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Review

Hydrogen energy systems: Technologies, trends, and future prospects

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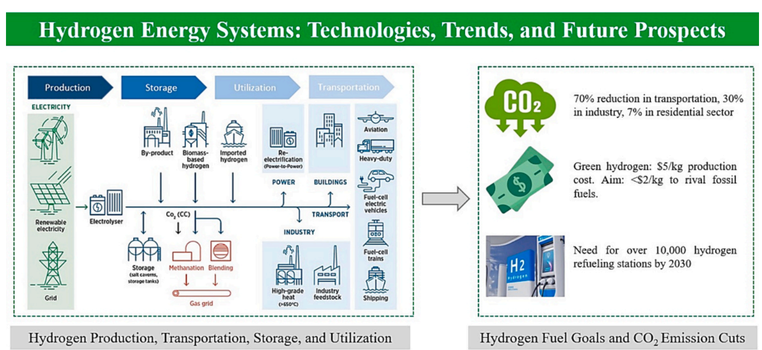
HIGHLIGHTS

- Study explores sustainable hydrogen solutions.
- Highlights hydrogen's role in reducing emissions
- Examines technological advances in hydrogen storage.
- Evaluates policy impacts on hydrogen adoption.

GRAPHICAL ABSTRACT



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ABSTRACT

This review critically examines hydrogen energy systems, highlighting their capacity to transform the global energy framework and mitigate climate change. Hydrogen showcases a high energy density of 120 MJ/kg, providing a robust alternative to fossil fuels. Adoption at scale could decrease global CO_2 emissions by up to 830 million tonnes annually. Despite its potential, the expansion of hydrogen technology is curtailed by the inefficiency of current electrolysis methods and high production costs. Presently, electrolysis efficiencies range between 60 % and 80 %, with hydrogen production costs around $5 per kilogram. Strategic advancements are necessary to reduce these costs below $2 per kilogram and push efficiencies above 80 %. Additionally, hydrogen storage poses its own challenges, requiring conditions of up to 700 bar or temperatures below −253 °C. These storage conditions necessitate the development of advanced materials and infrastructure improvements. The findings of this study emphasize the need for comprehensive strategic planning and interdisciplinary efforts to maximize hydrogen's role as a sustainable energy source. Enhancing the economic viability and market

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integration of hydrogen will depend critically on overcoming these technological and infrastructural challenges, supported by robust regulatory frameworks. This comprehensive approach will ensure that hydrogen energy can significantly contribute to a sustainable and low-carbon future.

Nomenclature

AEM	Anion Exchange Membrane
AB2	Type AB2 Metal Hydride
AB5	Type AB5 Metal Hydride
AFCs	Alkaline Fuel Cells
APUs	Auxiliary Power Units
ATR	Autothermal Reforming
BES	Bioelectrochemical Systems
$CaLi_2(BH_4)_4$	Calcium Lithium Borohydride
CaO	Calcium Oxide
CCS	Carbon Capture and Storage
CdS	Cadmium Sulfide
CFRPs	Carbon Fiber-Reinforced Polymers
CH_4	Methane
CLR	Chemical Looping Reforming
CO_2	Carbon Dioxide
COFs	Covalent Organic Frameworks
CNTs	Carbon Nanotubes
DRI	Direct Reduced Iron
GHGs	Greenhouse Gases
H^+	Protons
H_2	Hydrogen Gas
H-DRI	Hydrogen Direct Reduction
H0-DBT	Dibenzyltoluene
H18-DBT	Perhydro-Dibenzyltoluene
HPTSU	Hydrogen Production, Transportation, Storage, and Utilization
ICEs	Internal Combustion Engines
KOH	Potassium Hydroxide
LCA	Life Cycle Assessment
$Li_2Mg(BH_4)_4$	Lithium Magnesium Borohydride
$LiAlH_4$	Lithium Aluminum Hydride
$LiBH_4$	Lithium Borohydride
$LiNH_2$	Lithium Amide
Li_2NH	Lithium Imide
LOHCs	Liquid Organic Hydrogen Carriers
MCFCs	Molten Carbonate Fuel Cells
MECs	Microbial Electrolysis Cells
MFCs	Microbial Fuel Cells
$Mg(BH_4)_2$	Magnesium Borohydride
MgH_2	Magnesium Hydride
$Mg(NH_2)_2$	Magnesium Amide
MOFs	Metal-Organic Frameworks
NaOH	Sodium Hydroxide
N_2	Nitrogen
$NaAlH_4$	Sodium Aluminum Hydride
$NaBH_4$	Sodium Borohydride
NEC	N-Ethylcarbazole
NH_3BH_3	Ammonia Borane
NO_x	Nitrogen Oxides
O^{2-}	Oxygen Ions
OH^-	Hydroxide Ions
PAFCs	Phosphoric Acid Fuel Cells
P2G	Power-to-Gas
PCFCs	Protonic Ceramic Fuel Cells
PEM	Proton Exchange Membrane
PM	Particulate Matter
POX	Partial Oxidation
PAFs	Porous Aromatic Frameworks
p-BN	Porous Boron Nitride
SCWG	Supercritical Water Gasification
SE-SMR	Sorption-Enhanced Steam Methane Reforming
SMR	Steam Methane Reforming
SNG	Synthetic Natural Gas
SOE	Solid Oxide Electrolysis
SOFCs	Solid Oxide Fuel Cells
SO_x	Sulfur Oxides
TiO_2	Titanium Dioxide
TRL	Technological Readiness Level
VFAs	Volatile Fatty Acids
YSZ	Yttria-Stabilized Zirconia

