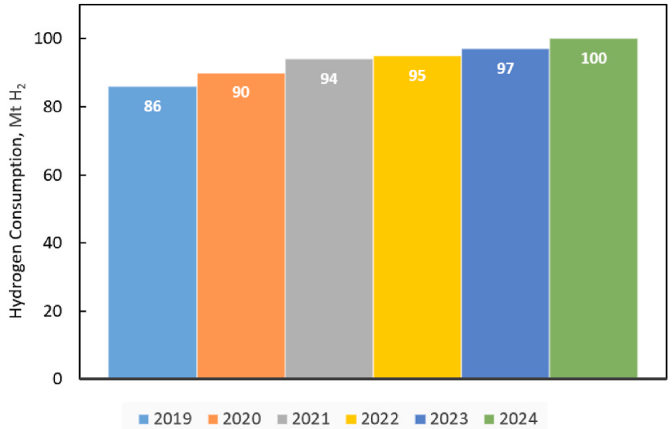


Fig. 4. Global hydrogen consumption [15,16,26].

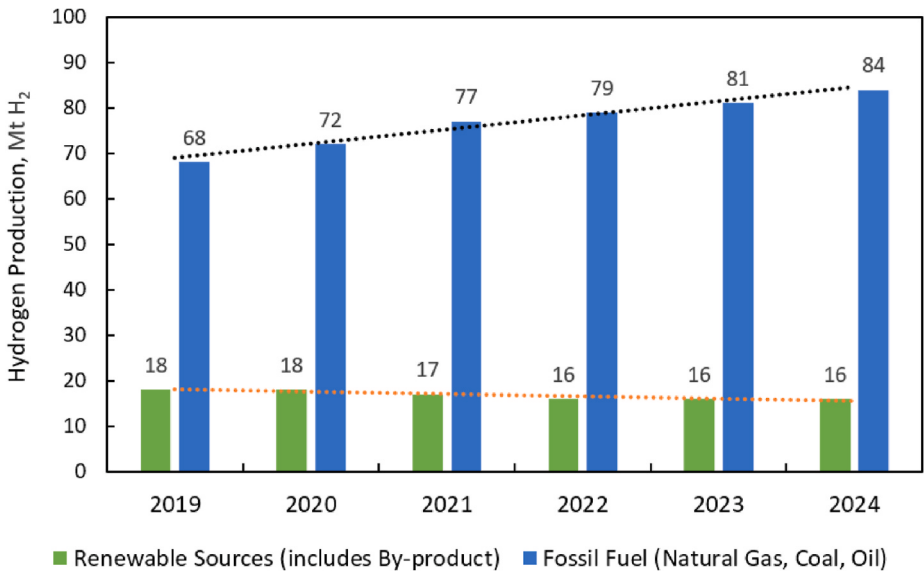


Fig. 3. Global hydrogen production from different sources [15,16,26].

upward trend demonstrates hydrogen's expanding role across a variety of industrial sectors, including refining, steel production, and chemicals, where it is crucial for several processes. The growth rate, approximately 2–3% per year, reflects both economic recovery post-2020 and a broader adoption of hydrogen in traditional sectors. Emerging applications, particularly in heavy industries and transport, are contributing to the increase, although they still account for a smaller share of overall consumption. As demand for hydrogen continues to grow, there is a critical need for substantial investments in infrastructure to support this rise. New pipelines, storage facilities, and refueling stations will be essential to create a reliable supply chain that meets future consumption needs. The IEA's report emphasizes the urgency of accelerating the transition to renewable hydrogen and fostering investment in the necessary technologies to shift away from fossil-based production methods.

In conclusion, two primary challenges need to be addressed to ensure hydrogen's role in a sustainable energy future: the need to scale up the production of green hydrogen and the necessity to develop robust infrastructure to support its growing consumption. Overcoming these obstacles will be vital to realizing hydrogen's potential as a cornerstone of a low-carbon, sustainable energy system.

2.3. Application of hydrogen energy

The application of hydrogen energy across different industries is essential for improving energy efficiency and reducing greenhouse gas emissions. Hydrogen is extensively utilized in several industries, such as petroleum refining, metal treatment, fertilizer manufacturing, and food processing, as reported by the Energy Information Administration (EIA). It plays a vital function in petroleum refineries, specifically in reducing the sulfur content in fuels, which leads to the creation of cleaner-burning products [27]. The importance of hydrogen in space travel is exceptionally noteworthy. Since the 1950s, NASA has been in the lead of using liquid hydrogen as a propellant for rockets and hydrogen fuel cells to create electrical power for spacecraft [21,28]. NASA's initial breakthroughs have enabled the widespread incorporation of hydrogen in numerous ongoing technologies and industries. Hydrogen blending is acknowledged as a critical strategy in the worldwide transition towards more environmentally friendly energy systems. This approach not only enhances energy efficiency but also significantly contributes to reducing carbon emissions in sectors such as transportation and heavy industry. The growing focus on hydrogen highlights its potential as a crucial component of a developing energy strategy. Fig. 5 highlights the diverse applications of hydrogen across various sectors, from space exploration to industrial processes, electricity generation, and transportation [21, 28].

2.3.1. Transportation

Hydrogen is revolutionizing vehicle power, offering cleaner and more efficient alternatives to traditional fuels. It is gaining popularity in

vehicles like cars, buses, and trucks due to their long-distance travel and quick refueling capabilities. Hydrogen is also being used in trains, ships, planes, and drones, contributing to reduced air pollution and greener skies [21,28]. Hydrogen FCVs convert hydrogen gas into electricity through an electrochemical process, allowing them to travel longer distances without refueling. They can be produced from various sources, reducing dependence on a single energy source [21,28].

Hydrogen has strong potential for decarbonizing heavy-duty transportation, maritime, and aviation sectors, where battery-electric vehicles (BEVs) face limitations due to lower energy density, heavier weight, and long charging times [29]. In heavy-duty transport, hydrogen fuel cells offer higher energy density than batteries, enabling longer ranges and faster refueling times, which are crucial for freight transport [17, 29]. This advantage extends to the maritime and aviation industries, where long distances and high energy demands make hydrogen an ideal alternative to conventional fuels. Hydrogen fuel cells can provide the necessary power for large ships and aircraft, which is challenging for batteries due to their weight and size [30].

When comparing hydrogen to BEVs for decarbonization, hydrogen is more suited to sectors requiring longer ranges and rapid refueling. While BEVs are more efficient for light-duty vehicles with an expanding charging infrastructure, hydrogen's higher energy density is better suited for heavy-duty vehicles, ships, and airplanes [29,31]. In maritime transport, hydrogen-powered vessels could enable longer journeys with fewer emissions, and in aviation, hydrogen is being explored as a cleaner substitute for jet fuel in long-haul flights [32]. In terms of infrastructure, BEVs depend on a growing network of charging stations, whereas hydrogen requires a more intricate setup, including refueling stations, storage, and distribution systems [29]. However, hydrogen refueling stations offer quicker turnaround times, which is particularly beneficial in transportation, shipping, and aviation, where reducing downtime is essential. While both hydrogen and BEVs play a role in reducing emissions, hydrogen is particularly suited to sectors with high energy needs and long distances, such as heavy-duty transport, maritime, and aviation [31,32]. With its high energy density, fast refueling capabilities, and ability to significantly reduce emissions, hydrogen could be key to decarbonizing these industries. Advancements in hydrogen technology and infrastructure will be critical to scaling its adoption.

2.3.2. Chemical industry

Hydrogen is a crucial feedstock in the chemical industry, used in the Haber-Bosch process to produce ammonia, methanol, and hydrodesulfurization in oil refining. It is used in green ammonia, a sustainable fertilizer in agriculture, and in environmentally friendly processes for methanol production. Hydrogen peroxide is widely used as a cleaning agent, and hydrogen also plays a key role in the development of synthetic fuels. A major challenge lies in its primary production source, natural gas, which is a significant contributor to CO₂ emissions. Transitioning to sustainable hydrogen production methods is essential to

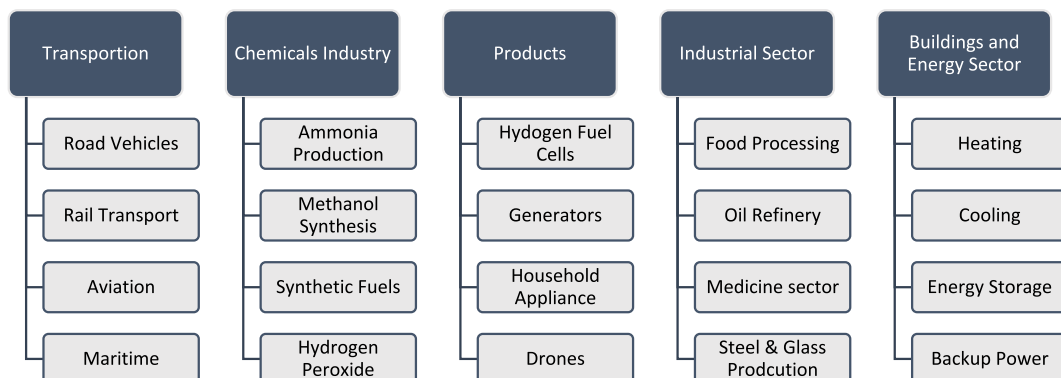


Fig. 5. Application of hydrogen across various sectors [21,28].

reduce the industry’s environmental footprint [21,28].

2.3.3. Products

Hydrogen is making everyday products more efficient and eco-friendlier. It powers small devices, like portable chargers for smartphones, and larger systems that supply energy to homes and businesses. Hydrogen is also utilized in generators and appliances such as stoves and boilers, offering longer lasting and cleaner energy solutions. Even drones benefit from hydrogen, operating more efficiently and sustainably [21, 28].

2.3.4. Industrial sector

Industries are increasingly turning to hydrogen to make their production processes cleaner and more efficient. In steel and glass manufacturing, hydrogen helps to reduce emissions and enhances process efficiency. It is also used in metal and ceramics processing, contributing to the production of stronger materials while minimizing environmental impact. In the food industry, hydrogen improves cooking and preservation techniques, making food processing more sustainable [8]. Hydrogen finds extensive use in medicine, particularly in therapeutic applications where clean, high-purity hydrogen is crucial. One common application is the inhalation of H₂ gas via ventilator circuits, facemasks, or nasal cannulas, providing a simple therapeutic method. Inhalation is considered highly effective in stress treatment, as H₂ gas diffuses rapidly and is absorbed throughout the body. Given the widespread and essential nature of hydrogen’s role in medicine, ensuring a clean, high-purity, and stable source of hydrogen gas is imperative in this field [8,21].

