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Review article

Advancements and challenges in green hydrogen production, storage, transportation, and utilization for climate-resilient energy systems

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ABSTRACT

Consuming large quantities of harmful fossil fuels is leading to significant disturbances in the ecosystem's health, increasing global Greenhouse Gas (GHG) emissions per capita of approximately 8.3% between 1990 and 2022. Increasing temperatures, frequent natural disasters, and rising sea levels are among the consequences of climate change that threaten Earth's sustainability. In this context, green hydrogen has been proven to be a sustainable, clean, and environmentally friendly solution to such challenges. Hydrogen can play a vital role in the storage, transportation, or provision of alternative energy. However, it contributes only 2% of global hydrogen production, whereas fossil fuels account for over 96%. This paper highlights the potential and crucial need to integrate green hydrogen into the current and future energy infrastructure, ensuring a smooth transition towards climate-resilient and environmentally safe systems. It also analyzes the components of a hydrogen-based economy and infrastructure, including green hydrogen production, storage, transportation, and utilization. Solar-powered systems, biomass gasification, wind or hybrid systems, and geothermal methods are examined and shown to improve production efficiency by 64% and reduce GHG emissions by 94%. Green hydrogen production methods, including the work presented, aim to identify the key advantages, challenges, limitations, and opportunities that hydrogen can bring to the global economy, as well as the potential of green hydrogen to provide a clean earth for future generations. This review highlights recent advancements in green hydrogen production and utilization technologies and identifies gaps that require attention from research, industry, society, and government. The work presented in this review is based on an analysis of over 140 scholarly publications spanning 2010 to 2025, highlighting current developments in the adoption of the hydrogen economy.

1. Introduction

Global energy demand has been rising in line with the growing human population. The global population is expected to range from 6.9 to 12.6 billion by 2100, peaking in 2070 [1]. The rapid population growth, driven by the critical need for energy, is also degrading ecosystem resilience because harmful energy sources are used to meet the ever-increasing demand. Over the past few decades, the world has witnessed rapid development in various anthropogenic activities, including industrial processes, the food and agriculture industry, waste management, land use and urbanization, energy production, the development of electronic devices, and transportation. Although advancing in these diverse areas is opening doors to a higher quality of life, meeting this demand has increased dependence on fossil fuels as the primary energy source. Anthropogenic activities have a significant impact on the environment, as they are the leading cause of increasing Greenhouse Gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The accumulation of these harmful gases in the Earth's atmosphere is directly driving climate change impacts, including rising global temperatures, frequent natural disasters, rising sea levels, unbalanced annual rainfall, water shortages, reduced crop productivity, and threats to biodiversity. Global GHG emissions per capita have increased by 8.3% between 1990 and 2022, indicating a significant and continuous impact of human activities on the atmosphere over this period of

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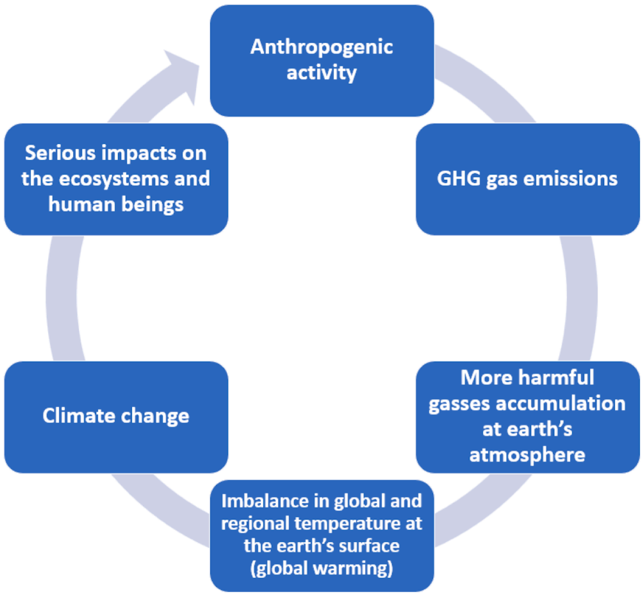

Fig. 1. Cycle showing how anthropogenic activity increases climate change impacts. The cycle begins with anthropogenic activities and culminates in ecosystems being severely impacted as GHG emissions accumulate in Earth's atmosphere. Continuing to neglect the harm that such activities cause threatens humanity's well-being and Earth's sustainability.

Fig. 2. Current challenges limiting the full utilization of RES.

mortality [2]. On the other hand, it has been proven that climate change affects human health physically and psychologically. Climate change can be a leading factor in mental health issues, including stress, anxiety, or depression [3]. In addition, air pollution, frequent heatwaves, and excessive heat conditions increase the period, acute morbidity, and respiratory diseases, such as asthma, among individuals [4]. A cycle of elevated GHG emissions leading to more substantial climate change impacts will continue until governments and societies undertake substantive measures and well-planned strategies to alleviate climate change. Fig. 1 illustrates the cycle associating anthropogenic activities with increased climate change impacts on the ecosystem.

Furthermore, the distribution of fossil fuels is uneven, posing challenges related to geopolitical tensions and energy security concerns [5]. Adapting energy systems to Renewable Energy Sources (RES) is a solution to the current challenges posed by an expanding population and climate change, including increased energy demand, environmental changes, energy security concerns, and geopolitical challenges. This has led governments to shift their focus to investing in clean and renewable energy sources, aiming to reduce fossil fuel consumption due to their environmental benefits, including reductions in harmful emissions. Renewable energy sources, such as solar, wind, geothermal, biomass, and hydropower, have been widely utilized as alternative, safe, and environmentally friendly energy resources. Although these resources are valuable and have shown an impact on reducing GHG emissions and decarbonizing global energy consumption, many challenges limit the reliance on RES to achieve a sustainable future. Fig. 2 summarizes key factors that limit the full utilization of RES.

In this context, the hydrogen economy has emerged as an alternative concept aimed at significantly reducing dependence on fossil fuels and decarbonizing current energy use. By utilizing hydrogen as the primary energy carrier, the transition to sustainable, clean energy systems is guaranteed to be fully realized. Hydrogen, as an alternative fuel and energy carrier, has significant potential to support the development of the energy sector. It can be integrated to overcome challenges associated with the current and expanding renewable energy infrastructure. Furthermore, it can be used as a clean fuel on a broader scale to meet the continuously growing energy demand.

Compared with other conventional hydrocarbon fuels, hydrogen is characterized by its high gravimetric energy density of *120–142 MJ/kg*. This property makes hydrogen a competitive and attractive element for use in the energy and fuel industry. However, the low volumetric energy density nature of hydrogen that reaches about *0.01 MJ / L under standard conditions* emphasizes the essential need for proper, innovative, and practical hydrogen storage technologies in its different forms that lead to serious advances in the deployment of fully integrated hydrogen energy networks [6].

Although many studies and reviews in the literature present current hydrogen technologies, most focus on specific aspects of these technologies. These may include studies examining one or more of the pillars of a well-established hydrogen economy, such as production, storage, and transportation. In addition, many existing reviews analyze older hydrogen systems or do not emphasize the recent advancements between 2020 and 2025. In particular, in areas such as solar-driven electrolysis, underground hydrogen storage, hybrid systems, and new regulations and policies. Most importantly, the current literature lacks practical, actionable steps for implementing a fully integrated green hydrogen infrastructure across all pillars of a hydrogen-based economy. Most of the literature presented focuses its efforts on current technologies. However, there is a crucial need to discuss and develop solutions for governments, societies, and industries to adopt a fully hydrogen-based economy. This review aims to bridge these gaps by providing a structured perspective on how hydrogen can be integrated into current and future energy systems, and outlining the key requirements, challenges, and responsibilities associated with each component of a fully deployed hydrogen economy.

The objective of this paper is to report and evaluate the recent advancements in green hydrogen production, storage, transportation, and utilization. The presented work critically examines how these developments align with the practical requirements of an effective hydrogen economy. The guiding hypothesis of this review is that the successful transition to large-scale, climate-resilient hydrogen systems depends not only on technological progress but also on the coordinated readiness of infrastructure, societal and industrial adoption, and policy frameworks. By evaluating the current literature within this framework, the review aims to determine whether existing hydrogen technologies and strategies are adequately positioned to support a realistic and sustainable transition.

This review contributes a comprehensive, up-to-date, and critical analysis of more than 140 scholarly publications spanning 2010–2025, with a strong emphasis on studies published from 2020 onward across the key pillars of a sustainable hydrogen infrastructure. It includes a structured analysis and recommendations on the most recent advancements in hydrogen-based systems.

2. Methodology

This comprehensive review follows the PRISMA framework to provide a systematic and fair analysis of recent advancements in green hydrogen technologies.

The objectives of the presented review paper are to provide a critical and reliable analysis and evaluation of recent technologies that enable larger-scale, climate-resilient hydrogen systems. It aims to give governments, researchers, and investors a comprehensive review of a highly advanced hydrogen-supportive infrastructure capable of using hydrogen as the primary energy carrier or fuel. The selected studies were examined using qualitative content analysis, in which production technologies, storage systems, transportation mechanisms, and utilization strategies were systematically analyzed, compared, and compiled to identify trends, challenges, and gaps across the hydrogen-based infrastructure elements.

The structured literature review is established by accessing the most recent papers published in the ScienceDirect database. Keywords used in the research, including “green hydrogen”, “hydrogen systems”, “hydrogen storage”, “green hydrogen production”, “electrolysis”, “hydrogen transportation”, and “hydrogen utilization”, were used to identify related work. The eligibility criteria were based on selecting peer-reviewed scholarly publications from 2010 to 2025 that featured renewable energy sources as the primary technology for hydrogen production and reported technical metrics, including efficiency, cost, and emissions. Duplicate records were removed, and only peer-reviewed journal articles, reviews, and technical reports were considered. Studies unrelated to renewable-based hydrogen systems or lacking quantitative or technical relevance were excluded. These inclusion criteria ensured that only high-quality and directly relevant publications were retained for analysis. The work featured in this review was selected to provide a diverse background and insights from either a geographic perspective or a technical background.

The climate-resilient hydrogen systems. It aims to provide governments, researchers, and investors with a comprehensive review of highly advanced hydrogen-supportive infrastructure capable of using hydrogen as the primary energy carrier or fuel. The selected studies were examined using qualitative content analysis, in which production technologies, storage systems, transportation mechanisms, and utilization strategies were systematically analyzed, compared, and compiled to identify trends, challenges, and knowledge gaps across the hydrogen-based infrastructure elements.

This work comprises more than 140 publications, which aligns with the typical range reported in comprehensive hydrogen technology reviews published in the last five years. Similar reviews analyzing green hydrogen systems, electrolysis advancements, or hydrogen economy transitions generally include 80–150 sources. Therefore, the sample size used in this review is appropriate for capturing the breadth of technological developments while maintaining analytical depth.

Relevant work was investigated and analyzed by clustering papers into four main domains. These include hydrogen production (from RES), storage, transportation, and utilization. Several statistical and quantitative metrics were extracted from the selected papers for comparison purposes. These include efficiency, emissions, and cost per Kg H_2. The key findings and takeaways are analysed and presented in figures, summaries, or comparison tables.

In this way, we ensure a fair, comprehensive, and up-to-date review of hydrogen’s potential for a sustainable future in climate-resilient energy systems.

Hydrogen Color	Hydrogen Production Source
Green	Electrolysis process powered by RES
Turquoise	Natural gas and RES
Yellow	Electrolysis powered by solar energy
Aqua	Oil fields
White	Natural geological hydrogen found underground
Pink/Purple	Electrolysis power by nuclear energy
Blue	Fossil fuels with carbon capturing
Brown	Lignite gasification
Black/Grey	Fossil fuels including hard coal

Fig. 3. The different hydrogen colors and the corresponding production source.

3. Hydrogen as an alternative fuel and energy carrier

Relying on hydrogen as an alternative fuel and energy carrier is demonstrated to be a practical and beneficial option. Hydrogen is characterized by many properties that allow its convenient integration into the energy system. It can be easily produced from renewable or non-renewable energy sources. In the literature, it is classified into multiple colors based on the production source, as shown in Fig. 3.

Grey or black hydrogen, produced from non-renewable energy sources such as hydrocarbons and fossil fuels, has a significant negative environmental impact and increases GHG emissions, thereby reducing the value and potential of hydrogen as a fuel. Furthermore, producing black or grey hydrogen is costly, energy-intensive, and environmentally damaging. Therefore, there is a pressing need to invest in reliable, efficient, clean, and cost-effective solutions for producing and utilizing hydrogen. This is achieved by producing green hydrogen from renewable energy sources, like solar, wind, geothermal, hydropower, and biomass. Unlike grey hydrogen, green hydrogen is environmentally friendly and does not produce toxic emissions that harm the climate. Green hydrogen is a promising solution in the hydrogen economy and sustainable energy transition. Today, only 2% of global hydrogen production is green, a small percentage compared to grey or black hydrogen, which accounts for 96% of global hydrogen production [7,8]. Industrial-scale Steam Methane Reforming (SMR) systems, such as those implemented in petrochemical facilities, typically operate with a hydrogen purity of 75% and an exergy efficiency of around 21%, highlighting the need for renewable alternatives [9]. Hydrogen utilization is a crucial factor in making hydrogen a vital component of a sustainable future and of the decarbonization of energy use.