1. Introduction

Global energy demands are escalating, driven by the confluence of demographic growth, economic development, and urban expansion. Projections indicate that with the global population expected to approach 9.7 billion by 2050, these factors will converge to amplify the imperative for increased energy production (Dias et al., 2021). Presently, approximately 80 % of the world's energy consumption is attributed to the use of fossil fuels, including natural gas, coal, and oil (Hassan et al., 2021a). The combustion of these resources leads to the release of significant quantities of Greenhouse Gasses (GHGs), primarily Carbon Dioxide (CO_2), thereby contributing to global warming and subsequent alterations in climate patterns. These shifts result in heightened occurrences of severe weather events, rising sea levels, and reduced biodiversity (Tiedje et al., 2022). Additionally, the burning of fossil fuels emits Sulfur Oxides (SO_x), Particulate Matter (PM), and Nitrogen Oxides (NO_x) into the atmosphere, significantly contributing to air pollution and posing substantial health risks (Asghar et al., 2021). Moreover, the unequal distribution of fossil fuel reserves has generated geopolitical conflicts and concerns related to energy security (San-Akca et al., 2020). In response to mounting environmental concerns and energy security issues, numerous countries have begun to invest in clean energy sources. Renewable energy sources like wind, solar, and hydroelectric power exhibit minimal or negligible GHGs, effectively reducing the carbon footprint associated with the energy sector (Rahman et al., 2022a). The increasing demand for sustainable and environmentally friendly energy alternatives has propelled advancements in technology related to the production, storage, and distribution of renewable energy. In this context, hydrogen has garnered significant attention as a promising clean energy carrier because of its high energy density, environmental compatibility, and versatility across various applications (Hren et al., 2023). As a potential solution to ongoing challenges in the energy sector, hydrogen has the potential to significantly contribute to the global shift toward a more sustainable, low-carbon future. This transformation can be facilitated by seamlessly integrating hydrogen systems with clean energy sources and addressing the intermittent nature of these sources (Striolo and Huang, 2022).

Hydrogen has been acknowledged as a vital component in the shift toward an economy with fewer GHGs. The essential components of the transition are the methods of Hydrogen Production, Transportation, Storage, and Utilization (HPTSU), as shown in Fig. 1. Several techniques employed to produce hydrogen to meet the increasing need for sustainable energy are referred to as hydrogen production technologies (Zhang et al., 2024). The processes mentioned above can be categorized into four main groups: thermochemical, electrochemical, biological, and photocatalytic production. Ensuring secure and efficient transfer of hydrogen from production sites to consumers is a pivotal factor in enabling widespread adoption of hydrogen as an energy carrier. Various methods for hydrogen transportation are encompassed within this process (Faye et al., 2022). The techniques can be categorized as modes of transportation for hydrogen in gaseous, liquid, and using hydrogen carriers. The use of hydrogen as an energy source necessitates the presence of hydrogen storage technologies, which are crucial for assuring the secure and reliable retention of hydrogen until it is needed (Speigel, 2020). The technologies involve the storage of hydrogen in gaseous, liquid, and solid-state forms. The incorporation of hydrogen into practical energy conversion processes and its diverse range of uses are included in hydrogen usage technologies (Faye et al., 2022). This area encompasses many technologies, including fuel cell technology, hydrogen combustion, energy storage, industrial processes, and grid balancing. This comprehensive review aims to offer a complete examination of recent developments, obstacles, and future possibilities in HPTSU technologies. The focus will be on the most intriguing and novel techniques currently being explored.