2.3.5. Building and energy systems

Buildings are leveraging hydrogen technology for more efficient and environmentally friendly heating and power solutions [21]. Hydrogen has the potential to replace natural gas in heating and cooling systems, such as boilers and furnaces in residential, commercial, and industrial buildings. It can also be used in fuel cell systems for energy efficiency and emissions reduction [21,28]. In cooling, hydrogen can generate electricity for air conditioning systems and absorption chillers. This transition faces challenges such as developing suitable appliances, ensuring safety, addressing low volumetric energy density, and adapting infrastructure. To achieve environmental benefits, hydrogen must be produced from low-carbon sources [21,28,33].

3. Technical challenges in hydrogen as an alternative energy source

3.1. Technical analysis of hydrogen

Fig. 6 illustrates the gravimetric energy densities of common fuels. Hydrogen’s exceptional gravimetric energy density of 143 Megajoules per kilogram (MJ/kg) positions it as one of the most energy-dense fuels available, exceeding many conventional fossil fuels by a significant margin [7,34,35]. For comparison, the energy density of methane at ambient pressure is 55.6 MJ/kg, while gasoline, diesel, and kerosene all have energy densities around 46 MJ/kg [7,34]. This difference means that hydrogen can deliver more than twice the energy of methane and over three times the energy of gasoline or diesel for the same mass. This high energy density offers substantial advantages, especially in sectors where efficient energy storage and transportation are crucial. In transportation, for instance, hydrogen’s superior energy content allows vehicles to travel greater distances on less fuel, making it particularly advantageous for long-haul trucking, aviation, and maritime shipping. Unlike battery-powered electric vehicles, which are limited by the lower energy density of current battery technologies, hydrogen fuel cells can store more energy in a given mass. This makes hydrogen an ideal solution for industries where weight and space are critical constraints.

Beyond transportation, hydrogen’s high energy density makes it an ideal solution for large-scale energy storage, crucial for balancing supply and demand in power grids increasingly dependent on intermittent renewable energy sources like wind and solar. It can be produced during periods of excess energy generation, stored, and later used for electricity or as fuel for industrial processes. This efficient energy storage capability positions hydrogen as a key player in future energy systems, particularly as the world moves towards low-carbon solutions. In energy-intensive industries like steel manufacturing and chemical production, hydrogen can significantly reduce carbon emissions by replacing fossil fuels. Its high energy density also enables the development of compact, high-capacity storage systems, particularly useful in remote or off-grid locations where regular fuel deliveries are difficult.

Hydrogen is distinguished by its exceptionally low flashpoint of approximately −231 °C, the lowest among commonly used fuels, as shown in Table 1 [34]. This unique characteristic allows hydrogen to vaporize and ignite with greater ease, simplifying the design of starting and ignition systems. As a result, hydrogen-powered engines are particularly reliable in extremely cold conditions, making them well-suited for operation in harsh environments. For example, hydrogen vehicles can start effortlessly even after prolonged exposure to freezing temperatures. In comparison, other fuels such as methane and propane

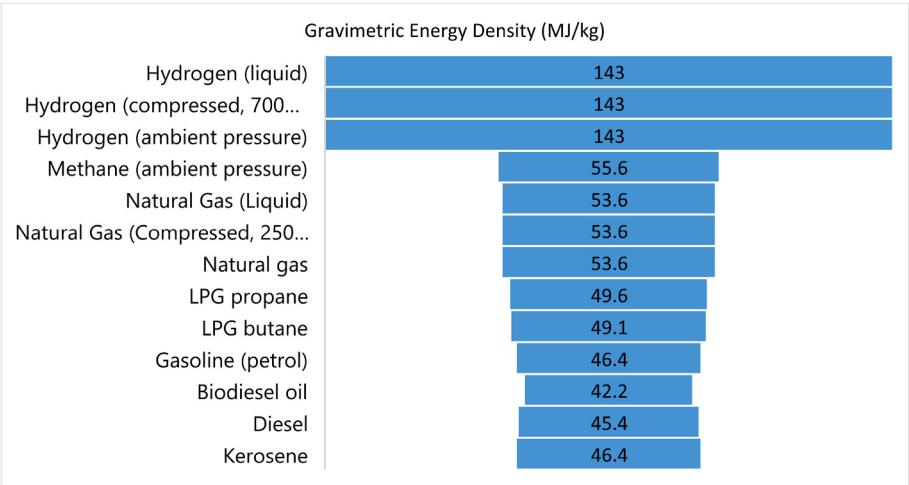


Fig. 6. Gravimetric energy densities of common fuels [7,34].

Table 1
Flashpoint and flammability range of some common fuels [7,34,35].

Fuel	Flashpoint (°C)	Flammable range (%)
Hydrogen	−231	4–75
Methane	−188	5.3–15
Propane	−104	2.2–9.6
Gasoline	−45	1–7.6
Methanol	11	6–36.5
Ethanol (70%)	17	3.3–19
Kerosene	36	0.7–5
Jet fuel	60	0.7–5
Diesel	62	0.6–5.5
Biodiesel	130	0.6–6

have higher flashpoints of -188°C and -104°C , respectively, which require more energy for ignition. Fuels like gasoline with a flashpoint of -45°C and diesel with 62°C , are even less volatile in cold conditions, making them less efficient for quick ignition in extreme environments [34].

Hydrogen's flammable range of 4–75% is significantly broader than that of other common fuels. For instance, gasoline has a flammable range of 1–7.6%, while propane's range is 2.2–9.6%, and methane's range is 5.3–15% [7,34]. This wide flammability range allows hydrogen to ignite and burn at various concentrations in the air, enhancing its performance across different conditions without the need for additional systems, such as turbochargers, which are often required for other fuels to operate efficiently at low pressures or high altitudes. Therefore, hydrogen's low flashpoint and wide flammability range make it an ideal fuel for applications in extreme environments and challenging conditions, offering reliable and efficient ignition and operation where other fuels may struggle.

Hydrogen, while having a high gravimetric energy density, is limited by its relatively low volumetric energy density compared to most conventional fossil fuels, as depicted in Fig. 7. This means that, per unit of volume, hydrogen contains significantly less energy than traditional fuels like kerosene, diesel, and gasoline. For instance, kerosene, which has one of the highest volumetric energy densities at 36.7 Megajoules per liter (MJ/L), contains nearly four times more energy per liter than liquid hydrogen, which has a volumetric energy density of only 10.1 MJ/L. Similarly, diesel with volumetric energy densities of 34.6 MJ/L and gasoline, with volumetric energy densities of 34.2 MJ/L, also vastly outperform hydrogen in terms of energy content per volume. Even when hydrogen is compressed to 700 bars, its volumetric energy density only reaches 5.6 MJ/L, which is still significantly lower than that of most

liquid fossil fuels. Methane at ambient pressure has a slightly higher volumetric energy density of 0.0378 MJ/L compared to hydrogen at ambient pressure, which has a mere 0.0107 MJ/L [7,34].

It is evident that the major challenge in storing hydrogen is to achieve the same amount of energy as fossil fuels, much larger storage volumes are required. This necessitates the development of specialized storage systems, which can be more expensive and complex, especially when considering infrastructure for transportation and refueling. For example, in transportation applications, vehicles would need to accommodate larger or more numerous fuel tanks to achieve a range comparable to that of gasoline or diesel-powered vehicles. The low volumetric energy density of hydrogen complicates the design of storage infrastructure for stationary applications, such as power generation or industrial use. Facilities would need to allocate more space and resources for hydrogen storage, potentially increasing costs and logistical complexities.

In summary, while hydrogen's low volumetric energy density presents significant challenges, particularly in terms of storage and infrastructure, it also drives innovation in the design of more efficient and compact storage systems. Overcoming these challenges is crucial for realizing hydrogen's full potential as a sustainable energy carrier in various sectors, including transportation, industry, and energy storage.

3.2. Challenges in hydrogen application

Hydrogen has significant potential as an energy carrier due to its high energy density, adaptability, and ability to be used in applications that produce no emissions. Despite these advantages, several challenges impede its widespread adoption as a primary energy source. It is essential to have a thorough understanding of these barriers to properly address and overcome them [8]. This section has addressed the primary obstacles linked to the utilization of hydrogen as an energy source.

3.2.1. Production and distribution complexity

The task of generating hydrogen in an environmentally friendly and economically efficient manner continues to be a major obstacle. The current dominant method is steam methane reforming (SMR), which relies on natural gas and produces carbon dioxide as a byproduct. Adopting lower-carbon or carbon-free production methods, such as using electrolysis driven by renewable energy, is crucial [18]. This transition is hampered by challenges such as increased expenses and the requirement for additional technological advancements. Alongside, the process of creating a widespread distribution network, which involves

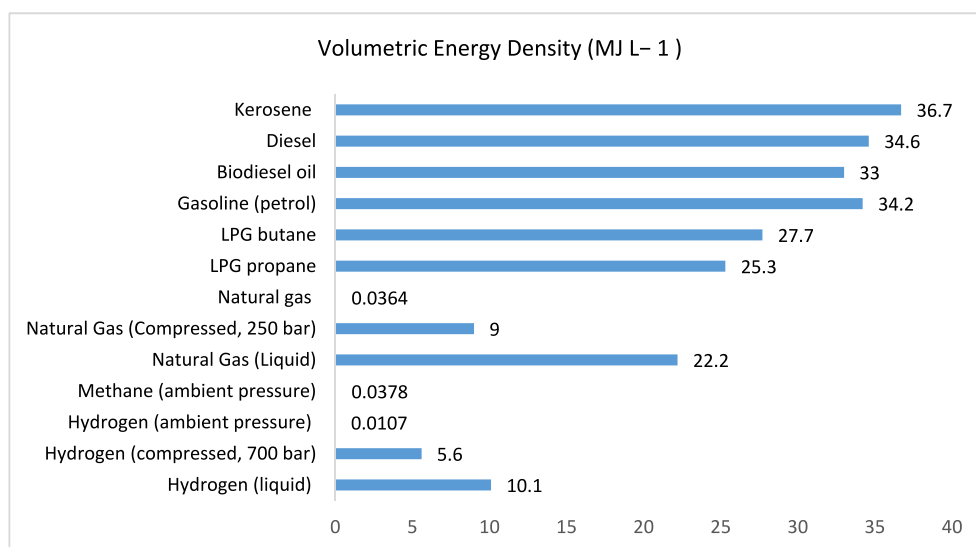


Fig. 7. Volumetric energy densities of common fuels [7,34].

building pipelines and filling stations, necessitates significant financial resources and careful organization [8,21].