Hydrogen and hydrogen-based systems play a significant role in ensuring a clean and safe planet for future generations, provided they are used wisely and across a broader range of sectors and applications. Hydrogen can be integrated into various sectors as a fuel, energy carrier, energy source, and feedstock. Fig. 4 illustrates the role of hydrogen and examples of its applications.

Large quantities of hydrogen can be produced through electrolysis using RES, where it can be stored in various forms depending on the application and available space. Several recent reviews emphasize that green hydrogen, produced through renewable-powered electrolysis, is emerging as a cornerstone of global decarbonization strategies, with increasing attention to challenges related to production efficiency, infrastructure scalability, and cost reduction [10]. When hydrogen is integrated with RES, the excess power generated can be readily used to produce additional hydrogen or to support future energy generation. In addition, conventional methods, such as road, rail, or ship transport, can readily transport hydrogen. The current pipeline infrastructure can support long-distance hydrogen transport and is more efficient than electricity transport. Hydrogen production and utilization technologies are

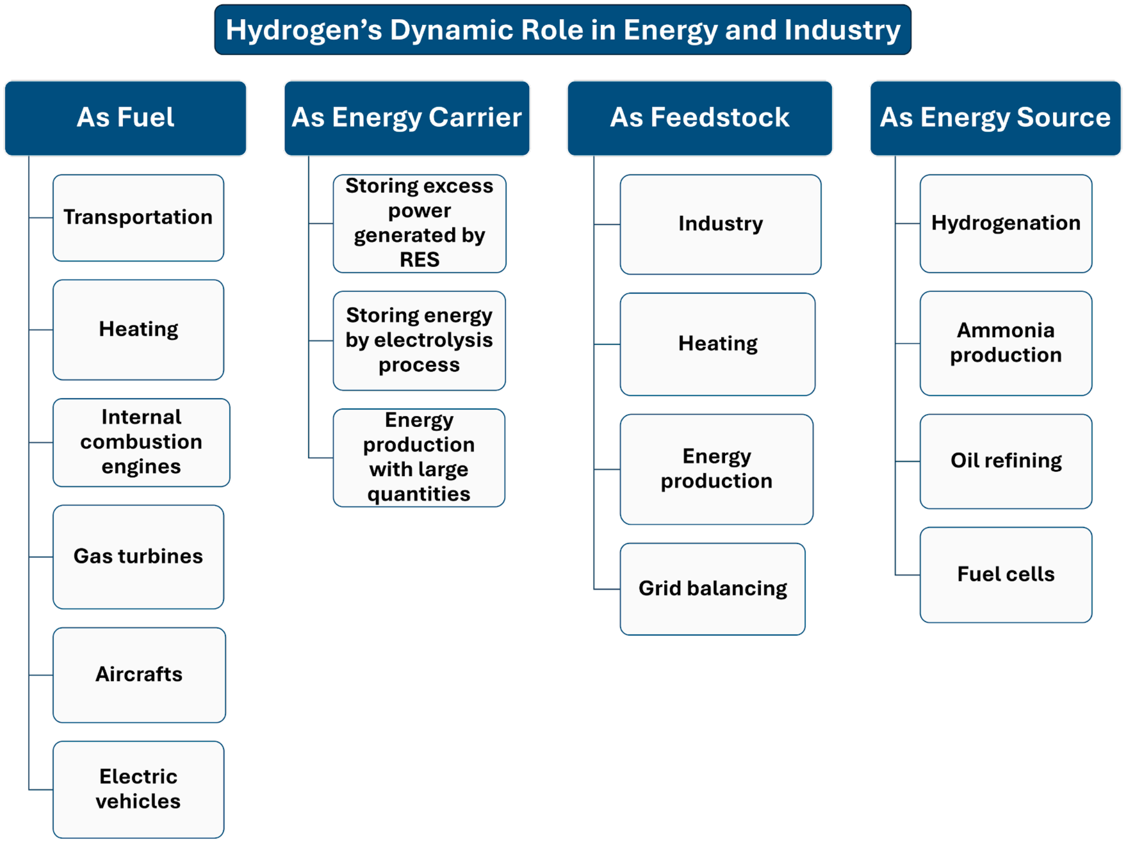

Fig. 4. The role of hydrogen across the versatile Energy and Industry applications.

shown to be clean and environmentally safe. In hydrogen production, water is the primary source of hydrogen via electrolysis. Using electricity to break water, hydrogen and oxygen are formed as shown by the reaction:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

Utilizing renewable energy sources (RES) to generate electricity for the hydrogen production process is a promising step toward a greener, cleaner, and more sustainable energy system. On the other hand, hydrogen can be utilized in many ways across the energy and industrial sectors as a clean energy source. For example, hydrogen is widely used in fuel cells inside electric cars to generate electricity, or it is burned and used directly as fuel in combustion engines, turbines, or boilers, as illustrated by the reaction:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) + \text{energy}$$

Both methods produce water as a byproduct, with no further harmful emissions, making hydrogen a clean and green energy carrier with great potential to transform the future of the energy and industrial sectors.

The objectives of this paper are: (i) review and discuss the critical elements of a prosperous hydrogen economy and hydrogen systems (ii) review the current challenges and advantages of the different aspects of a hydrogen-supporting infrastructure (iii) discuss the needs and requirements by governments, societies, and individuals to ensure a smooth transition toward climate-resilient hydrogen systems (iv) illustrates the potential and importance of investing in a green hydrogen economy for a sustainable planet. This review paper aims to identify and analyze the various current and future aspects and critical components of green hydrogen systems, spanning from production to utilization across different sectors.

4. Green hydrogen production

Hydrogen is a vital fuel alternative. This means that it is not a primary energy source, unlike other fuels such as coal, gas, or oil. As hydrogen acts as a secondary "energy carrier," it resembles the function of electricity as a primary energy source [1]. Hydrogen is widely available in nature and ranks as the third most abundant element on the Earth's surface; however, hydrogen forms chemical compounds with other elements in nature. Therefore, external processes that require energy, heat, or electricity are needed to produce pure hydrogen for various applications. Different sources, including both renewable and non-renewable options, can be used to produce hydrogen. The significant advantage of adopting a renewable-energy hydrogen production infrastructure is the provision of a clean, sustainable, cost-effective, reliable, and environmentally friendly energy source. Renewable sources, including solar, wind, biomass, and geothermal energy, are widely utilized to produce hydrogen. On the other hand, non-renewable energy sources rely heavily on hydrocarbons to produce hydrogen, contributing to climate change because, at larger scales, harmful gases such as carbon dioxide and methane are still emitted during the process. To produce hydrogen at a larger scale, there is a need to rely on renewable, efficient, sustainable, clean, and cost-effective sources. This will eliminate dependence on fossil fuels as an energy source, enable a decisive transition towards a sustainable energy landscape, significantly reduce greenhouse gas emissions, and replace the current power economy based on fossil fuels [11]. Additionally, hydrogen can revolutionize the renewable energy sector by providing more flexibility to renewable energy systems as an energy carrier or storage medium [12]. This section discusses green hydrogen production methods according to the green source used, highlighting their potential, challenges, and current advancements.

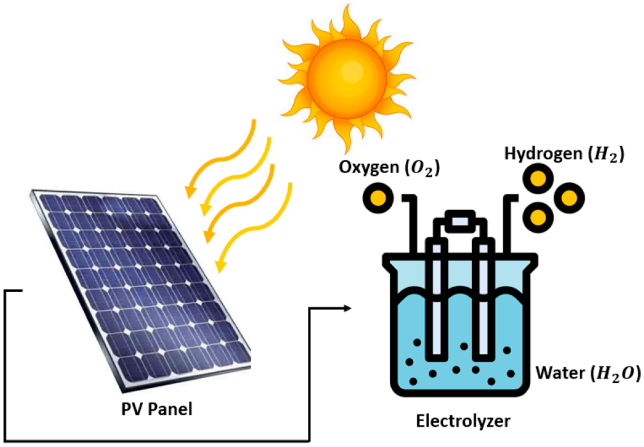

Fig. 5. Hydrogen production through a solar-powered electrolyzer schematic diagram.

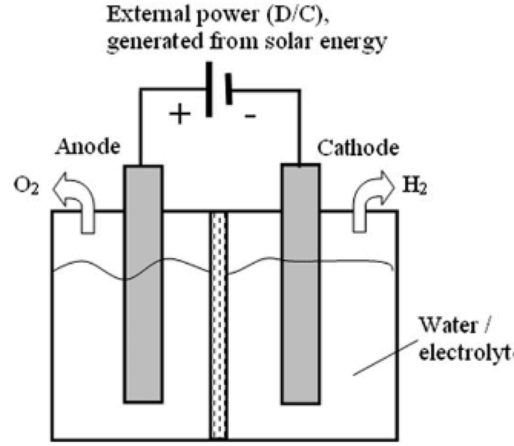

Fig. 6. A solar-powered electrolyzer based on [14].

4.1. Hydrogen from solar energy

Solar energy is an abundant renewable energy source with significant potential for sustainable hydrogen production in both the current and future hydrogen-based economies. Solar-based hydrogen production systems have gained considerable attention in both the governmental and industrial sectors due to their efficiency, reliability, and scalability, as evidenced by studies from 2020 to 2025. The wise utilization of this resource can significantly advance the vision of a clean, environmentally friendly global energy market. A techno-economic analysis of grid-independent Photovoltaic (PV)-electrolysis systems across six cities demonstrated annual hydrogen outputs of 16.8–21.1 t and Levelized Cost of Hydrogen (LCOH) between $6.43 and $8.81/kg, showing the strong influence of solar potential and site selection on system feasibility [13]. Hydrogen can be produced from solar energy utilizing various methods and technologies. They are generally categorized into solar-powered electrolyzers, Photoelectrochemical (PEC) water-splitting cells, thermochemical water-splitting cells, and hybrid solar systems [14]. The primary mechanism for hydrogen production from solar photovoltaics is the use of solar-powered electrolyzers. Recent studies have explored sustainable hydrogen generation routes such as metal–water reactions and transition metal nitride–based electrocatalysis, which offer cost-effective and environmentally friendly alternatives for green hydrogen production [15]. A solar-powered electrolyzer produces green hydrogen from the Solar Photovoltaic Electrolysis (SPVE) process. The electricity produced by the connected solar panels, which serve as an input to power the electrolyzers, is used to split water into hydrogen and oxygen. Fig. 5 shows a schematic of a hydrogen production system using a solar-powered electrolyzer. Electrolyzers are typically of Proton Exchange Membrane (PEM) or Alkaline types [16]. This method is considered clean, efficient, and renewable because it directly uses solar radiation to produce hydrogen, which can be captured, stored, and used as fuel.

As the output of this process is two non-toxic, environmentally friendly gases, solar-powered electrolyzers have great potential for current and future hydrogen production from solar energy.

A significant advantage of this method is its flexibility for integration with existing renewable energy infrastructure, as excess energy from solar-powered systems can be readily used for hydrogen production or stored for later use. Recent advancements in water electrolysis technologies have significantly improved system efficiency and reduced material costs, as reported by recent studies [17–20]. However, the lower efficiency and high capital costs of solar-based renewable systems are limiting their commercial implementation for hydrogen production. Fig. 6 illustrates the basic working principle of a solar photovoltaic electrolyzer for hydrogen production via electrolysis. An example of solar power electrolyzers that utilize solar power as a renewable energy source for hydrogen production is the Concentrated Solar Power (CSP) system. These systems were first developed in the 19th century and have recently received considerable research attention due to their potential for large-scale renewable energy generation and their ability to provide thermal energy storage [21]. Their high energy efficiency is a characteristic of CSPs. They are known to be the most reliable and energy-efficient method for hydrogen production because they operate at high temperatures [22]. The CSP systems work by harnessing solar radiation to generate electricity. A CSP system incorporates mirrors or lenses to concentrate solar radiation in a receiver, where it is converted into heat.

Steam is then formed using the heat generated in the later stage, driving a turbine to produce electricity. There are various configurations of CSP systems, each with different applications and hydrogen-production efficiencies. Solar radiation is concentrated and treated differently depending on the system configuration. The various mirror shapes, orientations, or receiver locations result in different systems, including parabolic troughs, central receiver towers, linear Fresnel reflectors, and parabolic dishes.