This review provides vital insights into the role of hydrogen as a crucial driver in creating a more environmentally conscious and sustainable energy landscape by examining the present state of HPTSU. Moreover, it underscores the need for additional study in certain areas to support the widespread use of hydrogen technology on a larger scale. Moreover, this analysis examines the fundamental obstacles and constraints associated with current hydrogen technologies, encompassing aspects such as financial implications, safety concerns, and infrastructural demands. This study seeks to delineate the essential research domains that require attention to effectively surmount these obstacles.

2. Hydrogen production technologies

2.1. Overview of hydrogen production technologies

Hydrogen production technologies comprise a range of methods employed to produce Hydrogen Gas (H_2) from various sources (Zhang et al., 2024). Several methodologies are available for hydrogen synthesis, encompassing thermochemical, electrochemical, biological, and photocatalytic techniques. Fig. 2 presents a comprehensive overview of the many approaches employed for hydrogen production. Thermochemical approaches encompass processes that involve reactions at elevated temperatures when input materials undergo transformations to produce hydrogen (Norouzi, 2022). Utilization of electricity in electrochemical processes facilitates the production of hydrogen through chemical reactions (Paul and Symes, 2021). Biological methodologies use microorganisms or their enzymes to facilitate hydrogen production through biological mechanisms (Pal et al., 2022). Photocatalytic methods use photocatalysts, which are materials capable of absorbing light, to promote the process of water splitting into oxygen and hydrogen upon exposure to sunlight (Luo et al., 2021).

2.2. Discussion of hydrogen production technologies

2.2.1. Thermochemical production

Methods involving thermochemistry for hydrogen production use heat and chemical processes to produce hydrogen from various basic components (Norouzi, 2022). These approaches are commonly employed for large-scale hydrogen production. Key thermochemical processes include Seam Methane Reforming (SMR), Partial Oxidation (POX), Autothermal Reforming (ATR), and biomass gasification. SMR is a well-established primary method for large-scale hydrogen synthesis. It involves the interaction between methane, a type of natural gas, and steam at high temperatures ranging from 700 to 1000 °C. This reaction occurs in the presence of a catalyst, typically made of nickel (Boretti and Banik, 2021). The core reactions involved in SMR are as follows:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

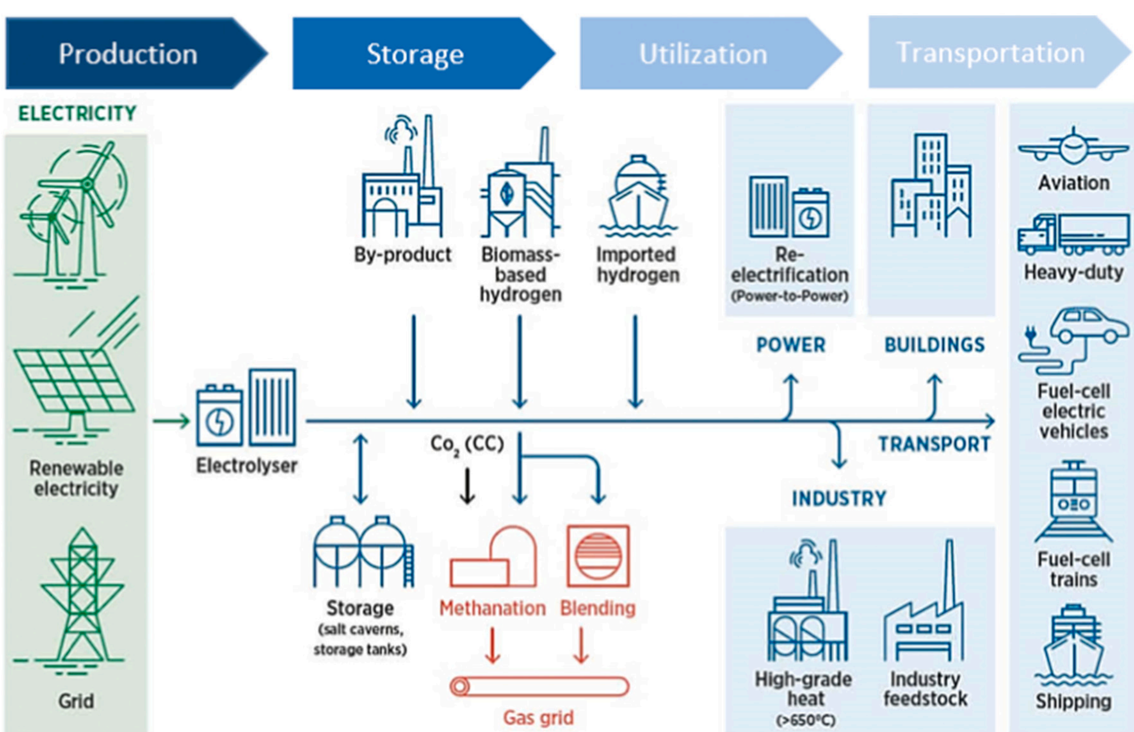

Fig. 1. Schematic diagram of HPTSU. Redrawn with permission from Ref. (Speigel, 2020).