3.2.2. Energy efficiency challenges

The production, storage, and transportation of hydrogen require a significant amount of energy, which has a negative impact on its overall efficiency. Substantial energy losses are incurred throughout the compression and liquefaction phases, which are essential for the purpose of storage and transportation. Maximizing the benefits and minimizing wastage of hydrogen requires a focus on enhancing energy efficiency throughout its entire lifecycle [21,28].

3.2.3. Storage technology limitations

The low volumetric energy density of hydrogen poses significant challenges for storage, as it requires much larger volumes compared to conventional fuels like gasoline to store the same amount of energy [21]. Storage methods, both physical and material-based storage method provide distinct benefits and drawbacks in terms of capacity, safety, and cost. For instance, compressed gas storage, while relatively straightforward, demands high pressures (typically around 700 bar) to store sufficient quantities of hydrogen, raising concerns about material fatigue, leakage, and overall system safety. Liquid hydrogen storage, on the other hand, requires extremely low temperatures (around -253°C) to maintain its liquid state, leading to challenges in insulation, energy consumption for liquefaction, and boil-off losses during storage and transport [21,36]. Cryo-compressed hydrogen storage combines cryogenic temperatures and high-pressure compression, offering higher storage densities and reduced boil-off losses but posing challenges due to its complexity and cost [37].

Material-based hydrogen storage offers safe, efficient, and compact solutions by storing hydrogen within solid materials, unlike traditional physical methods. These systems include physisorption, where hydrogen molecules are weakly adsorbed onto materials like MOFs (Metal-Organic Framework) and zeolites, providing fast, reversible storage but requiring cryogenic conditions for higher capacity. Alternatively, chemisorption involves chemical bonding with materials like metal hydrides, enabling high-density storage at ambient conditions suitable for long-term use, though it requires higher activation energy and is limited by reactive site availability [8,21,36].

With these specific challenges, all storage methods must address issues related to efficiency, scalability, and cost-effectiveness. For hydrogen to be adopted on a large scale, storage technologies must not only overcome these technical barriers but also become economically competitive with traditional fuels. This requires ongoing research and development efforts to improve the materials, designs, and processes involved in hydrogen storage, ensuring that they meet the safety, capacity, and cost requirements necessary for widespread use [21].

3.2.4. Safety and public perception

The high flammability of hydrogen, along with its broad range of flammability limits (4%–75% in air), presents significant safety challenges throughout its lifecycle, from production to storage and transportation [34]. Unlike conventional fuels, hydrogen can ignite more easily and burn with an invisible flame, increasing the risk of accidental fires or explosions if not handled properly [38]. These safety risks are heightened by hydrogen's low ignition energy and the ability to leak easily due to its small molecular size, which can permeate through materials that would typically contain other gases [39].

To mitigate the safety risks associated with hydrogen, which is highly flammable and can present significant dangers in storage, transportation, and production, it is essential to implement robust safety protocols. Key measures include employing advanced leak detection technologies such as infrared sensors and catalytic detectors, which provide early warnings for potential leaks [40]. High-pressure storage systems should be equipped with pressure relief and venting mechanisms to prevent over-pressurization [39,40]. Adequate ventilation and

separation zones are critical to avoid the accumulation of hydrogen in confined spaces, reducing the risk of ignition. The materials used in hydrogen storage systems must be selected for their resistance to hydrogen embrittlement, typically requiring specialized alloys and coatings [41]. Hydrogen infrastructure must follow established safety standards, such as those set by ISO (International Organization for Standardization) and the NFPA (National Fire Protection Association), to ensure consistent safety across different stages of the hydrogen value chain [42]. Fire and explosion risks can be minimized by employing inert gas flooding, explosion-proof equipment, and appropriate grounding measures. By integrating these safety practices, hydrogen systems can operate safely, paving the way for broader adoption of hydrogen as a sustainable energy source [42,43].

3.2.5. Stakeholder engagement and public perception

Public acceptance is a critical factor in the successful adoption of hydrogen technologies, but there are several obstacles that need to be addressed. Safety concerns are often at the forefront, mainly due to hydrogen's flammability and the relatively new application of hydrogen across various industries [21]. Additionally, many people may not fully understand the processes involved in hydrogen production, storage, and transportation, leading to uncertainties about its safety and reliability. Misconceptions about the environmental impacts of hydrogen, along with perceived complexities in infrastructure, may further hinder its widespread acceptance. To overcome these barriers, a comprehensive strategy involving education, clear communication, and policy initiatives is essential. Public education should focus on dispelling myths and providing easily accessible, accurate information about hydrogen's safety measures, environmental benefits, and its role in reducing emissions. Highlighting successful real-world examples where hydrogen is already being used effectively can build confidence and demonstrate its practical applications [21,36].

Encouraging public engagement through open discussions is vital for addressing concerns and fostering understanding. Public forums, educational outreach, and digital platforms can serve as spaces for people to ask questions and receive answers from experts. Ensuring that communities have a say in hydrogen-related decisions will also promote transparency and help build trust in the technology. Government policy can support public acceptance by establishing clear safety regulations and standards for hydrogen technologies, making it easier for the public to understand how safety is ensured. Additionally, providing financial incentives and support for the development of hydrogen infrastructure could lower the cost barrier, making hydrogen more accessible. A solid policy foundation will also reassure industries and consumers that hydrogen technology is viable and safe [21,36].

Finally, collaboration among government bodies, industries, and research institutions will be crucial in overcoming the barriers to public acceptance. By working together, these groups can advance hydrogen technologies, address concerns, and ultimately position hydrogen as a safe, sustainable, and transformative energy source, accelerating its role in the transition to a cleaner energy future.

3.2.6. Economic competitiveness

For hydrogen to effectively compete with traditional fossil fuels, it must overcome significant economic challenges in production, distribution, and use. Production of hydrogen is more expensive, especially when generated through renewable-powered electrolysis. While grey hydrogen is the least costly, USD 0.67–1.31 per Kilogram (Kg) of H_2 , it is unsustainable due to its high emissions (8.5 kg $\text{CO}_2/\text{kg H}_2$). Blue hydrogen, which integrates CCS to reduce emissions to 2 kg $\text{CO}_2/\text{kg H}_2$, offers a more sustainable alternative but comes at a moderate cost (USD 0.99–2.05/kg H_2). Green hydrogen is emission-free but remains costly (USD 2.28–7.39/kg H_2) due to the high expenses associated with renewable-powered electrolysis [44,45]. The costs of production, storage, and transportation infrastructure further challenge hydrogen's economic competitiveness with fossil fuels. Overcoming these barriers

will require technological advancements, such as more efficient production methods, improved storage solutions, and scaling up economies of scale. Supportive policies, including government incentives and subsidies for research and innovation, are essential to lowering costs and making hydrogen a more viable energy option. By addressing these economic hurdles, hydrogen has the potential to become a competitive and sustainable energy source.

3.2.7. Integration with existing infrastructure

Integrating hydrogen into existing energy infrastructure involves substantial technical challenges due to hydrogen’s unique characteristics. The retrofitting of current systems, such as pipelines and storage facilities, is complicated by hydrogen’s small molecular size, which can cause embrittlement in materials not designed to handle it. Also, hydrogen’s lower energy density compared to natural gas means that larger volumes need to be transported and stored, requiring modifications to storage tanks and transportation methods [8,21,46]. Developing entirely new infrastructure designed for hydrogen is also costly and logistically complex, as it must meet stringent safety standards to manage hydrogen’s high flammability and potential for leaks. Ensuring that this new infrastructure is compatible with existing systems while being economically viable demands significant innovation, investment, and regulatory support [8,21,46].

3.2.8. Scalability and resource management

Scaling up hydrogen production to meet growing demand requires substantial investments and efficient management of hydrogen feedstocks, such as water and renewable energy sources. Ensuring a reliable and sustainable supply chain is crucial for the long-term viability and scalability of hydrogen technologies. Addressing these complex challenges demands collaborative efforts from governments, industries, researchers, and policymakers. Investment in research, technology development, and supportive policies is essential to overcoming barriers and unlocking hydrogen’s full potential as a clean and sustainable energy solution. As advancements are made and economies of scale achieved, hydrogen is poised to play a pivotal role in achieving global energy transition goals toward a low-carbon future.

4. Hydrogen production: challenges and opportunities

4.1. Hydrogen production technologies

The environmental impact of hydrogen production varies widely, depending on the processes and feedstocks utilized. Each method of producing hydrogen has a unique environmental footprint, shaped by the specific chemical reactions involved and the resulting GHG emissions. This diversity in production techniques underscores the necessity of advancing towards cleaner hydrogen production to achieve global environmental objectives [4,8,21]. Fig. 8 outlines hydrogen production technologies divided into two primary categories: fossil fuels and renewable sources. From fossil fuels, hydrogen is generated through processes like coal gasification, hydrocarbon pyrolysis, and reforming techniques, including steam reforming, auto-thermal reforming, and partial oxidation. These methods typically have higher greenhouse gas emissions. Renewable sources, on the other hand, use biomass and water splitting. Biomass can be converted through thermochemical processes like pyrolysis and gasification, or biological methods such as bio-photolysis and fermentation. Water splitting includes electrolysis, thermal, and photocatalytic methods, leveraging electricity, heat, or sunlight to produce hydrogen with minimal environmental impact. Renewable-based methods, especially green hydrogen production, are emphasized for their lower emissions and sustainability.