Hydrogen is produced from CSP systems by utilizing the high-temperature heat generated when concentrating solar radiation in a thermochemical water-splitting process. High-temperature heat is used to dissociate water into hydrogen and oxygen. Two approaches can be used for hydrogen production via CSP. One uses metal oxide materials, such as cerium oxide or iron oxide, that undergo redox reactions in the solar thermochemical water-splitting process. At high temperatures, this reaction produces hydrogen and oxygen. The other method uses the CSP systems to drive a thermochemical cycle that produces hydrogen as a by-product [21].

Photoelectrochemical (PEC) Water Splitting is another method that uses direct sunlight to split water into hydrogen and oxygen. This technology is based on water splitting, converting solar energy into chemical energy using semiconductor materials. This system comprises a photoelectrochemical cell consisting of a photoanode and a cathode, both immersed in an electrolyte solution. This unit operates when the photoanode absorbs direct sunlight, generating electron-hole pairs that initiate the water-splitting reaction. Then, the excited electrons travel to the cathode through an external circuit. Then, the excited electrons are transferred to the cathode through an external circuit, while the holes oxidize water molecules to produce oxygen gas. Then, protons and electrons recombine to form hydrogen gas, which is collected and used as an energy source. As with the SPVE method, the PEC can be integrated with the current solar energy systems infrastructure to produce hydrogen as a clean fuel. As with the SPVE method, the PEC can be integrated with the current solar energy systems infrastructure to produce hydrogen as a clean fuel using semiconductor materials. A hybrid solar-biomass system presented in [23] incorporated an Organic Rankine Cycle, refrigeration, and a PEM electrolyzer and achieved 0.756 Kg/h of hydrogen, with energy and exergy efficiencies of 32.73% and 14.18%, respectively. Notably, the system had CO_2 emissions of 0.0029 Kg/s. Another hybrid hydrogen production system, based on solar and biomass, used corn stalks and hydrothermal gasification, yielding over 0.0197 kg/s of hydrogen. This system achieved system-wide energy and exergy efficiencies of 57.5% and 38.3%, respectively [24].

Although the efficiency and stability of these photoelectrode-based systems for hydrogen production [14]. Decavoli et al. investigated the role of the dye-sensitized photocatalytic and photoelectrochemical hydrogen production cells in [25]. It is shown that organic dye degradation in PEC cells typically exhibits lower stability, and different dyes pose performance trade-offs when using this method. In addition, the new generation of organic dyes must be carefully designed to enhance the stability, efficiency, and intermolecular interactions of PEC-based systems.

In the thermochemical water-splitting method, hydrogen is produced at high temperatures using heat. For example, the heat source could be generated using the CSP method, as illustrated earlier. This method is mainly used in large-scale hydrogen production applications. As this process is completed at high temperatures, it reduces energy loss and increases the system's overall efficiency. On the other hand, this system requires careful selection of metal oxide materials and critical decision-making on the heat transfer mechanism to optimize its performance [26].

Hybrid systems can also be used for hydrogen production. Hydrogen production through hybrid systems is widely available and used. In hybrid green hydrogen production systems, one or hydrogen production methods are combined to form multiple energy sources or technologies to produce hydrogen. The main aim is to optimize the energy use and overall system efficiency. In addition, combining these technologies enables the overcoming of operational limitations of individual technologies, reduces costs, increases reliability, and enhances stability. In the case of green hydrogen, hybrid systems integrate one or more renewable energy sources, such as solar, wind, or biomass, to produce hydrogen from renewable sources. The work presented in [27] proposed a hybrid system for hydrogen production that integrates biomass, photoelectrochemical, and hydrogenase catalytic technologies. The proposed hybrid system continuously produced hydrogen for 96 hours, even under natural aerobic conditions. Another example of a hybrid system is the novel cascaded system, which integrates the Kalina and Organic Rankine thermodynamic cycles with a solid electrolyzer, as proposed in [28]. The hybrid system produces green hydrogen and provides sustainable cooling using a solar-biogas hybrid heat source. Similar efficiency improvements were also observed in Organic Rankine Cycle (ORC)-based hydrogen systems utilizing cryogenic energy recovery from Liquified Natural Gas (LNG) streams [29]. The system involved a solid oxide electrolyzer for hydrogen production through electrolysis. Other technologies, including wind, can be integrated with solar to produce hydrogen. Solar-wind hybrid systems are widely used and have gained considerable popularity in recent research due to their availability, ease of integration, improved system efficiency, and energy-storage capabilities. These hybrid systems use the excess electrical energy from wind turbines and solar photovoltaic panels to produce hydrogen via water electrolysis. The primary advantage of this system is its ability to store excess energy as hydrogen for peak-demand hours and to produce hydrogen from clean sources. It can provide residential areas with power that is up to 26–28% energy efficient [30–32]. Another study investigated the feasibility of glucose-based hydrogen production using hydrothermal gasification of glucose at temperatures ranging from 375 to 1000 °C [33].

Likewise, a water gasification of wheat straw yielded 32.7 Kg/h of hydrogen at 700 ° C, with energy and exergy efficiencies of 17.2% and 22.1%, respectively [34].

4.2. Hydrogen from biomass

Our understanding and reliance on thermochemical or biological hydrogen production methods have been influenced by recent studies published since 2020, owing to the considerable efficiencies and waste-management benefits of deploying these methods. Energy production from biomass was the first renewable energy source used by humans to generate energy among all available renewable energy sources. The traditional method for producing biomass energy is direct combustion, which is still used in many regions worldwide [35]. Biomass is the world's third-largest primary energy source, accounting for 10.3% of the global energy supply and making it the most significant contributor to renewable energy [36]. The prominence of biomass as a renewable energy source is expected to increase substantially as the global shift toward clean, cost-effective, sustainable, and reliable energy sources intensifies. Biomass energy possesses excellent potential as a renewable energy source, as it is widely available in nature. Wood, agricultural products and waste, crops, plants, and animal waste are all sources of biomass used to generate energy, with wood being the primary source in biomass energy production. The process of producing hydrogen from biomass is categorized into two classes: thermochemical and biological processes [37–40].

The thermochemical processes include Combustion, Pyrolysis, Gasification, the Water-Gas Shift Reaction, and Steam Gasification.

The combustion process is implemented by directly burning biomass, such as wood or plants. The burning process is carried out directly in air. The output is heat, which is converted into chemical, mechanical, or electrical energy. The combustion process does not directly yield hydrogen. Instead, the combustion reaction is part of a sequence of processes, including biomass gasification, where hydrogen is one of the output gases. The combustion process provides the heat required for gasification. If hydrogen is produced directly from combustion, other harmful gases are also produced, including carbon dioxide, making it an inefficient method for sustainable biomass hydrogen production.

In pyrolysis, biomass is heated in the absence of air or oxygen to yield a mixture of gases, including hydrogen, carbon monoxide, methane, and charcoal, as well as bio-liquid outputs. Like combustion, pyrolysis is part of a sequence of processes to produce hydrogen and is usually followed by steam reforming or the water-gas shift reaction. Plants or biomass raw materials are heated to produce energy without combustion, and various output types can be created by this method. Usually, this process is carried out at high temperatures between 625 and 775 K, making the high-temperature requirement for complex production materials challenging for this method. Recent work, such as the comprehensive analysis presented in [41], has further highlighted the potential of biomass pyrolysis as an efficient and economically viable pathway for hydrogen production, particularly in regions with abundant agricultural and forestry residues.

Gasification is another thermochemical process used primarily to produce a mixture of gases from biomass. These gases include hydrogen, carbon monoxide, and methane. Unlike pyrolysis, oxygen is present during the heating of biomass. However, biomass heating reaches a high temperature before burning, and a combustible gas, known as syngas, is produced during the heating process. The output gases are then used in the hydrogen extraction process. The two methods mentioned earlier are used to enhance hydrogen production from the gasification process. These include steam reforming and the water-gas shift reaction. In the steam reforming process, the gases produced by gasification are converted into hydrogen. The water-gas shift reaction, on the other hand, converts the carbon monoxide and steam into hydrogen and carbon dioxide. The gasification process is used to produce hydrogen from biomass [40]. The main challenge of this method is that tar and ash are made during the process. The ashes could be controlled using fractionation and leaching techniques. The research field must shift toward designing optimal gasifier operation and tar control to minimize tar formation and enhance the performance of this method [35].

Biomass energy can be. Microscopic living creatures, such as bacteria or algae, are primarily used to produce hydrogen gas. Such processes may or may not require light to produce hydrogen successfully. Light-based methods, such as biophotolysis, use sunlight to degrade food or waste and produce hydrogen and oxygen by splitting water. On the other hand, light-independent methods, such as dark fermentation, degrade the food or waste to produce hydrogen gas. The biological method for producing hydrogen from biomass holds great potential as a renewable energy source. This resource is continually updated and expanded, making it a sustainable source for hydrogen production. Furthermore, this method effectively utilizes waste because the biological approach can process a wide range of biomass, including agricultural waste. This provides a valuable and sustainable solution to efficient resource utilization. Recent studies highlight that microalgal species represent a promising biological pathway for sustainable biohydrogen production, although the synthesis process still faces notable technical, environmental, and economic obstacles [42–44].The biological methods are also environmentally friendly, as the hydrogen is produced naturally. This property significantly reduces the dependence on fossil fuels and other harmful mechanisms for hydrogen production. Consequently, carbon and greenhouse gas emissions can be reduced using a natural, biological, clean, and environmentally friendly method, such as biomass. Although biomass energy offers a renewable and cost-effective means of producing hydrogen, the primary disadvantage of relying on this source is the lower and slower hydrogen output relative to other resources, including thermochemical methods [45]. Lower output yields significantly contribute to reduced efficiency, resulting in substantial limitations for large-scale applications. In addition, the use of biological methods requires complex maintenance for the microorganisms, which increases the cost of this method [46].

Biological methods can be classified into three types: Biophotolysis, Photo-fermentation, and dark Fermentation. Green algae, blue-green algae, also known as cyanobacteria or photosynthetic bacteria, are used to produce hydrogen naturally through a process called biophotolysis. As mentioned, these microorganisms directly decompose water into oxygen and biohydrogen in photosynthesis.

In photo-fermentation, photosynthetic bacteria, such as Rhodobacter and Rhodopseudomonas, produce hydrogen in a light-dependent process that utilizes organic acids under anaerobic conditions. Unlike photo-fermentation, dark fermentation uses Clostridium species to ferment organic compounds in the absence of light and produces biohydrogen as a product [45].

4.3. Hydrogen from wind energy

The increasing global energy demand pressures countries and governments to invest in and develop innovative solutions to meet these energy requirements. These solutions must address environmental concerns and mitigate or reduce greenhouse gas emissions to maintain a sustainable, environmentally safe world. As hydrogen attracts attention and investment as a fuel of the future, other renewable energy sources are being integrated to enable efficient, clean, secure, and cost-effective production of green hydrogen. One of the most reliable and well-established renewable energy sources for this purpose is the wind energy resource [47]. Wind energy is the least renewable source, contributing to greenhouse gas emissions in both the long and near future [48]. For example, offshore wind turbines have been proven to reduce greenhouse gas emissions by 48% per kWh of electricity produced, compared to onshore wind turbines [49]. In addition, wind energy implementations have been shown to noticeably reduce CO_2 and NO_x emissions. Hydrogen production from wind energy through electrolysis. A study done in Ireland showed a 9% and 90% reduction in CO_2 and NO_x emissions, respectively, for a wind penetration factor of 11% [50]. A study implemented by authors in [51] to assess the life cycle of wind-based hydrogen production in Western Canada revealed that hydrogen produced from wind energy has a life cycle assessment of 0.68 kg of CO_2 eq./kg H_2, and reduced greenhouse gas emissions with 94% in comparison with other methods like steam methane reforming. This demonstrates that wind energy has significant potential to reduce greenhouse gas emissions and mitigate climate change. The deployment of wind energy as a renewable energy source for hydrogen production could be manageable because hydrogen production with this source involves utilizing the excess electricity generated from these sources. Numerous studies support integrating hydrogen production with existing wind energy farms or systems, as hydrogen can be produced from wind turbines to store electricity for later use. Although hydrogen could help as a storage support for these systems, other challenges arise from the complexity of transporting hydrogen or electricity. The electrical grid's transportation and storage capacity should be upgraded and designed to maximize the efficiency and reliability of this mechanism [52]. On the other hand, wind fluctuations and variability pose another challenge that can be mitigated by incorporating hydrogen into wind-based systems to enhance reliability. Fig. 7 shows an example of an integrated electrical system based on wind and integrating hydrogen generation [52]. The example system demonstrates the practical functionality of integrating both res and hydrogen at a larger, more realistic scale. While part of the generated energy is used to meet instantaneous grid demand, excess energy is stored for energy production to enable effective hydrogen utilization. For example, electricity from wind farms or local wind turbines is converted and then used to produce hydrogen via electrolyzers. The produced hydrogen is stored and used to power electric cars.