Table 2 provides a comparative overview of the different hydrogen production processes, categorizing them by color-coded names. It highlights their feedstock sources and the importance of prioritizing environmentally sustainable methods to achieve global environmental goals. The conventional color-coding of hydrogen production methods can be misleading, as it presumes that green hydrogen consistently has a lower carbon footprint than blue or grey hydrogen. However, this is not universally accurate [47]. For example, while blue hydrogen is often perceived as less safe compared to green hydrogen, it does not emit carbon during use or throughout its production when carbon capture and storage (CCS) is employed effectively. Conversely, green hydrogen production can still contribute to greenhouse gas emissions under certain conditions. Bioenergy feedstocks, such as biomass, release pollutants like methane (CH₄), sulfur oxides (SO_x), nitrogen oxides (NO_x), and carbon dioxide (CO₂) during growth or thermochemical conversion processes. Additionally, CCS technologies used in blue hydrogen

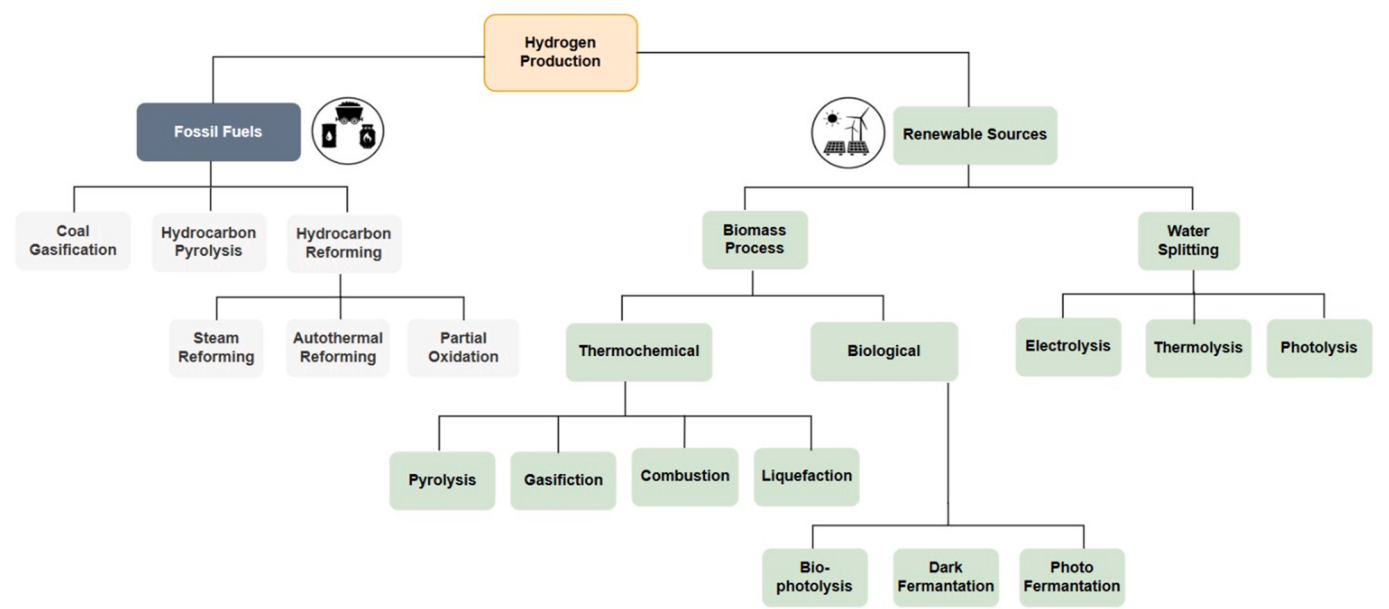


Fig. 8. Hydrogen production technologies [4,8,21].

Table 2

A comparative overview of the different hydrogen production processes [21,49,50].

Hydrogen Produced (With Color Code)	Production Process	Feedstock Source	Environmental Impact emission (GHG)
Green H ₂	Electrolysis	Renewable energy sources (Hydro/ Solar/ Wind/ Tidal)	Minimal. Water is the by product
Yellow H ₂		Grid electricity	Medium
Pink H ₂		Nuclear Energy	Minimal
Black H ₂	Gasification (no CCUS)	Black Coal	High
Brown H ₂		Brown Coal (Lignite)	High
Grey H ₂	SMR	Natural Gas (CH ₄)	Medium
Blue H ₂	SMR+CCUS Gasification + CCUS	NG Coal	Low
Turquoise H ₂	Methane Pyrolysis	Natural Gas (CH ₄)	Solid Carbon (by product)/ No CO ₂ emission
White H ₂	Naturally occurring hydrogen	Geological formations, industrial byproducts	
Gold H ₂	Biological fermentation in depleted wells	Residual hydrocarbons	Low

production can significantly mitigate harmful emissions, underscoring its potential environmental benefits in specific scenarios [47].

Green hydrogen, produced via electrolysis powered by renewable energy (such as hydro, solar, wind, or tidal), is the most eco-friendly, generating minimal emissions with water as the only byproduct [21, 48]. Yellow hydrogen, also from electrolysis but using grid electricity, has a medium impact, depending on the grid's energy mix. Pink hydrogen utilizes nuclear energy for electrolysis, maintaining low emissions but with considerations for nuclear waste. In contrast, Grey, Brown, and Black Hydrogen are produced from fossil fuels without CCUS. Brown, and Black Hydrogen are produced by gasification process from coal (brown) or other fossil fuels (black) without CCUS [21]. Grey hydrogen, produced through steam reforming of methane (natural gas), also emits substantial CO₂, although it remains a prevalent production method [21]. These methods involve significant CO₂ emissions, contributing substantially to the greenhouse effect and making them less environmentally favorable with grey being the least and black the most polluting among them. Blue Hydrogen is derived from natural gas but includes CCS to mitigate emissions. Although it reduces direct CO₂ emissions compared to other fossil fuel-based methods, its sustainability heavily relies on the efficiency and effectiveness of the CCS technology. Turquoise hydrogen offers an innovative approach, producing solid carbon instead of CO₂ through methane pyrolysis, providing a valuable industrial byproduct with no direct CO₂ emissions. White hydrogen occurs naturally in geological formations and as a byproduct of certain industrial processes, while gold hydrogen, derived from fermenting microbes in depleted wells, offers a low-carbon, potentially neutral production process [21,49,50]. This varied landscape of hydrogen production highlights the critical need to transition towards renewable-based methods. Doing so is essential to fully harness hydrogen's potential as a clean and sustainable energy carrier for the future.

Integrating hydrogen production with renewable energy sources such as solar and wind offers significant advantages for sustainability and efficiency. It allows for the generation of hydrogen with minimal emissions through renewable-powered electrolysis, contributing to decarbonization efforts [51]. This approach can utilize surplus renewable energy, minimizing waste and enhancing cost-effectiveness. Hydrogen also serves as an effective means of energy storage, addressing the intermittency of renewables and ensuring grid stability [51]. By

linking the energy, transportation, and industrial sectors, this synergy enables broad decarbonization, particularly in challenging applications like heavy transport and industrial processes. Additionally, it encourages energy self-reliance through local renewable resources, supports decentralized energy systems in remote areas, and drives advancements in both renewable and hydrogen technologies, aligning with long-term climate objectives [51,52].

Utilizing excess renewable electricity for hydrogen production presents both technical and economic advantages [53]. Technically, this approach mitigates the issue of renewable energy curtailment during periods of oversupply, ensuring optimal use of generated power. Excess electricity can drive electrolysis processes to produce green hydrogen, which can then be stored and utilized during low renewable energy generation periods, enhancing grid reliability [54]. Economically, this creates a value stream from otherwise wasted electricity, reducing the levelized cost of hydrogen production over time. However, challenges such as the need for scalable and efficient electrolyzers, energy storage infrastructure, and the integration of hydrogen systems with the grid must be addressed to fully realize this potential [53,54].

4.2. Challenges and opportunities of hydrogen production technologies

Most of the hydrogen produced for commercial purposes is now derived from fossil fuels, such as coal gasification or natural gas reforming. Likewise, biomass feedstocks can be used to produce hydrogen using comparable methods. Water electrolysis, which has been utilized in specific industrial sectors for many years, has gained renewed attention due to recent technological breakthroughs and the accessibility of inexpensive electricity. Several future forecasts for hydrogen generation primarily depend on electrolysis, nonetheless, developing methods like thermolysis and photolysis exhibit potential in utilizing thermal or solar energy more efficiently. The current dominant direction is focused on the production of green hydrogen by means of water electrolysis utilizing environmentally sustainable renewable energy sources. The utilization of renewable energy sources, such as solar, wind, hydroelectric, and tidal energy, is expected to make this production process more economically efficient compared to industrial methods, as the main expense is the cost of power.

As illustrated in Fig. 9, electrolysis, which uses electricity to split

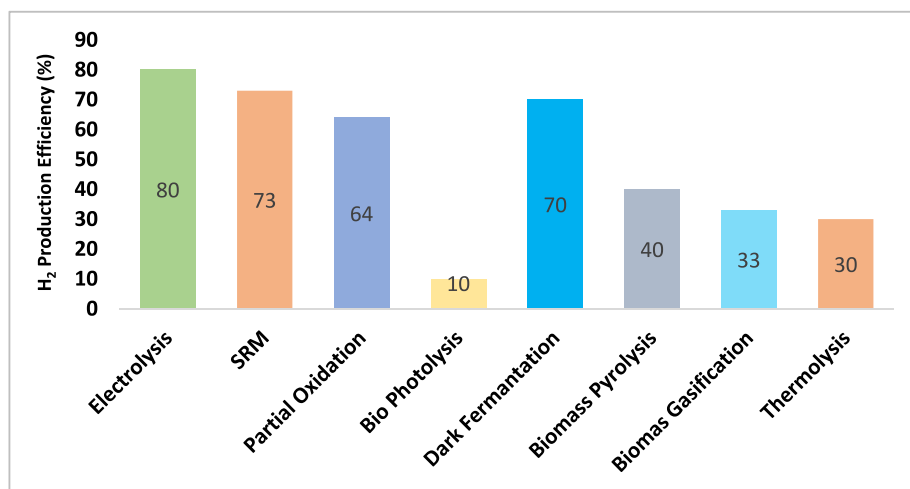


Fig. 9. Hydrogen production efficiency through different processes [4,8,44].

water, is the most efficient at 80%, especially when powered by renewable energy. SMR, at 73%, is the dominant industrial method but emits significant CO₂. Dark Fermentation, with 70% efficiency, biologically converts organic matter into hydrogen without light. Partial Oxidation, at 64%, and Biomass Pyrolysis and Gasification, with efficiencies of 40% and 33% respectively, convert hydrocarbons and biomass into hydrogen. Emerging technologies like Bio Photolysis (10%) and Thermolysis (30%) show potential but are less efficient [4,8].