The primary mechanism for producing hydrogen from wind energy is electrolysis, as discussed earlier. As shown in Fig. 8, wind turbines are used in a conversion process that converts the kinetic wind energy to electricity. The electricity output of the conversion process is then used as the input power to the electrolyzer. Based on its type, the electrolyzer unit splits water (H_2O) into H_2 and O_2 gases [53]. The output hydrogen gas can then be stored in various ways, including as a compressed gas, for later use, such as powering the grid.

4.4. Hydrogen from geothermal energy

In addition to the wide range of renewable energy systems currently available for energy production in general and hydrogen production in particular, geothermal energy, as a renewable energy source, is getting attention in both research and industrial areas. If tools and technologies support its working mechanism, geothermal energy holds significant potential as a cost-effective method for producing green hydrogen [54]. The research shows that hydrogen production systems based on or incorporating geothermal energy reduce production costs compared to other technologies, such as electrolysis, wind, solar thermal, and photovoltaics [55]. The competitive production cost provides a necessary solution to the rising cost of hydrogen production, making it a valuable resource as a sustainable, cost-effective global source. In addition, the availability of this source, along with its economic viability, makes geothermal energy a strategic investment worth pursuing globally [56]. Many studies have examined the financial feasibility of green hydrogen production using geothermal energy and electrolysis, demonstrating their efficiency and reliability [54]. On the other hand, research has identified the need for advances in hydrogen liquefaction using geothermal energy to address current limitations.

Hydrogen production from geothermal energy uses heat from the Earth's interior. A process for extracting the heat stored in the form of hot water and steam by accessing the geothermal reservoirs. This high-temperature steam and hot water are then transported to the earth's exterior, and the energy of the hot-temperature water is used to produce electricity. Two methods can be utilized to produce hydrogen from geothermal energy. The first method uses a steam-driven turbine. The turbine generates electricity, which is used to power an electrolyzer to produce hydrogen via electrolysis. The second method directly uses geothermal energy to produce hydrogen. Geothermal heat is primarily used to heat water, thereby increasing the efficiency of the electrolysis

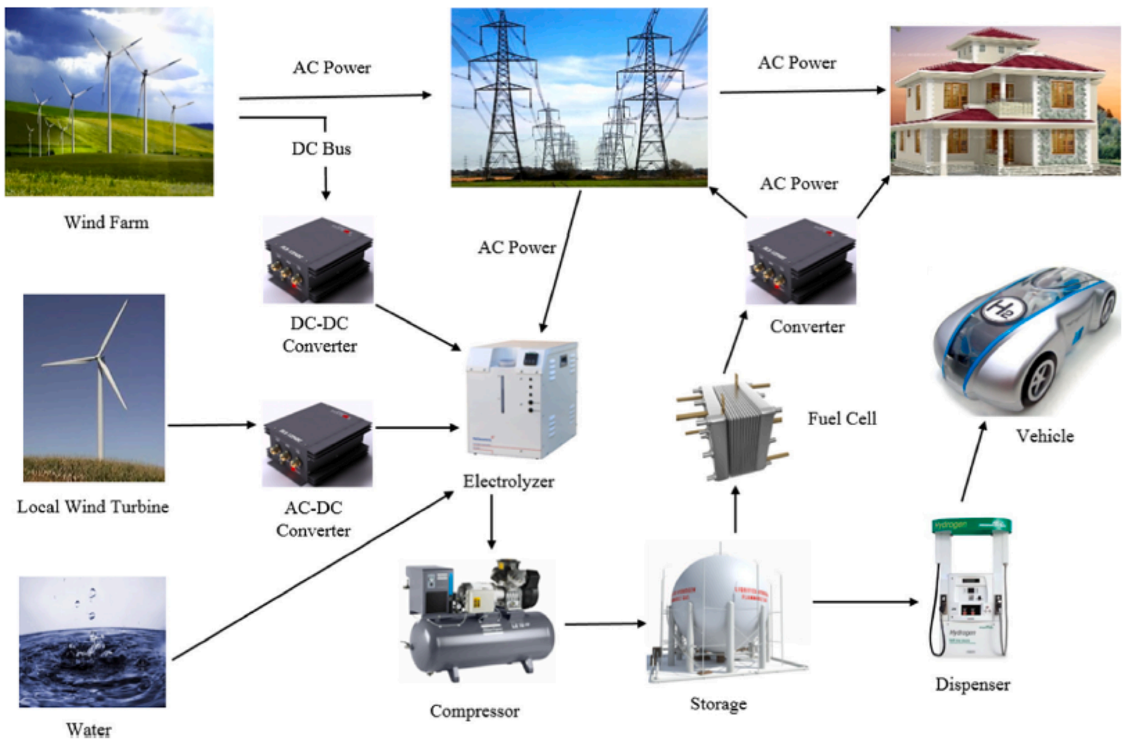

Fig. 7. An example of an integrated system for hydrogen/electricity generation utilizing wind energy, reproduced [52].

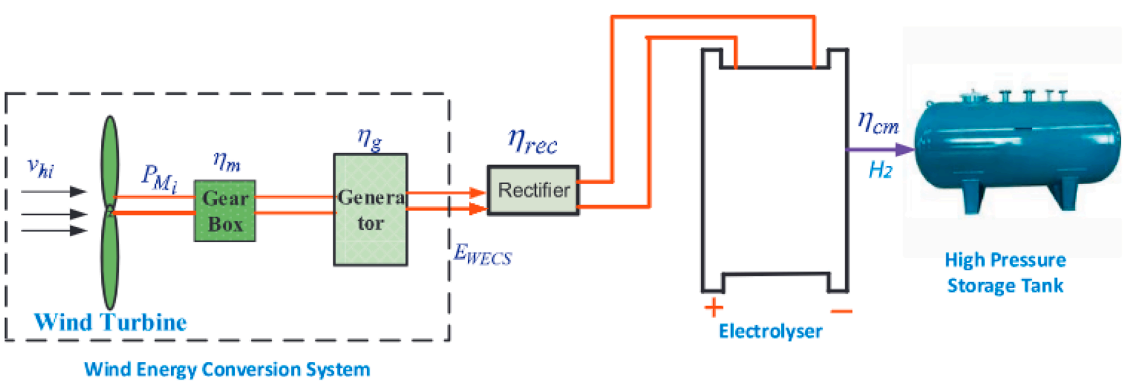

Fig. 8. Adapted from [53], the hydrogen production chain and storage through wind turbines.

process. For example, a study in [57] proved that increasing the geothermal fluid temperature from 130 °C to 200 °C improved the production system's energy efficiency from 38% to 64%. In addition, higher temperatures in the PEM electrolyzer, ranging from 60 to 85 °C, increased the hydrogen production efficiency from 39% to 44%. Fig. 9 shows the working principle of a hydrogen production unit utilizing geothermal energy [22].

Geothermal energy for hydrogen production is a resource that could be well utilized as a renewable, highly efficient, and economically effective solution. Some challenges associated with this method have been reported in the literature. However, research efforts should be shifted toward addressing related challenges to ensure the effective use of renewable sources for hydrogen production. Geothermal power can be widely implemented on an industrial scale and make a significant contribution to the hydrogen-based economy. One challenge is the lack of reliable and long-term storage units for geothermal energy. Storage methods that incorporate liquid hydrogen have been proposed as an efficient approach to geothermal energy storage [57,58]. In addition, highly efficient turbines and energy conversion systems must be utilized in geothermal power production. The components used in the production process significantly influence hydrogen production efficiencies and power loss. These include flash separators, condensers, and turbines. Another critical challenge affecting public acceptance of geothermal power plants is the release of hydrogen sulfide during production. Different models for hybrid geothermal power plants integrating other renewable resources have been proposed to overcome this challenge. For example, a model that blends solar, wind, and geothermal energy for hydrogen production is presented in [59]. This model suggests using a hydrogen sulfide abatement unit in conjunction with the electrolyzer to control harmful hydrogen sulfide emissions. Multigenerational systems, which integrate multiple renewable energy sources, have been the focus of research due to their enhanced efficiency and cost benefits [60]. In addition, a novel model utilizing a thermoelectric unit in place of ORC machines is proposed as a solution for low-enthalpy geothermal sources, and it has been shown to increase hydrogen production efficiency [61].

Table 1 provides a comparative summary of the different green hydrogen production technologies in terms of efficiency, cost, and GHG emissions across the investigated work. As evident from the analyzed resources, wind-powered electrolyzers have the highest potential among competitive renewable energy technologies, with lifecycle emissions

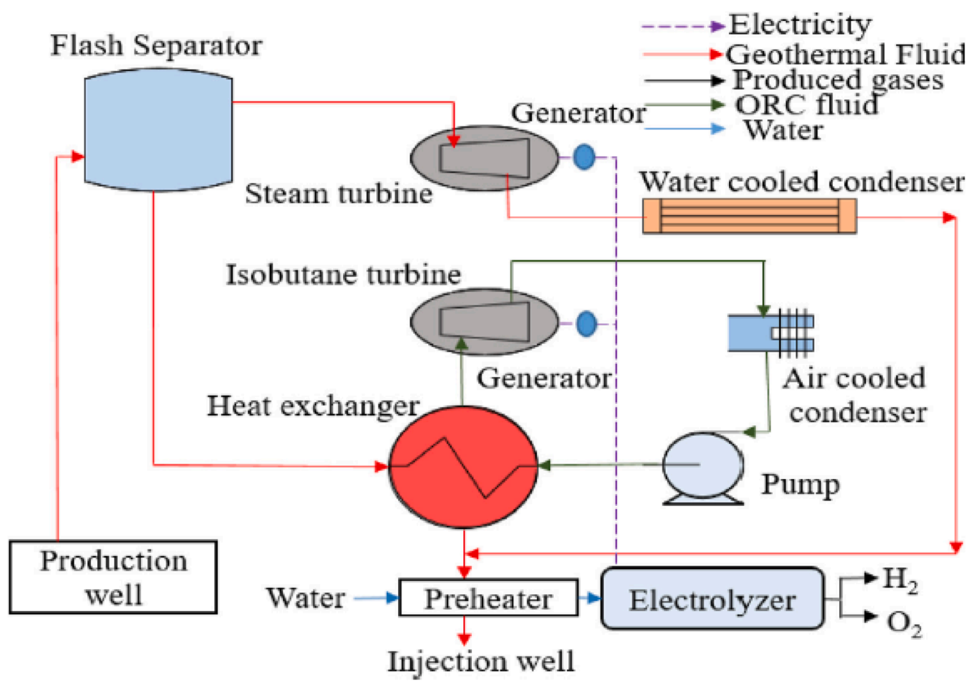

Fig. 9. Hydrogen production through geothermal energy schematic diagram, reproduced from [22].

Table 1
Comparative analysis of hydrogen production methods.

Method	Efficiency	Cost	GHG Emissions	Sources
Solar Electrolysis (SPVE)	18–24%	Not specified	Low / Zero (Clean output)	[14,16,21]
CSP (Solar Thermal)	High (Qualitative)	Not specified	Near Zero(Thermochemical cycles)	[21,22]
Wind-Based Electrolysis	Not specified	\$0.68 CO_2-eq/kg H_2	94% less than SMR	[51–53]
Biomass Thermochemical	20–60% H_2 in syngas	Not specified	Low (Process-dependent)	[35–40,45]
Geothermal Electrolysis	38–64%(130–200 °C)	Not specified	Very Low	[22,54–57]

performance reaching up to a 94% reduction. Geothermal-assisted electrolyzers are among the highest production efficiencies, with records reaching up to 64%. Despite the promising efficiencies and GHG elimination presented, these key technologies still face cost inefficiencies and limitations in the investigation of such systems.

5. Hydrogen storage

The transition to a global hydrogen-friendly economy and infrastructure cannot be achieved without proper consideration of hydrogen storage. Hydrogen storage is as essential as hydrogen production, mainly when renewable energy resources are utilized. As discussed, hydrogen will complement renewable energy sources because it can store energy, and its economic value is tied to its energy-carrying properties. Therefore, strategic hydrogen storage mechanisms and technologies, especially when integrated with renewable energy resources, are crucial to effectively mitigate the effects of climate change and ensure a seamless and efficient transition towards green hydrogen systems and the economy. Efficient, lossless, durable, and safe hydrogen storage systems should be widely available, ready for use, and integrated with hydrogen production to enable reliable and sustainable utilization of hydrogen. In addition to integrating renewable energy resources, hydrogen storage is crucial for other applications that rely on hydrogen as a fuel. This includes electric vehicles and hybrid systems that rely on hydrogen as an energy source. This means that different hydrogen storage units with varying sizes are required for industrial and public use. Recent advancements in hydrogen storage, particularly systems integrated with renewable energy sources, have demonstrated significant improvements in system stability, reduced curtailment, and enhanced hydrogen retention performance [62–65].Two primary challenges in hydrogen production stem from the unique properties of hydrogen as a chemical element. The first is that hydrogen has a relatively low atomic weight and a small molecular size. Hydrogen is the lightest element available in nature. This characteristic of hydrogen makes it more challenging to liquefy and store than methane and propane [66]. Furthermore, the low atomic weight of hydrogen makes it readily escape from containment vessels, necessitating stricter and better-designed storage standards. Additionally, on a volumetric basis, hydrogen has a lower energy density than other fuels. Therefore, a larger fuel tank is required for vehicles operating. Additionally, on a volume basis, hydrogen has a lower energy density than hydrogen. Although low-scale storage mechanisms have been developed, a large-scale hydrogen storage system is worth the investment and research as an infrastructure supporting a hydrogen economy.

Hydrogen storage can be classified into four main categories, as shown in Fig. 10. These categories include physical, adsorption, or chemical storage for hydrogen [67].

5.1. *Physical storage*

The physical form of hydrogen storage could be compressed, cryogenic, or cryo-compressed hydrogen. This method is widely used for various applications, ranging from fuel cell vehicles to industrial and storage purposes. Compressed hydrogen storage is the most mature technology of all hydrogen storage systems [68]. It involves storing hydrogen gas under high pressure in steel or composite storage vessels, and investing in and researching as well. This increases energy density and ensures safe containment of the gas under high pressure. The major

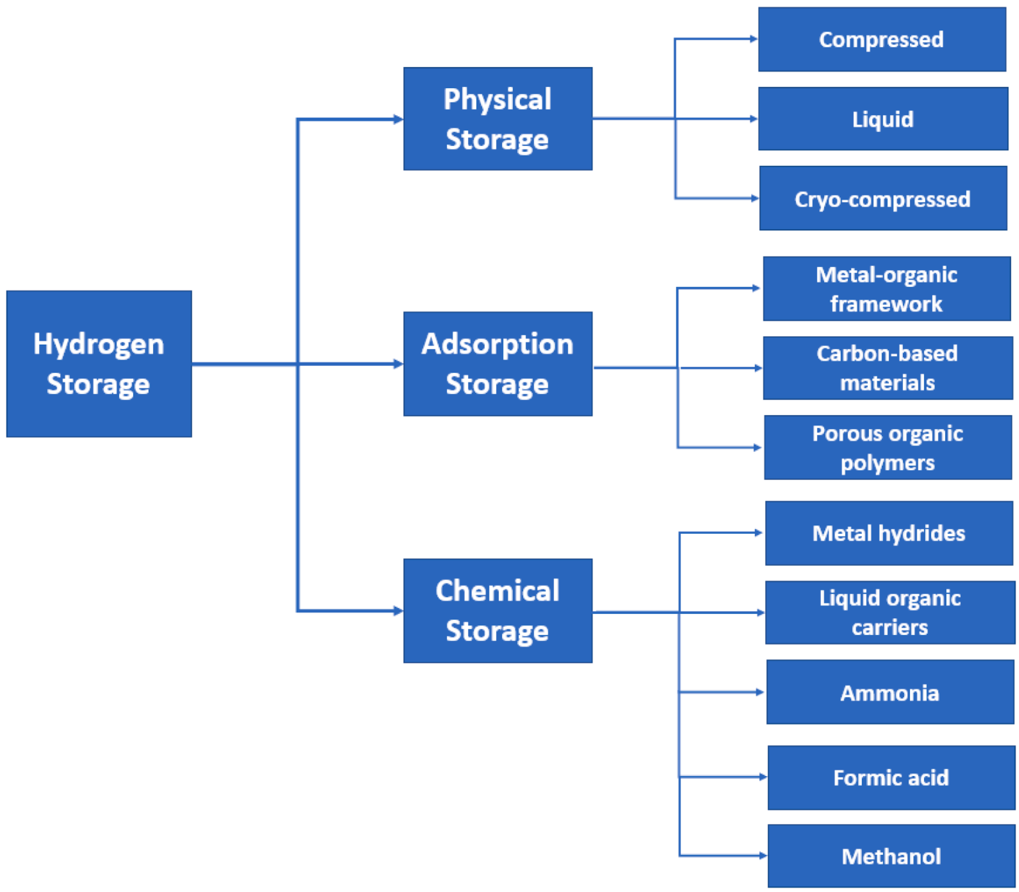

Fig. 10. Hydrogen storage classification.

challenge associated with this method for hydrogen storage is the higher cost. This significantly reduces its economic value, especially for storage tanks and vessels [69]. On the other hand, space limitations pose a challenge, especially for applications requiring limited space [70].

The cryogenic hydrogen storage method is implemented by liquefying and storing the hydrogen gas at extremely low temperatures (between -150 °C and -253 °C) [71,72]. These low temperatures directly increase the hydrogen storage density, allowing larger quantities of hydrogen to be stored in smaller volumes.

Additionally, the energy loss is reduced when hydrogen is stored at cryogenic temperatures [73]. A method for combining both compressed and cryogenic hydrogen storage technologies is available. Cryo-compressed hydrogen storage is characterized by storing hydrogen at low temperatures, between 60 and 100K, and high pressure, between 10 and 100 MPa [74]. In general, the pressure in hydrogen storage by compressed methods, including cryogenic compression, ranges between 5–70 MPa and 900–1000 bar, depending on the application, space, and storage requirements [75,76]. The combination of the two strategies expands the energy density of hydrogen. Fig. 11 shows the temperature versus hydrogen density curve for compressed hydrogen, cryogenic liquid hydrogen, and cryo-compressed hydrogen, respectively [72]. The hydrogen storage capabilities are dependent on the storage method, particularly in terms of temperature. Liquid hydrogen has the highest density at cryogenic temperatures, whereas compressed gaseous hydrogen has a lower density. On the other hand, compressed hydrogen combines high pressure and lower temperatures, making it a valuable candidate due to its performance and flexibility.

The cryo-compressed method (CcH_2) has garnered research and industry interest, with numerous studies in the literature demonstrating its capabilities. For example, it can power small Unmanned Aerial Vehicles (UAVs) and has been shown to increase their flight endurance by

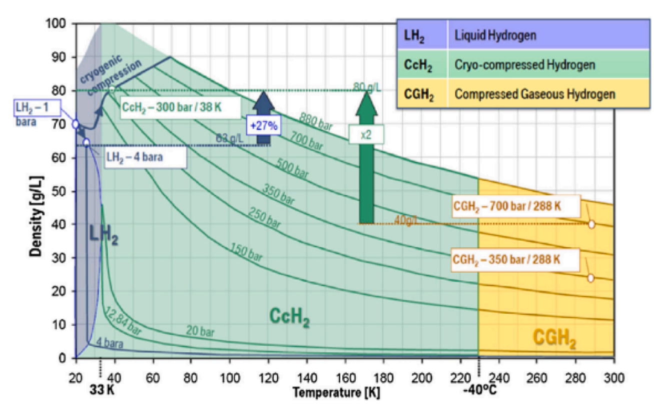

Fig. 11. Compressed hydrogen, liquid hydrogen, and cryo-compressed hydrogen temperature vs. hydrogen density curve as published in [72].

43% [77]. Additionally, it can be integrated into a hydrogen-based fueling system utilizing fuel cells for heavy-duty trucks, as noted in [78]. Furthermore, cryo-compressed hydrogen can be utilized widely in hydrogen refueling stations. The characteristics of hydrogen storage using this technology, such as low-temperature and high-pressure storage conditions, are essential for reducing hydrogen leakage risks and enabling reliable filling [79].

5.2. Physical adsorption

Physical adsorption is another technology used for hydrogen storage. This method is based on the reversible transformation of hydrogen (H_2) into other materials for later use. Hydrogen molecules are transformed, through physisorption, into different forms of porous materials [80]. The most common examples of these materials are Metal-Organic Frameworks (MOFs), activated carbons, Covalent Organic Frameworks (COFs), Microporous Metal Coordination Materials (MMOMs), clathrates, organotransition metal complexes, and zeolites [81,82]. Porous materials [83,84]. MOFs are the most commonly researched porous materials due to their high surface area and adsorbing capabilities [85–87]. MOFs adsorb hydrogen molecules through the weak van der Waals force, resulting in rapid desorption kinetics [80,88]. The significant advantage of physical adsorption is the minimum energy required to store hydrogen, making it a suitable solution for many applications with higher energy-efficiency needs. Several factors influence the adsorption capacity of these materials, including temperature, pressure, and pore size. In this method, high hydrogen adsorption density can be achieved at low temperatures and moderate pressure. The adsorption process is reversible, and hydrogen can be extracted when needed. Adsorption is a promising technology for hydrogen storage and warrants greater focus from both the research and industry sectors. It provides a fast and reversible hydrogen storage solution.

5.3. Chemical storage

Storing hydrogen can also be implemented using chemical methods in the form of hydrogen-rich compounds under ambient conditions. Chemical hydrogen storage, also known as solid-state storage, is a promising alternative to conventional techniques such as compression and liquefaction, which require specific temperature and pressure conditions. Hydrogen forms chemical compounds with other chemical elements or substances in this method. Hydrogen can be easily removed using thermal processes [89]. Various hydrogen carriers are being studied. These include dimethyl ether, methanol, formic acid, dibenzyl toluene, metal hydrides, ammonia, and methanol [67,81,90]. Chemical hydrogen storage offers several advantages over traditional methods, including reduced pressure and temperature requirements, improved safety of storage vessels, enhanced selection of tank materials, minimized energy loss, and lower costs. Chemical storage has practical applications, particularly in the industrial sector, owing to the presence of hydrogen and other chemical compounds. This eliminates the need for low temperatures or high pressures in the storage carriers. Chemical hydrogen storage holds promise for the future hydrogen economy, as it is expected to be implemented on a large scale.

6. Hydrogen transportation

Hydrogen transportation is a critical aspect that requires proper planning and consideration as a building block toward a hydrogen-based economy. A well-established hydrogen transportation infrastructure significantly contributes to the efficiency of hydrogen utilization as an alternative fuel and energy carrier. Additionally, it enables convenient utilization of hydrogen across various applications. That is because hydrogen transportation links hydrogen production, utilization, or storage. Multiple methods and forms of hydrogen are utilized to transport it. The hydrogen transportation mechanism is classified based on whether the hydrogen is stored in a form before or after transportation. Therefore, hydrogen transportation can be classified into three categories: gaseous, liquid, and solid-state (using hydrogen carriers) [91].

These different methods have their advantages and disadvantages. However, most methods discussed in the literature require further research to identify new materials with high insulating properties, thereby minimizing hydrogen leakage or maximizing pressure containment in liquid hydrogen tanks or storage vessels. Table 2 summarizes these methods, their advantages, disadvantages, development stage, and future work [91]. Furthermore, appropriate transport mechanisms should minimize heat transfer by maintaining low temperatures when the hydrogen is in liquid form. This increases hydrogen efficiency and utilization. The cost of hydrogen transportation is crucial when considering the use of hydrogen as an alternative fuel. Investing in hydrogen transportation infrastructure or utilizing existing infrastructure prepares for a future hydrogen economy. Hydrogen storage and transportation are very similar. This is because both depend on the form hydrogen takes, whether it exists as a gas, liquid, or solid. Generally, hydrogen transportation can happen through three standard mechanisms: application, destination, distance, and hydrogen form. These include pipelines, trucks, tube trails, ships, and flexible pipes [92].

6.1. Gaseous hydrogen transportation

Transporting hydrogen in its gaseous state is a method used for distributing hydrogen, known as gaseous hydrogen transportation. As discussed in the storage section, hydrogen is stored as a gas by compression under very high-pressure conditions. The compressed hydrogen is then stored in steel or nickel vessels or cylinders to withstand the high gas pressure. This method of hydrogen storage is the most widely used. It is the most feasible hydrogen transportation technique for long-distance and large-scale applications, with a cost of $3 per kg for distances up to 7000 km [93,94]. Studies show that flexible pipes offer a solution for large-scale hydrogen transportation due to their low minimum allowable bending radius, which supports their ability to handle larger relative motions. This property makes flexible pipes an ultimate choice for dynamic applications. Compressors store hydrogen in these vessels immediately after production. The filled storage vessels or cylinders are then packed into specialized tube trailers for safe transportation of the compressed hydrogen. The loaded tube trailer transports the high-pressure storage vessels to the destination, where hydrogen will be used or to the hydrogen storage facilities. Pipeline transportation of hydrogen is also used for long distances. Hydrogen is compressed along the pipeline and then transported. The pipeline method requires regular maintenance due to its higher risk of hydrogen leakage. Additionally, standard safety measures and regulations should be properly maintained, including leak detection, pressure regulation, and shutdown systems [95]. Furthermore, transporting gaseous hydrogen through pipelines is challenging because hydrogen reactions weaken or embrittle the pipelines. This challenge can be limited by investigating new materials with high hydrogen resistance. This will not only ensure the durability of the transportation pipeline but also contribute to the pipeline's cost, maintenance, and reliability.