When comparing hydrogen production methods, the long-term environmental impacts and costs vary significantly. Table 3 presents a comparison of production costs and associated emissions for various hydrogen production processes. Green hydrogen, produced via electrolysis, is emission-free but costly, ranging from USD 2.28–7.39/kg H₂. However, as technology advances, the cost is expected to decrease. Pink hydrogen, produced using nuclear energy, is also free of emissions and more affordable (USD 2.18–5.92/kg H₂) compared to green hydrogen. In contrast, grey hydrogen, the cheapest option (USD 0.67–1.31/kg H₂), has a significant environmental drawback, emitting 8.5 kg CO₂ per kg of hydrogen produced. Blue hydrogen offers a middle ground, costing USD 0.99–2.05/kg H₂, with much lower emissions (2 kg CO₂/kg H₂) due to carbon capture and storage (CCS), making it a viable transitional option. Turquoise hydrogen, produced by pyrolysis, is relatively cost-effective (~USD 2/kg H₂), and its emissions could potentially be controlled, depending on how the solid carbon byproduct is managed [44,45].

Black/brown hydrogen, produced through gasification, is the most energy-intensive, requiring 236 MJ/kg. Green hydrogen, produced via electrolysis, follows with an energy input of 192 MJ/kg, relying on renewable electricity. Yellow and pink hydrogen, also based on

electrolysis (solar and nuclear-powered, respectively), likely have similar energy inputs. Grey hydrogen, from steam methane reforming (SMR), requires 167–223 MJ/kg, with blue hydrogen using SMR or gasification plus carbon capture (CCUS) in the same range. Turquoise hydrogen, produced by pyrolysis, has a similarly high energy demand. Overall, black/brown hydrogen is the most energy-consuming, while green and pink hydrogen have a higher environmental benefit despite higher energy input.

The current method of hydrogen generation mainly depends on grey hydrogen, which is economically efficient but not sustainable in the long run due to its substantial carbon emissions. In terms of long-term environmental impacts, relying on grey hydrogen raises concerns due to its high emissions and dependence on fossil fuels. Over time, this could hinder efforts to reduce global greenhouse gas emissions. Green hydrogen, on the other hand, has a much more sustainable environmental profile, with zero emissions, though it is currently more expensive. At present, SMR is widely favored because it is a cost-effective process. Nevertheless, it produces significant amounts of carbon emissions, resulting in the release of huge quantities of CO₂ into the atmosphere [56,57]. To minimize this effect, it is imperative to incorporate CCS, notwithstanding the challenges associated with controlling methane feedstock and optimizing automated control systems. The use of CCUS to obtain blue hydrogen significantly escalates the expense of hydrogen manufacturing.

Blue and green hydrogen offer pathways to achieve net-zero emissions, although they are presently more expensive [18]. Accelerating the adoption of blue and green hydrogen will require substantial investments in research, development, and infrastructure, including the establishment of new pipelines and distribution networks. Electrolysis, particularly if powered by renewable energy, offers a pathway to green hydrogen but comes with its own set of issues [18]. It requires large quantities of water—approximately 9 L per kilogram of hydrogen—posing challenges in water-scarce regions. Proton Exchange Membrane (PEM) electrolysis relies on expensive catalysts like platinum and iridium and suffers from shorter electrode lifespans compared to alkaline electrolysis [58]. Accordingly, the cost of the electrolysis process remains higher. Green hydrogen, produced through water electrolysis using renewable energy sources like solar and wind power, presents a compelling opportunity across diverse sectors such as heavy industry and transportation. The demand for green hydrogen is burgeoning, particularly in Europe, driven by initiatives to reduce dependence on fossil fuels, especially during peak demand seasons such as winter. This trend is poised to expand significantly across Asia in the near future [4,44].

Coal gasification, which mainly produces brown and black hydrogen,

Table 3

Comparison of hydrogen types based on cost and environmental impact [44,45,55].

Type of Hydrogen	Cost [USD/kgH ₂]	Emissions [kgCO ₂ /kgH ₂]	Energy Input (MJ/kg)	Process Used
Green H ₂	2.28–7.39	0	192	Electrolysis
Yellow H ₂	6.06–8.81	–		
Pink H ₂	2.18–5.92	0		
Black H ₂	1.2–2	20	236	Gasification (no CCUS)
Brown H ₂	1.2–2	20		
Grey H ₂	0.67–1.31	8.5	167	Steam methane reforming (SMR)
Blue H ₂	0.99–2.05	2	169/223	SMR + CCUS, gasification + CCUS
Turquoise H ₂	~2	Solid carbon	–	Pyrolysis

used predominantly in the chemical and fertilizer industries, is another method that emits high levels of CO₂ and other pollutants, such as sulfur oxides, necessitating effective sulfur reduction systems [59,60]. This method also faces challenges in cooling the high-temperature gases produced and managing impurities in the feedstock. Biomass gasification presents a more sustainable option, converting organic material into hydrogen through biochemical processes like aerobic digestion. This technology is not fully mature, with issues like catalyst poisoning from tar formation and the high cost and availability of biomass limiting its scalability. Across all methods, converting hydrogen into easier-to-store and transport fuels like ammonia, synthetic hydrocarbons, and methanol could alleviate some logistical challenges, but the inherent production hurdles remain substantial [61–63].

To make renewable-powered electrolysis a more economically viable alternative to fossil fuel-based hydrogen production methods SMR, several advancements are necessary [18,20]. These include reducing the cost of electrolyzers through increased production scale and the development of cheaper catalysts, moving away from precious metals [20, 28]. Efficiency improvements, such as those from high-temperature electrolysis and advanced membrane technology, are also essential for enhancing scalability. Ensuring a stable hydrogen supply also depends on efficient integration with renewable energy sources and the development of reliable storage systems to manage energy fluctuations effectively. Addressing water use for electrolysis, including exploring seawater electrolysis, is vital for broadening the availability of water resources [20]. Policy measures like carbon pricing, subsidies, and investments in hydrogen infrastructure are needed to make renewable hydrogen more competitive. While fossil fuel-based methods like SMR benefit from established infrastructure and lower production costs, transitioning to renewable methods requires reducing reliance on fossil fuels and mitigating their carbon emissions. Operational improvements and minimizing the environmental impact of renewable-powered electrolysis will be key to scaling this clean alternative effectively.

Despite several opportunities, significant challenges persist. The technologies for producing hydrogen from biomass, algae, and biotransformation processes are still in the research and testing phases, supported by national hydrogen strategies and implementation budgets [8]. The transition away from fossil fuels faces formidable hurdles, including the entrenched geopolitical influence of oil and gas, which continues to overshadow alternative fuel sources. The global energy crisis, exacerbated by rising greenhouse gas emissions and more frequent extreme weather events, underscores the urgency of prioritizing clean energy solutions. Achieving a renewable energy economy requires overcoming numerous economic and geopolitical obstacles. It necessitates a fundamental restructuring of the global energy system, which serves as the cornerstone of the current geopolitical order. Addressing these challenges will require concerted efforts in technology innovation, infrastructure development, and policy frameworks to realize hydrogen's full potential as a sustainable energy carrier [4,8].

5. Hydrogen storage systems: challenges and opportunities

5.1. Hydrogen storage technologies

Efficient hydrogen storage is vital for realizing hydrogen's potential as a clean, sustainable energy source. This has spurred global research efforts to develop technologies that meet the growing energy demand while addressing climate change. Reliable storage systems are critical for hydrogen's role in both mobile applications, like vehicles, and stationary uses, such as power generation. In transportation, hydrogen stands out for its high energy content. While it can power internal combustion engines, the future is likely to favor PEM fuel cells, which convert hydrogen directly into electricity with remarkable efficiency and near-zero emissions. Advancing storage technologies is key to unlocking hydrogen's full potential and cementing its place in a sustainable energy future [36]. Once produced, hydrogen must be stored

effectively, either as a gas or liquid, depending on its use. Stationary storage systems support power plants and on-site applications, while mobile storage caters to vehicles and transportation needs [64–66]. Thanks to its chemical stability, hydrogen can be stored for long periods using various techniques, each with distinct advantages. Hydrogen storage methods are categorized into two main types: physical-based and material-based. Physical-based methods include storing hydrogen as a gas, a liquid, or using cryo-compressed techniques, which combine elements of both [8]. Material-based methods rely on absorbing or adsorbing hydrogen through chemical or physical processes. Together, these technologies offer versatile solutions for efficient hydrogen storage [36]. Fig. 10 provides an overview of these techniques.

The storage of hydrogen is as critical as its generation for effectively harnessing its potential as a clean energy source. With its exceptional energy density and versatility in powering fuel cells and engines, hydrogen presents immense opportunities. However, its low density and high volatility pose significant challenges, making safe and efficient storage a top priority. To establish hydrogen as a viable and sustainable energy option, developing storage systems that are both cost-effective and highly efficient is essential. Current research focuses on enhancing energy density, safety, and the practicality of various storage technologies, enabling their application in sectors like transportation and power generation. Table 4 provides a comparative analysis of key hydrogen storage technologies, evaluating their cost, efficiency, scalability, and environmental impact.

5.1.1. Physical based storage

Hydrogen storage is crucial for advancing hydrogen as a sustainable energy source, with physical-based storage methods playing a key role due to their straightforward handling of hydrogen in gas or liquid forms. Three primary methods stand out, each tailored to different needs and applications. Compressed gaseous hydrogen storage utilizes high-pressure vessels to store hydrogen gas, making it ideal for scenarios demanding large hydrogen volumes or rapid refueling [8]. Despite potential risks like leakage and safety issues, this method is well-established and reliable. Liquefied hydrogen storage, on the other hand, involves cooling hydrogen to cryogenic temperatures (−253 °C) and storing it as a liquid in insulated containers [36]. This method offers high volumetric density, making it efficient for long-distance transport and applications that need compact storage solutions, though it is energy-intensive and prone to boil-off losses. Cryo-compressed hydrogen storage merges cryogenic cooling with high-pressure compression, allowing hydrogen to be stored at lower temperatures and higher pressures, resulting in higher storage densities and reduced boil-off losses compared to liquid hydrogen storage. Although promising for high-energy density applications, cryo-compressed storage is complex and costly due to the need to maintain stringent cryogenic and high-pressure conditions. Each method brings distinct advantages and challenges, essential for the diverse requirements of a hydrogen-based economy [8,36]. The following Table 5 provides a detailed comparison of these storage methods, highlighting their advantages, disadvantages, and typical applications.

5.1.2. Material based storage

Material-based hydrogen storage systems are increasingly important for their ability to store hydrogen safely and efficiently within solid materials. Unlike traditional physical-based storage methods that rely on containing hydrogen gas or liquid in large, often bulky, systems, material-based storage offers compact, high-capacity solutions. These methods are divided into two main types: physisorption and chemisorption [8,21,36].