6.2. Liquid hydrogen transportation

Hydrogen is also transported in its liquid form. By keeping hydrogen at very low cryogenic temperatures, it becomes liquid, and it can be transported and stored in this form. After the production process, hydrogen is liquified and kept at cryogenic temperatures. Although the transformation requires more energy, storing hydrogen as a liquid enables a higher hydrogen storage density, thereby increasing transportation and storage efficiency. One method for transporting liquid hydrogen is container-based. Storage tanks are used to store and maintain hydrogen at low temperatures; they are used to store hydrogen directly after liquefying it. Cryogenic tankers, equipped with insulated tanks, are used to store liquid hydrogen by transferring it from the storage tanks. These cryogenic tankers are used to transport the hydrogen. The insulated tanks are designed to safely maintain the pressure and cryogenic temperature of liquid hydrogen during transportation. Ensuring the required insulation and minimizing heat transfer in cylindrical transportation tanks is achieved using passive insulation technologies, including high-vacuum jacketed adiabatic containers, high-vacuum multilayer adiabatic methods, and high-vacuum powder adiabatic methods. Furthermore, liquid nitrogen cold shields and small refrigerators are used as active refrigeration systems to reduce heat transfer, maintain insulation, and store at low temperatures. The cryogenic tankers distribute hydrogen to end-users and storage facilities by road, ship, or rail, depending on the distance and application. The transported liquid hydrogen

Table 2
Comparison between the different hydrogen transportation mechanisms and technologies [91].

Technology	Advantages	Disadvantages	Development Stage	Future Outlook
High-pressure tube trailers	Easy deploy and scale Flexible routing	Limited capacity Higher transportation costs Safety concerns due to high-pressure	Mature	Improvements in materials and design to increase capacity Advanced safety features
Pipelines	Large capacity Low operating costs Reliable	High initial investments Limited geographic reach Susceptibility to leaks and sabotage	Mature	Expansion of pipeline networks Improved materials and leak detection technologies
Liquid transportation	Higher energy density Established technology	Cryogenic storage High energy consumption	Advanced	Enhanced insulation materials, energy- efficient processes
Hydrogen carriers transportation	Ease of handling, transportation, and storage	Complex chemical processes Energy-intensive	Developmental	Advances in carrier materials, efficient release methods

is transferred to the storage facilities and can be used in various applications by warming it to ambient temperatures. Like gaseous hydrogen transportation, continuous monitoring of the transportation system is necessary. This includes pressure, temperature, and leakage detection. Pipeline transportation can also be used to transport liquid hydrogen. However, it is considered costly as specialized infrastructure for distribution pipelines requires investment and a workforce for deployment. In addition, specialized materials, regular maintenance, construction and operating standards, and pressure and temperature requirements make pipeline transportation challenging, despite its promising large-scale capabilities. Liquid hydrogen transportation is a promising solution that, if invested wisely, would contribute significantly to the hydrogen economy and distribution infrastructure. Although this method is considered costly and energy-intensive, it is the most efficient for transporting large quantities of hydrogen, as liquid hydrogen has the highest storage density [96–98].

6.3. Hydrogen carriers transportation

Hydrogen carriers are compounds and chemical materials used for direct hydrogen storage. These materials are used to chemically store or transport hydrogen, as hydrogen is chemically bound and can be extracted for later use via other processes. The significant advantage of this method is its ease of transport, as it eliminates the low temperatures or high pressures required for transporting gaseous or liquid hydrogen. Furthermore, this method eliminates the risks of hydrogen leakage or interactions with transportation pipes or storage tanks. Using hydrogen carriers for hydrogen transportation also contributes to a safe and environmentally friendly hydrogen infrastructure by reducing the risk of hydrogen storage explosions due to hydrogen's inflammability. This method has several advantages compared to transporting hydrogen as a gas or liquid. A variety of hydrogen carriers are used for hydrogen transportation, ranging from small molecules such as ammonia and methane to more complex hydrocarbons, such as formic acid [6]. Liquid organic hydrogen carriers (LOHCs) are the most common ones researched and used [99]. They offer convenient and efficient hydrogen transportation and storage options due to their high storage density and compatibility with the current transportation infrastructure [100]. Additionally, they are energy-efficient, as they require low energy at ambient conditions to hydrogenate and dehydrogenate the chemical hydrogen carriers for hydrogen storage or retrieval [101]. Furthermore, the hydrogen carriers in general, and the LOHC in particular, provide an economically friendly solution to store and transport green hydrogen, as the logistics could vary in cost between 0.28 and 0.37 e/kg H_2 [102]. The transport of hydrogen carriers begins with the hydrogenation process. Hydrogenation is a catalyzed process that usually requires high pressure, during which hydrogen is absorbed and stored in chemical carriers or materials. The materials are then transported using conventional methods, including trains, trucks, or ships. To extract hydrogen, a reversible thermal dehydrogenation process is implemented to release hydrogen for use. A closed-loop transportation and recycling process can be managed by returning the hydrogen carriers for re-hydrogenation.

7. Recent governments' policies and regulations for green hydrogen production, storage, and applications

With the increasing demand and a trending shift towards green hydrogen systems that integrate renewable energy sources, many governments are adopting new regulations and policies to support the deployment of green hydrogen. These regulations provide clarity, safety, stability, international standards, and environmental integrity. On the other hand, as demand increases and the shift towards green hydrogen systems that integrate renewable energy sources grows, many governments are adopting new regulations and policies to support the deployment, investment, and economic growth of hydrogen systems, as well as public confidence.

India has established the Green Hydrogen Mission (2023), which aims to annually produce 5 Million Metric Tons (MMT) of green hydrogen by 2030 by allocating special funding for electrolyzers and encouraging industrial use through incentives [103]. Regarding hydrogen storage, governments are currently investing in Underground Hydrogen Storage (UHS) systems and are aiming to establish robust policies and regulations for pressure vessels and geological storage of hydrogen [104].

Furthermore, the development of hydrogen transportation infrastructure policies and guidelines is advancing rapidly, particularly under the European Union (EU)'s Fit for 55 policy and the United States Department of Energy (US DOE) 's standards for hydrogen [105].

In the application and hydrogen utilization sectors, governments are moving towards encouraging initiatives that mandate and incentivize the adoption of hydrogen as a fuel in transportation, including electric cars powered by fuel cells, ammonia production, and the energy sector. For example, China has developed a regional plan that aligns with its central visions and decarbonization goals [106]. Table 3 provides an overview of recent regional policies and regulations programs across different countries.

8. Hydrogen utilization

The shift towards climate-resilient hydrogen systems begins by maximizing the utilization of hydrogen across sectors and applications [107]. Reducing or eliminating dependence on fossil fuels as the primary energy source is the first step toward controlling climate change. Address-

Table 3
Summary of key government policies for green hydrogen development.

Country/Region	Key Policy or Program	Year Introduced	Target Sector
India	National Green Hydrogen Mission	2023	Electrolyzers, industrial H_2, mobility
China	Central-Regional Hydrogen Policy Framework	2016–2024	H_2 industrialization and manufacturing
European Union	EU Hydrogen Strategy / Fit for 55	2020 (updated 2023)	Green H_2 in energy and industry
United States	Inflation Reduction Act (Hydrogen Tax Credits)	2022	Clean H_2 production, tax credits
Global Maritime (IMO)	IMO IGF Code & Maritime H_2 Safety Regulations	2023–2024	Safety & fuel use in maritime transport

ing the issue of green hydrogen production solely through renewable energy sources is insufficient to ensure a climate-resilient future. On the other hand, hydrogen utilization is one of the main pillars of a hydrogen-based economy, next to production and distribution [108]. It is crucial to shed light on both green hydrogen production and its utilization to ensure an integrated hydrogen economy that is comprehensive in its coverage of hydrogen operations and utilization. Not only that, but there is also considerable responsibility on societies, governments, researchers, and individuals to support and utilize hydrogen as an energy carrier, and to embrace its growth by developing innovations and sustainable solutions that replace those that depend on climate-harsh systems. The proper, comprehensive, efficient, and wise utilization of hydrogen in the different sectors is the first building block in a sustainable and emissions-free environment. Hydrogen utilization refers to a wide range of methods or systems implemented for the effective, efficient, and practical use of hydrogen as an energy source. The primary aim of this concept is to maximize the effective utilization of hydrogen. Clean, reliable, and efficient utilization is achieved when hydrogen systems operate on green hydrogen, and no hydrogen waste is reported. With the rapid development of hydrogen systems in various sectors today, climate neutrality can become a reality by 2050 [109].

Hydrogen utilization can be classified into different categories based on three aspects. These include the sectors of hydrogen utilization, applications where hydrogen is used, and the role of hydrogen in the system. Fig. 12 illustrates the classification of hydrogen utilization according to the specified categories. Hydrogen, as an energy source, can be utilized in various sectors, including transportation, energy and power generation, biorefining, aerospace, pharmaceuticals, metallurgy, electronics, buildings, and aviation [107,110]. Table 4 summarizes the major sectors in which hydrogen can be utilized, with examples of the applications in each industry.

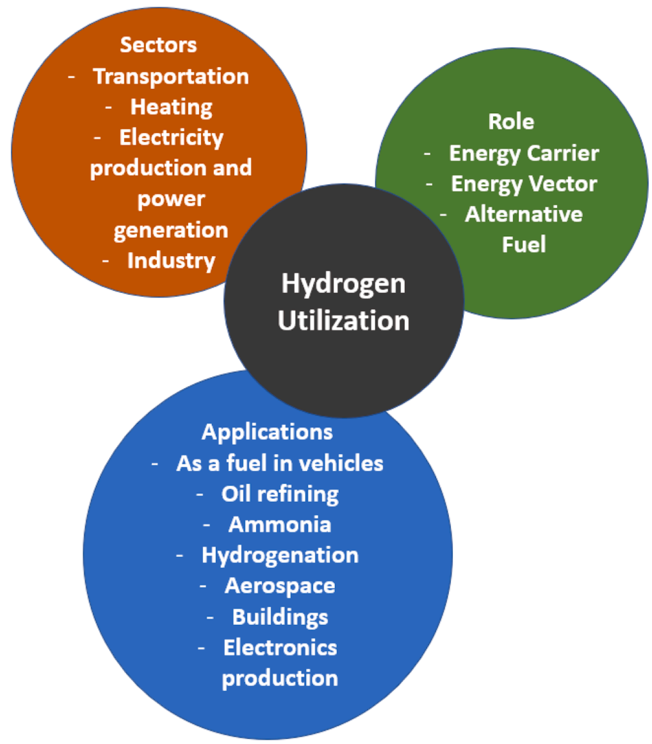

Fig. 12. Hydrogen utilization based on sectors, applications, and role of hydrogen.

8.1. Transportation

The transportation sector is one of the leading sectors threatening climate resilience today [111]. A significant portion of greenhouse gas (GHG) emissions comes from transportation. The emissions from transportation are mainly caused by the burning of fossil fuels in the different forms of vehicles, including cars, trucks, ships, and buses [112]. Transportation contributes to around 14–15% of the GHG emissions globally and is responsible for emitting over 20% of the equation for emitting over 20% of the CO_2 emissions [113,114]. With the increasing GHG emissions, more build-ups of these harmful gases in the Earth's atmosphere are piling up. These harmful gases act as a cover that traps heat and causes severe climate change effects on the Earth's surface, especially over time. The continuous, increasing use of vehicles powered by fossil fuels results in constant emissions. Therefore, sustainable and eco-friendly solutions need to be implemented in a broader range to reduce the GHG emissions produced by this transportation method effectively. Hydrogen applications in the transportation sector involve replacing the fuel used in conventional vehicles. Hydrogen, as a fuel, can be used in freight transportation [107], hydrocarbon fuel processing and upgrading [115], internal combustion engines, and fuel-cell electric vehicles [116]. Effective utilization of hydrogen in the transportation sector will act as a long-term zero-emission, efficient, and sustainable solution to GHG emissions and significantly reduce the effect of climate change [117]. Additionally, the maritime sector has numerous applications for hydrogen. Hydrogen can be included by using hydrogen fuel cells as an alternative to the existing diesel-based propulsion systems on coastal ferries [117].

Among the safe and clean hydrogen utilization solutions available today, hydrogen fuel cells hold a promising and valuable place. This is due to the fuel cells' safe, clean, reliable, and efficient hydrogen-conversion mechanism and their ability to generate electricity. Fuel cells are promising for hydrogen utilization, particularly in transportation, owing to their ease of integration and potential for large-scale deployment. Fuel cells produce electricity from fuel, like hydrogen, through an electrochemical reaction. In general, the fuel cell unit consists of an anode, a cathode, and an electrolyte. Hydrogen gas (H_2), as a fuel, is supplied to the anode, while air or oxygen is delivered to the cathode. An oxidation reaction occurs on the anode side, forming positively charged hydrogen ions (H+) and releasing electrons (e) that flow through an external circuit, producing an electric current that can be used for various purposes. The hydrogen ions then travel through the electrolyte to the cathode side. Meanwhile, the electrons from the anode move in an external circuit, creating an electric current that can be utilized for different applications. At the cathode, the oxygen supplied by air, hydrogen ions, and electrons combine to form water as a byproduct of the process. A catalyst is also used on the anode side to facilitate the process and enhance cell efficiency by reducing the energy required for hydrogen oxidation. Furthermore, the catalyst enhances hydrogen separation,

Table 4
Applications in different sectors.

Sector	Applications
Transportation	• Electric vehicles and fuel cells • Large mode transportation, including buses, trucks, ships, planes, and trains • Freight transportation
Energy and Power Generation	• Energy storage, with RES • Fuel cells for power generation in power plants • Balancing electricity grids • Remote power generation
Industry	• Production of ammonia for fertilizers • Oil and petroleum refining • Production of methanol • Steel production • Chemical production • Semiconductor industry • Electronics industry • Aerospace • Metallurgy • Pharmaceuticals
Buildings	• Heating • Cooking • Electricity production
Food	• Margarine production • Preserving materials • Cooking oils

enabling the free electrons to move efficiently. Currently, platinum is the most commonly used catalyst in fuel cells due to its stability and high efficiency. However, ongoing research aims to expand the materials used as catalysts in the future to enhance efficiency, such as carbon-coated nickel, nitrogen-carbon mixtures, and transition metal nitrides [118]. The electrochemical process in the fuel cell is environmentally friendly and has been shown to yield net-zero emissions.

In transportation, hydrogen-related applications primarily use hydrogen to generate electricity in fuel cell systems. Fuel cells have the potential to replace internal combustion engines by integrating them into vehicle powertrains. They are also used as a supplement to the battery system, increasing the vehicle's driving range [119]. The shift towards Engines (ICEs) promoting a healthy, clean, and sustainable transportation system. Internal Combustion Engines (ICEs) emit harmful pollutants as fuel is burnt in their chambers to provide the necessary power. However, as discussed earlier, fuel cells are clean and zero-emission solutions. Electric fuel cell vehicles are shown to decrease the use of fossil energy by 5–33% if fossil fuels produce hydrogen, and they lower the GHG emissions by 15–45% in comparison with conventional gasoline-based ICE vehicles [120]. Therefore, using hydrogen in fuel cells for transportation is worth the investment and research effort, as green hydrogen will significantly reduce harmful emissions and help promote a sustainable hydrogen economy.

The most predominant fuel cells in vehicles and the most researched are the Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) [121,122]. Both types are known for their high efficiency, low emissions, high energy-conversion efficiency, and ease of integration into various systems and applications, including vehicles. PEMFCs are characterized by their high-power density ranging from 0.2-0.25 W/cm^2, fast startup time, and low-temperature operation (60-90 °C) [123]. However, the high cost of the materials used in this type of fuel cell, including platinum, is a limiting factor in the use of PEMFCs [91]. Therefore, they are widely integrated into automotive applications and vehicles, including cars, two-wheeled vehicles, miniature aircraft, and drones. On the other hand, SOFCs can provide higher efficiencies by operating at higher temperatures (600-1000 °C), achieving power densities between 0.1 and 1 W/cm^2. SOFCs are used in large- or medium-scale vehicles [124].

Implementing fuel cell vehicles is a practical solution that promises to utilize hydrogen well, especially when green hydrogen is used. It has been proven that hydrogen fuel cell vehicles can operate at higher efficiency, provide a safe and clean environment, reduce noise, and make a significant contribution to the hydrogen economy. However, they have limitations that require a focused research approach. These include performance limitations, particularly voltage degradation and energy balance, as well as management challenges due to long-term operation, temperature, and humidity fluctuations [125]. In addition, the presence of water in the cell during operation and membrane hydration can introduce operational complexities, threatening the smooth integration of fuel cells into vehicles [126,127]. Furthermore, there is a significant need for energy storage devices to cater to a wide range of applications, including transportation. Fuel cell vehicles require energy storage devices, such as supercapacitors or batteries, to enhance performance. Therefore, this could be a limitation for integrating fuel cells into large-scale vehicles such as airplanes or trains, as it requires space for hydrogen storage or battery integration. Overall, the integration of fuel cells into transportation is advancing rapidly, but further economic and public commercialization is needed to ensure a smooth transition in the future [127].

8.2. Energy and power generation

Hydrogen has great potential for integration in power systems and energy storage. It addresses numerous challenges, particularly in renewable energy systems and power generation, including storage efficiency, energy conversion, and battery cost. In this context, hydrogen is primarily used as an energy carrier and vector, replacing conventional fuels and providing a clean and efficient energy source [128,129]. Hydrogen is used in energy and power systems to develop energy storage and grid-balancing technologies. Different forms of these technologies have the potential to be an essential part of the future energy sector, which is envisioned as clean, sustainable, and safe. Hydrogen is used in energy storage through the power-to-gas (P2G) concept, cogeneration, tri-generation, and methanation. Hydrogen can play as an energy storage medium, especially in renewable energy plants, as illustrated in the Green Hydrogen Production section [130]. In this way, hydrogen is used to effectively address the energy storage issue and provide a clean, environmentally friendly solution that reduces GHG emissions and mitigates the effects of climate change. P2G technology refers to converting electricity into hydrogen (H_2) or other gases, such as methane (CH_4), for later usage [131]. Hydrogen can be produced for two primary purposes: to utilize the excess power or electricity output from a power generation plant, or it is produced by the actual generated power to store the output electricity in the form of hydrogen gas. Hydrogen gas can then be utilized in various forms. These include the use of hydrogen for fuel cells to produce electricity [132]. Re-electrification using hydrogen is a crucial technology that can serve as a temporary grid-failure solution or provide short-term power supply in remote areas, reducing dependence on fossil fuels and limiting associated harmful emissions. Additionally, hydrogen production in the context of energy presents an opportunity to reduce greenhouse gas emissions by utilizing the methanation process. Methanation is defined as a process that produces methane, also known as synthetic methane or natural gas, CH_4, from combining carbon dioxide CO_2 and hydrogen H_2 [133]. Producing methane using this method helps mitigate harmful emissions, such as carbon dioxide, thereby promoting a cleaner environment and supporting the decarbonization of the economy [134]. In addition, methane serves as a mediator in the hydrogen economy due to its high molecular energy density [135,136]. Methane production is a vital technology for hydrogen utilization, as it serves as a substitute for natural gas. It can be easily integrated into the current infrastructure and injected into the distribution network, making it a proper fuel for versatile applications, including heating, transportation, and electricity generation. A recent study developed an Internet-of-Things-based energy management system that coordinates renewable sources, storage, and hydrogen units, showing that intelligent scheduling can improve green-hydrogen yield and reduce system cost compared with conventional strategies [137]. P2G plants are expected to significantly reduce synthetic natural gas costs by 2030 and 2050, making them viable options for long-term, efficient, and large-scale renewable energy storage [138]. In addition, it plays a vital role in supporting the current and future renewable energy economy and infrastructure, as it offers a solution to integrating RES into the grid. The P2G technology is a crucial step towards a net-zero-emissions future, as it not only uses hydrogen in various applications but also reduces GHG emissions in the reverse direction. To promote a smooth transition to technologies such as P2G, current challenges related to energy conversion efficiency and methane leakage must be well addressed and overcome. Another application for hydrogen in power systems is its use in cogeneration and tri-generation technologies. Cogeneration is defined as the simultaneous generation of power, heat, and electricity from the same energy source. In contrast, trigeneration is the generation of adequate heat, cooling, and electricity from the same energy source [139]. Bi-level scheduling of electricity-carbon-hydrogen systems shows that co-optimizing P2H and fuel cells with flexible loads can cut total cost by 49%, nearly eliminate load shedding (≈99%), and reduce renewable curtailment by ≈96% [140]. For standalone PV microgrids, a hybrid battery-superacapacitor storage with a fuel cell and a Reduced Fractional Gradient Descent (RFGD)-based Energy Management System (EMS) reduced hydrogen use by 15% and eased battery stress, improving off-grid reliability [141]. Hydrogen is incorporated as an alternative fuel for electricity generation. That could be achieved through traditional methods, such as diesel engines, or renewable energy sources. The excess heat is then used from the same source to warm water for other applications, including domestic use. On the other hand, trigeneration mitigates energy waste by capturing heat through absorption cooling [142,143].

8.3. Industry

The desired transition towards a hydrogen-based economy can be well-established with the wise and complete integration of green hydrogen into current and future industry sectors. That not only includes integrating hydrogen into various existing industries but also identifying new industries that could be better served by hydrogen. Hydrogen's role in industry extends beyond serving as an alternative fuel or energy carrier. Hydrogen can be utilized in various industries as a raw material, auxiliary component, or supplementary material to enhance efficiency and performance in other sectors. In addition, since industrial processes significantly contribute to greenhouse gas emissions and climate change by emitting harmful gases, incorporating hydrogen into industrial processes will substantially help maintain a sustainable environment and achieve clean, safe, and emissions-free industrial sectors. This plays a crucial role in guaranteeing a secure and convenient transition toward hydrogen-based systems. The various industrial methods and applications that primarily or partially depend on hydrogen for their operation, to boost energy security, secure a sustainable environment, and reduce GHG emissions, can be referred to as industrial processes for hydrogen utilization technologies. The definition can be generalized across diverse industries; however, hydrogen can be integrated into many of them. Key industrial processes that incorporate hydrogen include oil refining, ammonia production, methanol production, steel production, petroleum production, chemical production, the semiconductor industry, aerospace, pharmaceuticals, metallurgy, the food industry, the building industry, aircraft construction, and more. Table 5 illustrates a breakdown of the different examples of industrial processes in which hydrogen can be utilized. These applications in the industry sector should be well-invested in, as their proper and strategic implementation will ensure a smooth transition to a hydrogen-based economy and a sustainable future.

8.4. Hydrogen economy

The hydrogen economy is a concept that was introduced in the 1970s. It refers to the vision of utilizing hydrogen as the primary energy carrier and alternative. This vision has garnered broad interest from governments, industries, researchers, and individuals due to the primary need for a clean, sustainable future with minimal or even zero harmful emissions that threaten humans and other life on Earth. The importance of the hydrogen economy lies in its alignment with building an energy infrastructure based on renewable energy sources, as hydrogen complements these systems by providing a solution to storage and operation. The hydrogen economy should also focus on green hydrogen. The current hydrogen production is primarily gray, which is based on fossil fuels. However, relying on green hydrogen produced from renewable and clean energy sources will ensure a safe and decarbonized reduction in greenhouse gas emissions. The deployment and integration of green hydrogen into current systems are advancing rapidly and continuously. To achieve an economy that relies on hydrogen as its primary energy source, governments and societies must support the transition to hydrogen-based systems and technologies.

The key components of the hydrogen economy can be summarized in four elements. These include renewable and clean production sources, secure and efficient storage mechanisms, a well-established transportation network, and innovative utilization systems. Fig. 13 shows an overview of an infrastructure that supports the elements of a hydrogen-based economy. It illustrates a fully interconnected grid that utilizes hydrogen as an energy carrier and fuel, beginning with energy sources, proceeding through production, storage, transportation, and culminating in utilization. Renewable or fossil-based power generation methods are used to produce hydrogen via thermochemical, electrochemical, and biological processes. The hydrogen generated is then stored in gaseous, liquid, or solid form and transported via pipelines, ships, or trucks for use in buildings, clean transportation, industry, and energy generation. However, there are still limitations related to hydrogen's nature as a storage medium, the current hydrogen infrastructure, production cost, energy losses, and integration with industrial processes [170,171].

Table 5
Industrial processes and hydrogen utilization technologies.