Physisorption-Based Hydrogen Storage: Physisorption involves the weak physical adsorption of hydrogen molecules onto the surfaces of solid materials through van der Waals forces [36]. Common materials used for this method include carbon-based structures, MOFs, zeolites, and polymers with intrinsic microporosity (PIMs). Physisorption is

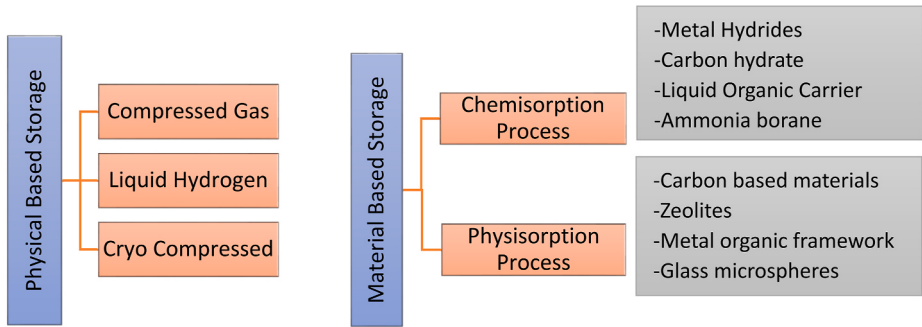


Fig. 10. Different hydrogen storage techniques [8,21,36].

Table 4
A comparative Analysis of Hydrogen Storage Technologies [8,21,36,67].

Technology	Cost	Efficiency	Scalability	Environmental Impact
Compressed gaseous storage	Moderate	Moderate; requires high pressure (up to 700 bar)	High for short-term applications	Moderate; energy-intensive compression required
Liquefied hydrogen storage	High	Low; liquefaction consumes ~30% of hydrogen's energy content	Limited; large-scale use faces energy challenges	Significant; cryogenic cooling increases emissions
Cryo-compressed storage	High	Moderate; combines benefits of gas and liquid storage	Promising for advanced applications	Reduced boil-off but still energy-intensive
Physisorption	Moderate	Low; limited by weak binding energies	Experimental; scaling depends on material availability	Low; minimal environmental risks
Chemisorption	Variable (depending on materials)	High; strong chemical bonds enable efficient storage	Experimental; complex materials needed for scaling	Moderate; some materials have toxic byproducts

Table 5
Comparison of different physical based storage technologies [8,21,36].

Storage Method	Advantages	Disadvantages	Typical Application
Compressed gaseous storage	- Mature technology with well-established standards. - Quick refueling times. - Operates at ambient temperatures. - Suitable for high-volume and long-distance transport.	- High-pressure storage poses safety risks, especially in populated areas. - Lower energy density compared to liquid hydrogen. - Potential for hydrogen leakage.	- Industrial applications. - Transportation, including hydrogen fuel stations. - Backup power systems.
Liquefied hydrogen storage	- High volumetric density (70.8 kg/m³). - Suitable for long-distance and large-volume transportation. - Efficient for applications needing compact, high-capacity storage.	- High energy cost to liquefy hydrogen (−253 °C). - Requires complex and costly cryogenic tanks. - Boil-off losses due to temperature increases.	- Intercontinental transportation via ships. - Aerospace applications. - Fixed storage facilities with large spherical tanks.
Cryo-compressed storage	- Higher storage density than compressed gas alone. - Minimizes boil-off losses compared to liquid storage. - Combines benefits of both gaseous and liquid storage methods.	- Technically complex and costly. - Requires maintenance of cryogenic temperatures and high pressures. - More expensive due to advanced insulation and containers.	- Advanced hydrogen-powered vehicles. - Aerospace applications. - Situations needing high energy density and efficient space use.

advantageous due to its fast and reversible adsorption and desorption processes. Its effectiveness is limited by low hydrogen storage capacity at room temperature, often necessitating cryogenic conditions to achieve higher storage density [8].

Chemisorption-Based Hydrogen Storage: Chemisorption involves the chemical bonding of hydrogen atoms with materials to form stable hydrides. This process occurs when hydrogen molecules dissociate into atoms and chemically bind to the storage material, which is usually metals or metal alloys [36]. Chemisorption allows for high-density hydrogen storage at ambient conditions and is suitable for applications needing long-term and stable storage. It requires higher activation energy and is limited by the availability of reactive sites on the storage material [8].

Below is a comparison of these two material-based hydrogen storage methods. Table 6 summarizes the key characteristics, advantages, disadvantages, and typical applications of physisorption and chemisorption-based hydrogen storage systems, highlighting their roles in advancing hydrogen storage technologies for the future.

Table 6
Comparison of different material-based storage technologies [8,21,36].

Storage Type	Materials Used	Advantages	Disadvantages	Application
Physisorption	Carbon materials, MOFs, zeolites, PIMs	Fast adsorption/desorption, reversible process	Low storage capacity at room temperature, needs very low temperatures for higher density	Gas storage, catalysis, sensors
Chemisorption	Metal hydrides, metal alloys	High storage density, stable at ambient conditions	Requires high activation energy, complex material interactions	Hydrogen storage in vehicles, backup power systems

5.2. Challenges in hydrogen storage

Hydrogen storage systems are fundamental to the development and deployment of hydrogen as a sustainable energy carrier. They not only ensure the efficient containment of hydrogen but also enable its safe and practical use across various applications, from transportation to energy generation. The advancement of hydrogen storage technologies faces several challenges that need to be addressed to unlock their full potential. At the same time, these challenges present numerous opportunities for innovation and growth within the hydrogen economy [21]. Below, we explore the key challenges and opportunities associated with hydrogen storage systems.

5.2.1. Technical complexity and efficiency

Hydrogen storage systems face significant challenges due to the low volumetric energy density of gaseous hydrogen, which limits its practical storage and transport. To achieve useable storage densities, hydrogen must either be compressed or liquefied, both of which introduce technical complexity [8]. Compressed hydrogen must be stored at very high pressures (typically around 700 bar), requiring specialized high-strength containers and compressors, which present significant engineering challenges, including concerns about leakage, material strength, and safety risks. Compressing hydrogen demands a substantial amount of energy, which reduces the overall efficiency of the process [36]. Liquefaction, another storage method, involves cooling hydrogen to its cryogenic liquid state at -253°C . This process is energy-intensive due to the need for complex refrigeration systems that require substantial energy to maintain hydrogen at such low temperatures [36]. Insulation systems are also required to minimize energy losses and keep the hydrogen in liquid form, further complicating the process [8,21,36].

To address these challenges, innovative materials and storage methods are being explored. One promising approach is metal hydride storage, where hydrogen is chemically bound to a metal alloy, forming a solid compound that is easier to store and transport at lower pressures and moderate temperatures [36]. But the activation energy required to release hydrogen from these hydrides is high, limiting their efficiency and longevity. Cryo-compressed storage, which combines both compression and cryogenic cooling, is also being investigated to balance storage density with technical feasibility. This approach faces challenges in optimizing both the energy required for cooling and the structural requirements for high-pressure containment [8,21]. Other methods like physisorption (using porous materials such as metal-organic frameworks or carbon nanotubes) are being explored as well. These materials can store hydrogen at relatively low pressures and temperatures but often require cryogenic conditions to achieve the necessary storage capacities, making them energy-intensive and less practical for large-scale storage [21,36]. While chemisorption involves high activation energies and intricate bonding interactions, limiting their practical application and longevity [8]. Addressing these challenges is crucial to advancing hydrogen storage technologies and realizing their full potential in a sustainable energy landscape.

Hydrogen compression and liquefaction are among the most energy-demanding stages in the production and distribution process, often leading to energy losses as high as 30–40%. In contrast, processes such as electrolysis and SMR, while still contributing to inefficiencies, generally experience lower losses. To improve these processes, advanced compression technologies like isothermal or multi-stage adiabatic compressors can help reduce energy consumption by managing heat more effectively. Enhancements in liquefaction technologies, such as the application of more efficient cryogenic systems, can also reduce energy use. Alternative storage methods, such as solid-state or metal hydride storage, can lessen the need for compression and liquefaction altogether. Optimizing the distribution infrastructure, such as using advanced sealing technologies and composite materials in pipelines, can decrease energy losses during transportation. Integrating energy recovery systems into compression and liquefaction stages can further improve

efficiency by reclaiming and reusing some of the energy. These improvements, along with ongoing research and technological advances, are essential for reducing energy losses and increasing the competitiveness of hydrogen as a sustainable energy source.

5.2.2. Safety and regulatory concerns

Hydrogen storage systems face critical safety challenges due to hydrogen's highly flammable nature and its propensity to escape containment because of its small molecular size. These issues are especially problematic in high-pressure storage (up to 700 bar) and cryogenic environments (below -253°C), where advanced containment technologies are necessary to handle extreme conditions and prevent material degradation, such as hydrogen embrittlement [21,36]. Mitigating these risks requires robust safety measures, including highly sensitive leak detection systems, pressure relief valves, and stringent operational protocols designed to reduce the likelihood of accidents. In urban or industrial settings, these precautions are vital to protecting both people and infrastructure from potential hydrogen explosions or fires. Another significant obstacle is the lack of uniform regulatory standards for hydrogen storage. This absence of globally consistent guidelines complicates the widespread adoption of hydrogen technologies, creating inefficiencies in design, implementation, and safety compliance. Establishing standardized regulations is crucial to ensure safe practices, simplify integration, and enhance confidence in hydrogen as a viable energy solution [8,21,36].

Innovative materials and techniques are being developed to address these challenges. For instance, advanced composites and specialized alloys that resist hydrogen-induced material damage are being utilized for high-pressure tanks. Research into solid-state storage using metal hydrides or porous materials is offering safer alternatives by reducing the need for extreme pressures or temperatures. Different chemical carriers like ammonia borane and formic acid are gaining attention as they can store hydrogen in a more stable form. By focusing on these technological advancements and creating robust safety regulations, the limitations of current hydrogen storage systems can be effectively overcome, facilitating their role in the transition to a sustainable energy future [8,21].

5.2.3. Economic and infrastructure barriers

The expense associated with hydrogen storage technologies remains considerable, largely due to the demand for sophisticated materials, complex engineering solutions, and stringent safety protocols. This high cost poses a substantial barrier to widespread adoption, particularly for emerging storage approaches such as cryo-compressed storage and advanced material-based systems [8,21]. Hydrogen distribution infrastructure faces significant challenges, including the lack of dedicated pipelines, compatibility issues with existing natural gas networks, and an inadequate number of refueling stations [17]. Addressing these gaps requires targeted investments in retrofitting current pipelines for hydrogen transport, scaling up refueling station networks, and advancing alternative transport solutions like cryogenic tankers and chemical carriers. Developing large-scale storage facilities and enhancing regional integration with renewable energy sources are also essential. Besides, global harmonization of safety and regulatory standards will be critical for fostering secure and widespread adoption of hydrogen technologies.

5.3. Opportunities in hydrogen storage

5.3.1. Technological innovation and efficiency improvements

Continued advancements in materials science are driving the evolution of storage materials, promising enhanced capabilities for hydrogen storage systems. Innovations are focused on materials like MOFs, PIMs, and advanced metal hydrides [8]. Hydrogen's unique properties, such as its small molecular size and high diffusivity, pose challenges like material embrittlement, leakage, and degradation under

high-pressure or cryogenic conditions [68]. Innovative alloys, such as high-strength steels with enhanced resistance to hydrogen embrittlement, address these issues by minimizing structural failures [69]. Hydrogen-compatible coatings, including nickel-based alloys and surface treatments, provide protective barriers, reducing the risk of hydrogen permeation [70]. Polymers with advanced resistance to hydrogen permeability and degradation are critical for sealing and insulation in pipelines and storage tanks. For example, elastomers with tailored properties, such as nitrile rubber (NBR) and ethylene-propylene-diene monomer (EPDM), are being optimized for long-term durability in hydrogen environments [71]. Composite materials, integrating polymers with carbon fiber reinforcements, enable lightweight yet robust storage tanks capable of withstanding pressures above 700 bar, which are essential for transportation and fueling applications. Further, solid-state hydrogen storage materials, such as metal hydrides and porous frameworks, promise safer and more efficient alternatives by chemically binding hydrogen, eliminating the need for extreme pressures or cryogenic temperatures [70,72]. Such advancements not only improve storage efficiency but also enhance safety by mitigating risks of leakage and flammability.

These developments aim to increase storage capacity, improve efficiency, and enhance the reversibility of material-based hydrogen storage. There is substantial potential for refining existing storage methods. This includes optimizing cryo-compressed systems to lower energy consumption and enhance safety standards. Improvements in insulation technologies, pressure vessel designs, and cryogenic systems are crucial for achieving more efficient and economically viable storage solutions [8,36]. Together, these developments in material science underpin the reliability and scalability of hydrogen infrastructure, ensuring safer and more durable systems for future energy applications.

5.3.2. Integration with renewable energy systems

Hydrogen storage serves a crucial function in integrating renewable energy sources such as wind and solar into the energy grid. By storing surplus energy generated from renewables in the form of hydrogen, these systems effectively buffer grid fluctuations, bolstering the reliability and stability of renewable energy infrastructure. Hydrogen storage plays a key role in decentralized energy systems by enabling the localized storage and utilization of renewable energy. This decentralized approach minimizes transmission losses and enhances energy security in remote or off-grid areas, thereby promoting wider adoption of renewable energy technologies [36].

5.3.3. Economic incentives and policy support

Government initiatives worldwide are increasingly acknowledging the potential of hydrogen storage technologies, leading to substantial financial support, subsidies, and tax incentives aimed at accelerating their advancement [68]. These policies are crucial for reducing the costs associated with hydrogen storage and promoting infrastructure development, thereby fostering broader adoption of hydrogen technologies. Global collaborations and the establishment of standardized regulations, safety protocols, and technology benchmarks are pivotal for the widespread adoption of hydrogen storage solutions. International cooperation facilitates shared knowledge and coordinates efforts, which are essential for overcoming economic and technical challenges and driving the global expansion of the hydrogen economy [21,36].

5.3.4. Expanding market applications

The transportation sector is undergoing a significant transformation towards zero-emission solutions, placing hydrogen storage technologies at the forefront of innovation. This shift is particularly evident in the rapid growth of fuel cell vehicles, which depend on efficient hydrogen storage systems [73]. Supported by expanding infrastructure and decreasing costs, fuel cell vehicles are poised for substantial expansion. Hydrogen storage is gaining traction beyond transportation, finding diverse applications in industries and energy sectors worldwide. These

include critical areas such as backup power systems, grid energy storage, and industrial processes requiring high-purity hydrogen. The adaptability of hydrogen storage technologies is creating new market opportunities and expanding their utility across a wide range of sectors [21, 36].

In recent years, there has been a surge of interest in new and innovative solid materials for hydrogen storage, particularly those utilizing the chemisorption process. These materials have garnered attention for their superior hydrogen chemisorption properties, characterized by both safety and efficiency, as well as their ability to achieve high hydrogen densities at extremely low pressures. These materials represent promising avenues for advancing hydrogen storage technology and addressing key challenges in hydrogen utilization [36]. Currently, hydrogen fuel is stored as gas using various methods. For transportation, it's stored as compressed gas in special tanks made of steel with carbon covers or lightweight composites, typically at pressures over 300 bars. Hydrogen can be stored underground in salt caverns, rock caves, and depleted oil and gas fields. This method maintains hydrogen stability despite weather changes, making it ideal for large-scale storage [74]. As future hydrogen demand is expected to surpass the capacity of existing surface infrastructure like pipelines and tanks, underground storage will allow for off-peak production and secure storage, ensuring long-term energy security and supply stability [8,21,36].

6. Hydrogen transportation: challenges and opportunities

Hydrogen transportation from production sites to end-users utilizes several methods based on factors such as distance, quantity, and geographic territory. These methods are generally classified into road, pipeline, and sea transport [75]. For shorter distances within a region, compressed hydrogen in pressurized tanks transported by trucks is effective for smaller-scale needs [8]. Due to the low volumetric density of hydrogen gas, long-distance transport presents challenges. To address this, higher-density hydrogen carriers such as liquid hydrogen, liquid organic hydrogen carriers (LOHCs), and ammonia are used [8,76]. These solutions involve energy-intensive processes like cooling, pressurization, chemical conversion, and re-release. When it comes to large volumes of hydrogen over longer distances, sea transport becomes the most viable option.

Fig. 11 illustrates the various stages involved in hydrogen transportation, outlining the methods for both local and international deliveries. The process begins with Stage 1, where hydrogen is produced from various sources, including natural gas reforming, water electrolysis, or biomass gasification. Once produced, Stage 2 focuses on pre-treatment methods such as hydrogenation and liquefaction, which are necessary for efficient transportation over long distances. These processes help increase hydrogen density, making it easier to store and transport. Following pre-treatment, Stage 3 moves hydrogen into road transportation and storage. Cryogenic tank trailers carry the hydrogen across shorter distances, typically delivering it to storage facilities or final distribution hubs. This stage is repeated at various points in the transportation chain, depending on whether the hydrogen requires further movement within regional territories. Stage 4 involves the sea transportation of hydrogen via ships, a method primarily used for large-scale, long-distance, or intercontinental transport. Liquid hydrogen or hydrogen in other forms like ammonia or LOHCs is often transported across oceans in specialized ships, maintaining stable conditions to prevent evaporation or other losses. Upon arrival at a seaport, Stage 5 represents road transportation and storage again, as the hydrogen is prepared for its final delivery. This stage may involve further movement via trucks or trailers to reach local stations or facilities. Next, Stage 6 sees post-treatment processes, where the transported hydrogen undergoes dehydrogenation or autothermal reforming to revert it to a useable gaseous state. This is particularly important when hydrogen is transported in chemical forms like ammonia or LOHCs, requiring conversion back to its pure form. Finally, in Stage 7, hydrogen reaches its

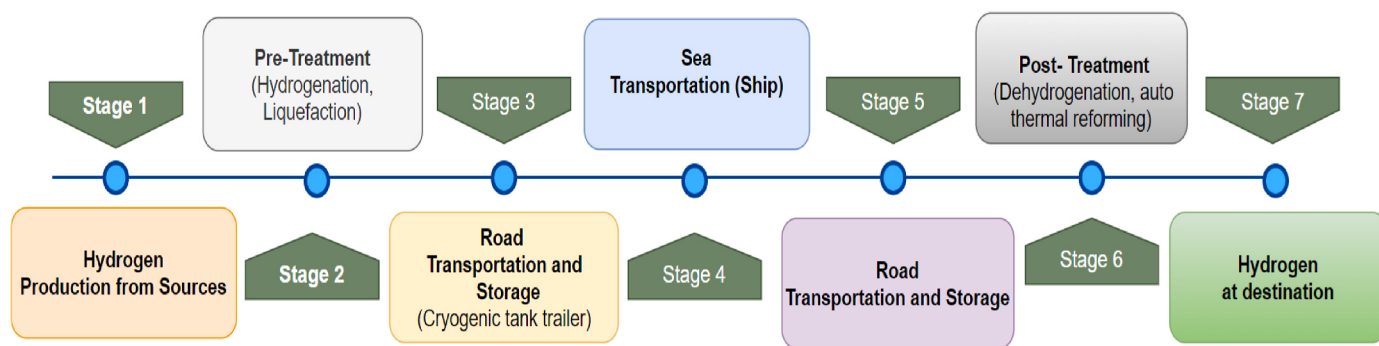


Fig. 11. Different stages of the hydrogen delivery pathways [8].

destination, whether for industrial use, power generation, or fueling stations. Each step in this transport chain highlights the complexities of hydrogen logistics, particularly in managing its density and ensuring efficient delivery across varied distances and geographic locations [5,8].

For long-term, intercontinental transportation, hydrogen is generally converted into liquid forms such as liquid hydrogen, ammonia, or LOHCs. Transporting liquid hydrogen poses significant challenges due to the need to manage boiling and evaporation as the temperature inside the container increases. Thus, ammonia and LOHCs, which offer better control and are more cost-efficient, have become the preferred options for long-distance hydrogen transport.

6.1. Liquid hydrogen and alternative carriers

Liquid hydrogen and ammonia provide effective solutions for addressing the geographic and volumetric challenges associated with hydrogen transport. Both liquid hydrogen and LOHCs require energy-intensive processes, including cooling, pressurization, and chemical conversion, to facilitate their transportation. Ammonia is advantageous due to its established manufacturing and distribution infrastructure. It boasts a high hydrogen density, making it more efficient for storage and transport. The process of releasing hydrogen from ammonia through catalytic decomposition is relatively straightforward, enhancing its practicality as a hydrogen carrier for long-distance transport [8].