Reference	Year	Sector	Key contribution / substantial matter	Hydrogen utilization technology / findings
Oil & Gas / Refining				
Yue et al. [143]	2021	Oil refining	Review of hydrogen energy systems	Hydrotreating / hydrogenation for clean fuels
Wang et al. [144]	2017	Oil refining	Co-hydrotreating algae + waste oil	H_2-assisted conversion to gasoline/diesel
Morales et al. [145]	1996	Oil refining	Early hydroconversion with metallic compounds	Hydroprocessing heavy crudes with H_2/CH_4
Romero-Piñeiro et al. [146]	2025	Oil refining	Techno-economic + LCA of H_2 supply chains	Electrolysis vs. biomass gasification; salt-cavern storage advantageous
Zhang et al. [147]	2024	Oil & gas	Hydrogen's role in transition	Thermal recovery, pipeline blending, UHS; CCUS/policy challenges
Ammonia production				
Elsherif et al. [148]	2015	Ammonia	Review of H_2 management in plants	Haber-Bosch (H_2 + N_2) integration
Kyriakou et al. [149]	2017	Ammonia	Electrochemical synthesis progress	Alternative NH_3 pathways / H_2 carrier
MacFarlane et al. [150]	2020	Ammonia	Roadmap to ammonia economy	NH_3 as storage / carrier
Dabar et al. [151]	2024	Ammonia	TEA/LCA (Djibouti)	Wind LCOH 2.25 $/kg vs. solar 4.17 $/kg; NH_3 export feasibility
Methanol production				
Lamb et al. [152]	2019	Methanol	Catalytic decomposition / storage links	Methanol reforming
Gadhe & Gupta [153]	2007	Methanol	Supercritical-water methanol reforming	Cu catalysis for H_2 production
Lindström et al. [154]	2003	Methanol	Combined reforming over monoliths	H_2-rich gas for fuel cells
Leonzio et al. [155]	2019	Methanol	CO_2 hydrogenation simulation	Methanol as H_2 carrier
Palone et al. [156]	2023	Methanol & ammonia	TEA of chemical-looping H_2	174 kg/h MeOH + 910 kg/h NH_3; low CO_2 emissions
Steel / Metallurgy				
Liu et al. [157]	2021	Green steel	Review of H_2 in steel decarbonization	H-DRI and hydrogen plasma smelting
Semiconductors				
Cho et al. [158]	2010	Semiconductor	High-density hydrogen plasma	Wafer cleaning / photodiode formation
Food industry				
Puprasit et al. [159]	2020	Food	Plasma hydrogenation for margarine	Lower trans-fat formation
Alwazeer [160]	2025	Food	Hydrogen-assisted extraction review	Green, scalable extraction aid
Transport / Vehicles				
Veeraraghavan et al. [161]	2025	Engines	Dual-fuel WTOB50 + H_2	+4.1% efficiency, -5.2% BSEC; reduced NO_x
Lei et al. [162]	2024	Vehicles	Ammonia-hydrogen synergy	Fuel cell + engine hybrid (FCEAP) optimized
Biofuels				
Prachapitukkun et al. [163]	2025	Biofuels	LCA/LCC of BHD from palm by-products	PFAD lowers impacts; renewable H_2 reduces footprint
Buildings / Energy systems				
Samsatli & Samsatli [164]	2019	Buildings	Renewable H_2 chains	Inter-seasonal storage, decarbonizing heat
Khalid et al. [165]	2016	Buildings	Integrated H_2 energy systems	Decentralized building power
Endo et al. [166]	2019	Buildings	Zero-emission building with H_2	RES + H_2 for electricity/heating
Ozturk & Dincer [167]	2020	Buildings	RES with H_2 + NG	Cleaner combustion
De Masi et al. [168]	2024	Buildings	Experimental SOFC in nZEB	1 kWel SOFC; surplus 23.8 kWh; TRNSYS modeling
Chemical industry				
Pal & Kumar [169]	2024	Chemical industry	Hydrogen's role in chemical sector	Hydrogenation; NH_3/MeOH; fuel cells in plants

8.5. Government norms and safety standards in the hydrogen economy

In the energy and industrial sectors, hydrogen is an essential building block for a green and sustainable future. Its role in decarbonizing global energy systems is associated with safety risks arising from its natural properties, including high flammability, a wide explosive range in air, ease of leakage, and low ignition energy. Since hydrogen is available throughout the typical pipeline, including production, storage, transportation, and utilization, a higher probability of associated risks is considered. Therefore, governments and regulatory institutions have a responsibility to critically analyze and develop safety codes, policies, and procedures when hydrogen energy systems are deployed, to control and prevent associated hazards. These norms and regulations not only control and mitigate risks but also play a vital role in building public trust and enhancing private-sector investment in the hydrogen economy. In the United States, several standards have been established for the safe handling of hydrogen as an energy carrier and fuel. These include International Organization for Standardization (ISO) 19880-1, which governs the administration of hydrogen fueling stations; ISO/TR 15916, which specifies basic principles of hydrogen safety; and National Fire Protection Association (NFPA) 2, which addresses the protection against hydrogen fire and explosion [172].

The urgent and growing need for reliable and effective hydrogen technologies should not overpower the need for secure safety measures and regulations. These regulations ensure a smooth and trusted transition towards a hydrogen-based economy. In China, the growing demand for hydrogen systems has raised serious concerns regarding accident management, gas-leakage control, and regulatory visibility. The lack of responsive, reliable, clear, and strict safety regulations can lead to serious risks, including fragmented oversight, insufficient risk modeling, and unclear emergency protocols, as reported in [173]. Likewise, hydrogen utilization is promising for transforming the maritime transportation sector into a zero-emission field. However, a recent assessment reveals the fragility of the current naval regulations, including the International Maritime Organization (IMO) International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) Code, in controlling and mitigating the associated hydrogen risks in maritime transport, which highlights the need to develop and deploy an integrated, reliable, and safety-norms system [105].

A pressing challenge also lies in the adoption of UHS systems. Underground hydrogen storage poses additional safety risks. These include geological stability, long-term containment, hydrogen migration, and microbial interactions. As presented by Guduru et al. in [104], Europe and North America are beginning to regulate and control UHS by incorporating protocols that support proper site selection, pressure monitoring, emergency venting systems, and environmental protection measures.

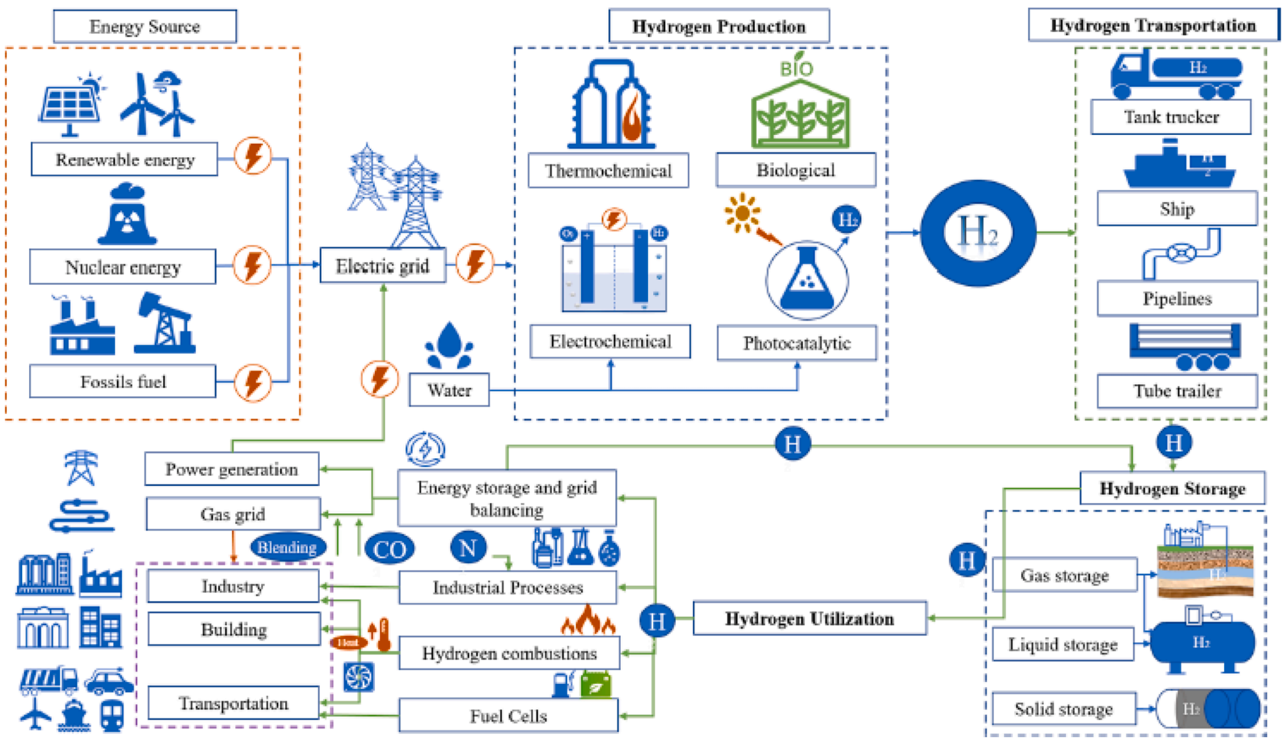

Fig. 13. Overview of key elements needed for a hydrogen-based economy. These include production, storage, transportation, and utilization. Image reproduced from: [91].

9. Conclusions

In conclusion, the successful shift towards a sustainable future, based on the hydrogen economy, requires the deployment of a fully integrated network designed to safely, reliably, and efficiently produce, store, transport, and utilize hydrogen through the development of hydrogen systems. Therefore, the focus of research should not only be on creating, storing, or distributing hydrogen, but also on developing solutions that empower hydrogen systems as a clean alternative to traditional energy systems. The vision of a clean, climate-resilient system for a sustainable future is, first and foremost, dependent on a hydrogen-friendly solid renewable energy infrastructure. In other words, the adoption of green hydrogen, using renewable energy sources to enhance existing and future renewable energy infrastructure, is the guaranteed path to a clean, intelligent, sustainable system.

The deployment and use of green hydrogen as an alternative energy source are crucial steps toward mitigating the effects of climate change, particularly when it is used for transportation, industrial, and commercial applications. Hydrogen can play a vital role in mitigating many challenges that arise from the integration of renewable energy systems. Hydrogen powers renewable energy systems by storing energy from various renewable sources, including solar, wind, biomass, and geothermal. Many efficient and reliable hydrogen storage methods are under active development for storing hydrogen as an energy carrier and for electricity production, including physical and chemical processes. However, many challenges limit its deployment at the larger scale desired, including cost and space requirements. Therefore, a well-planned shift towards green hydrogen-based systems requires extensive research to produce hydrogen at a lower cost, distribute it efficiently, and store it safely.

This review investigated the most recent advancements in hydrogen-based technologies, including production, storage, transportation, and utilization, which are the key pillars towards a sustainable, integrated, and robust hydrogen economy as follows:

- Reviewed current green hydrogen production technologies through adopting renewable energy sources through electrolysis methods, and reported on their efficiency
- Analyzed the technological and economic challenges associated with the deployment of green hydrogen production technologies
- Evaluated and studied the available hydrogen storage technologies, including compressed gas, liquid hydrogen, metal hydrides, and underground hydrogen storage, and compared their performance, advantages, and challenges
- Presented a pipeline for an efficient and safe hydrogen transportation infrastructure based on tube trailers, maritime shipping, and presented associated risks, challenges, and governmental policies needed
- Evaluated the large-scale hydrogen deployment across different applications, including transportation, buildings, energy, food, ammonia production, and industry
- Summarized and presented international strategies and current movements towards a safe and well-deployed green hydrogen economy

By completing the comprehensive review presented, several key conclusions and takeaways have emerged, providing a continuing path to further development and adoption of a hydrogen-based economy, as discussed in its full pipeline. While the following key findings and takeaways illustrate the promising, climate-resilient future that hydrogen enables, they also highlight areas that require serious strategic planning and improvement to optimize its use.

- The total percentage of green hydrogen production relative to global hydrogen production is only 2%. In contrast, grey or black hydrogen, produced by harmful methods, contribution reaches approximately 96%, which emphasized on the global needs for green hydrogen prduction from clean and renewable energy sources for a cleaner hydrogen economy

- Solar-based renewable energy systems in intergration with concentrated solar power (CSP) systems present a promising model in comparison with other methods for hydrogen production, despite the current limitations emposed by its capital cost and efficiency
- Wind based and hybrid hydrogen production technologies have shown a promising potential for GHG emissions reduction. Lifecycle assessments show up to 94% reduction in GHG emissions in comparison with steam methane reforming, presenting lower lifecycle emissions reaching 0.68 CO_2-eq/KG H_2
- Biomass energy is the most excellent renewable energy source, contributing to more than 10.3% to the global energy supply.
- Hydrogen production increases significantly by adopting geothermal-assisted electrolysis, from 38% to 64% with geothermal fluid temperature ranging from 130 °C to 200 °C.
- Advanced and robust hydrogen storage technologies are to be adopted and developed due to their high gravimetric energy density of 120–142 MJ/kg and low volumetric energy density of 0.01 MJ/L at standard conditions.
- Hydrogen transportation methods include road, rail, ship, or pipeline. However, the existing pipeline infrastructure provides a more efficient method than electricity transmission in some situations, with the need to address associated risks such as embrittlement
- Fuel cells are increasingly used in many applications related to transportation and industries. They play a vital role in utilizing hydrogen as it generates electricity with only water as a byproduct, with a critical need for coming up with more technologies and applications using it as the leading energy source
- Many nations including India, China, and EU member states, are adopting national hydrogen strategies and serious moves to effectively increase green hydrogen capacity and reduce dependency on fossil-based sources

CRediT authorship contribution statement

Mohammed Ghazal: Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization; **Malaz Osman:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation; **Marah Alhalabi:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation; **Abdalla Gad:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation; **Maha Yaghi:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation; **Mohamad Ramadan:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization; **Mohammad Alkhedher:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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