6.2. Ammonia as a hydrogen carrier

Ammonia, which is produced industrially through the well-established Haber-Bosch process, serves as an efficient medium for hydrogen storage, particularly due to its lack of CO₂ emissions at the point of use [8]. With a higher energy density than both liquefied and compressed hydrogen, ammonia becomes a viable option for long-distance hydrogen transport, especially at relatively low pressures [48]. This reduces the logistical challenges associated with hydrogen's low volumetric density. Despite its advantages, ammonia transport and usage come with certain challenges, including its inherent toxicity, which requires careful handling and safety measures. Residual traces of ammonia can remain in the hydrogen after decomposition, posing potential purity and contamination issues that must be addressed for effective use in hydrogen applications [8,77].

6.3. Liquid-organic hydrogen carriers (LOHCs)

LOHCs offer a promising method for hydrogen transport by utilizing unsaturated liquid organics such as naphthalene and toluene. These carriers enable hydrogen to be stored and transported through reversible chemical reactions: hydrogenation, where hydrogen is chemically bonded to the carrier, and dehydrogenation, where hydrogen is released at the point of use [78]. This process allows for safe and efficient storage and transportation of hydrogen under ambient conditions, making

LOHCs particularly advantageous for long-distance and large-scale hydrogen logistics. LOHCs offer sustainability benefits, as the carrier liquids can be recycled and reused multiple times after hydrogen release, contributing to lower overall emissions. Their ability to integrate with existing infrastructure and provide a safe, high-density storage solution makes them suitable for a wide range of fixed and mobile applications across the globe, from industrial use to transportation sectors [79]. Despite the energy required for hydrogenation and dehydrogenation processes, LOHCs remain a highly versatile and scalable option for hydrogen transport [8].

6.4. Chemical hydrides as hydrogen carriers

Chemical hydrides are solid or liquid compounds capable of storing hydrogen by chemically bonding it within their molecular structures. Unlike reversible methods like LOHCs, chemical hydrides release hydrogen through irreversible chemical reactions, often involving hydrolysis or thermal decomposition [68]. Examples include ammonia borane (NH₃BH₃), sodium borohydride (NaBH₄), and hydrazine (N₂H₄). These materials offer high hydrogen storage densities and operate under mild to moderate conditions, making them suitable for compact and portable hydrogen storage systems [68,80]. Chemical hydrides enable efficient hydrogen release for end-use applications, but they face challenges such as the need for catalysts, recycling of byproducts, and high production costs [81]. For instance, NH₃BH₃ offers a high hydrogen content (~19.6 wt%) but requires high temperatures for release, while NaBH₄ releases hydrogen through hydrolysis but requires efficient recycling of sodium metaborate [82]. Hydrazine, a liquid chemical hydride, provides carbon-free byproducts but poses toxicity and safety concerns. While chemical hydrides are not designed for repeated hydrogenation cycles like LOHCs, they represent a promising hydrogen carrier solution for applications requiring lightweight and high-capacity storage, particularly in portable or emergency energy systems [68,81]. Further research is ongoing to address challenges in cost, byproduct management, and operational safety.

Hydrogen transport faces significant challenges due to its low volumetric density, which necessitates the use of higher-density alternatives like liquid hydrogen, ammonia, and LOHCs for long-distance transportation [8,77]. Although these methods require substantial energy input, they offer viable solutions for meeting the needs of global transport. Ammonia, with its high hydrogen density and existing infrastructure, shows promise but must overcome concerns related to toxicity and residual impurities. LOHCs provide flexibility and environmental benefits, though improvements in safety measures and regulatory frameworks are needed. As hydrogen transportation expands across continents, significant progress is anticipated in both storage and transport technologies for gaseous and liquid hydrogen. The next few decades will likely witness critical innovations that improve efficiency and safety, supporting the transition towards a more sustainable energy landscape.

7. Future directions for hydrogen in achieving environmental sustainability

Hydrogen stands out as a key energy solution for achieving global sustainability, offering transformative potential across production, storage, and transportation. The success of hydrogen adoption centers on addressing several technical and economic challenges, as outlined in Table 7, which highlights major hurdles, potential solutions, and forward-looking strategies for hydrogen development. Efforts to enhance hydrogen production must prioritize the scalability of green hydrogen technologies, including electrolysis powered by renewable energy and innovative methods such as photoelectrochemical cells. Simultaneously, the development of high-capacity, lightweight storage materials and optimization of storage systems for various applications are essential to ensure efficient and safe hydrogen use. Transportation systems also require significant investment, focusing on advanced hydrogen carriers, cryogenic technologies, and standardized refueling infrastructure to support widespread adoption.

To achieve these objectives, strong policy and regulatory support is critical. Governments must implement comprehensive hydrogen strategies, promote innovation through incentives, harmonize global standards, and establish carbon pricing mechanisms to enhance competitiveness. Public-private partnerships and international collaboration are equally essential, combining resources and expertise to overcome technical barriers. Educational initiatives, knowledge-sharing programs, and awareness campaigns will play pivotal roles in building a skilled workforce and fostering public understanding of hydrogen's potential.

As detailed in Table 7, addressing these challenges through coordinated efforts and leveraging innovative solutions will pave the way for hydrogen to drive the transition to a low-carbon energy future, ensuring its role as a cornerstone of sustainable energy systems.

8. Conclusion

Hydrogen stands out as a transformative energy carrier with exceptional promise due to its high energy density, clean combustion properties, and versatility in applications such as fuel cells and industrial processes. This paper highlights the potential of hydrogen to replace conventional fuels, mitigate greenhouse gas emissions, and drive the transition toward a sustainable energy future. While hydrogen's promise is undeniable, significant challenges remain in its production, storage, and transportation. Current methods like steam methane reforming (SMR) are cost-effective but carbon-intensive, while renewable-powered electrolysis offers sustainability at the expense of efficiency and economic viability. Similarly, storage technologies must overcome hurdles such as high energy requirements, scalability issues, and safety concerns. Transportation infrastructure further compounds these challenges, necessitating extensive innovation and investment.

To address these challenges, future research should focus on improving electrolysis efficiency, developing low-carbon production methods, advancing materials for storage, and creating cost-effective infrastructure. Additionally, policy incentives and global safety standards will be critical to driving adoption. By integrating hydrogen into energy systems, particularly in sectors like transportation and renewable energy balancing, hydrogen can play a pivotal role in the transition to a sustainable, low-carbon future. With sustained innovation, investment, and policy support, hydrogen has the potential to become a cornerstone of the global energy economy, overcoming current limitations and contributing significantly to addressing the world's energy and environmental challenges.

CRedit authorship contribution statement

Md Monjur Hossain Bhuiyan: Formal analysis, Investigation, Resources, Methodology, Writing - original draft, Formal analysis, Formal

Table 7
Challenges, solutions, and future prospects for hydrogen technology development [3,21,83].

Challenge Area	Description	Potential Solutions	Future Prospects
Infrastructure gaps	Limited availability of pipelines, refueling stations, and transportation vessels obstructs hydrogen production, storage, and distribution.	Adopt public-private partnerships for investment, establish standardized regulations, and promote global collaboration for infrastructure planning.	Development of a robust and interconnected global hydrogen infrastructure to meet future energy demands and support widespread adoption.
High costs	Hydrogen production, storage, and distribution remain costly due to advanced technology and infrastructure requirements.	Control economies of scale, adopt advanced technologies to boost efficiency, and implement supportive policies and financial incentives.	Reduction in overall costs, making hydrogen solutions economically viable and competitive in energy markets.
Production efficiency	Current production methods often rely on fossil fuels, limiting sustainability and scalability.	Scale up electrolysis using renewable energy sources, develop advanced catalysts, and explore innovative methods.	Expansion of green hydrogen production, reducing reliance on fossil fuels and contributing to decarbonization efforts.
Transportation challenges	Safe and efficient transportation faces barriers due to limitations in existing storage methods and transport containers.	Invest in advanced materials for lightweight containers, improve cryogenic hydrogen transport, and develop carrier technologies.	Enhanced safety, efficiency, and scalability in hydrogen transportation, paving the way for broader energy applications.
Storage limitations	Storage requires advanced materials to address issues of energy density, safety, and environmental conditions.	Develop advanced lightweight storage systems and optimize solid-state methods for diverse applications.	Efficient storage solutions for various industrial, commercial, and energy sectors, with improved energy density and safety standards.
Lack of collaboration	Fragmented research efforts delay innovation and slow progress in hydrogen-related technologies.	Encourage joint research and development initiatives across industries and countries to share knowledge.	Rapid advancements in hydrogen production, storage, and transportation technologies.
Pilot testing needs	Technologies require real-world validation to assess feasibility and scalability for widespread deployment.	Implement large-scale pilot projects and demonstration programs to refine technologies and address operational challenges.	Proven feasibility and readiness of hydrogen technologies for commercial and industrial deployment.
Market development barriers	Limited market adoption due to high costs, insufficient awareness, and lack of consumer	Encourage innovative business models, support start-ups with incentives, and launch public	Increased market competitiveness and consumer confidence, leading to a thriving

(continued on next page)

Table 7 (continued)

Challenge Area	Description	Potential Solutions	Future Prospects
	trust in hydrogen solutions.	campaigns to promote hydrogen benefits.	hydrogen economy.
Standardization issues	Lack of global standards impacts the reliability and safety of hydrogen technologies.	Establish internationally recognized standards and certification schemes to ensure uniformity and reliability across the hydrogen value chain.	Harmonized global standards facilitating safer and more reliable hydrogen deployment across industries.
Workforce and knowledge	Limited technical expertise and skilled workforce pose a challenge to the growth of the hydrogen sector.	Share best practices, conduct training programs, and build capacity through international collaborations and partnerships.	Development of a skilled global workforce equipped to handle advanced hydrogen technologies and drive innovation.
Environmental alignment	Hydrogen technologies must align with climate and energy goals to drive sustainability.	Integrate hydrogen strategies with broader climate initiatives and adopt low-carbon production techniques.	Accelerate the transition to a sustainable energy future, with hydrogen reducing greenhouse gas emissions and fossil fuel dependence.

analysis, Investigation, Methodology, Resources, Writing – original draft. **Zahed Siddique:** Conceptualization, Writing – review & editing.

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