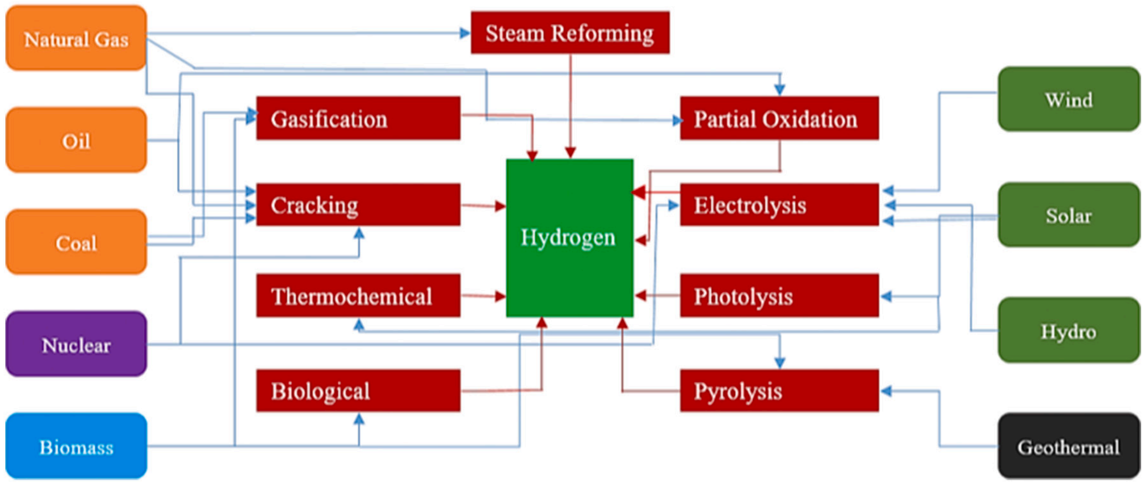

Fig. 2. Overview of various hydrogen production methods. https://www.intechopen.com/chapters/72194

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

Following production, hydrogen undergoes a series of steps, including isolation from other gasses, purification, and compression or liquefaction to aid in storage and transportation. The POX process involves exposing a hydrocarbon feedstock, like oil, coal, or heavy residue, to POX using either air or oxygen at elevated temperatures (approximately 1150–1500 °C) within a reactor containing refractory components (AlHumaidan et al., 2023). The primary reactions observed in the POX process are:

$$C_nH_m\frac{n}{2}O_2 \rightarrow nCO + \frac{m}{2}H_2 \quad (3)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (4)$$

The resulting syngas, which comprises a combination of CO_2 and hydrogen monoxide, undergoes a cooling process, during which hydrogen is separated from the carbon monoxide and purified. The ATR methodology integrates the fundamental concepts of both SMR and POX, thus presenting a more effective use of energy resources. In ATR, a hydrocarbon feedstock undergoes POX using air or oxygen while simultaneously introducing steam into the reaction. The phenomenon of ATR occurs at elevated temperatures, often ranging from 900 to 1100 °C, and under moderate levels of pressure (AlHumaidan et al., 2023). The primary reactions exhibit similarities to those observed in SMR and POX, leading to the production of hydrogen, which is subsequently subjected to separation, purification, and further treatment to facilitate its storage and transportation. Biomass gasification is the application of heat to biomass materials, such as agricultural waste or wood, at high temperatures (about 800–1000 °C) using steam, air, or oxygen within a gasifier (Inayat et al., 2021). The key reactions that are significant include:

$$C + H_2O \rightarrow CO + H_2 \quad (5)$$

$$C + O_2 \rightarrow CO_2 \quad (6)$$

$$C + CO_2 \rightarrow 2CO \quad (7)$$

The resulting syngas comprises carbon monoxide, hydrogen, and CO_2. Before entering a water-gas shift reactor to boost hydrogen production, the syngas undergoes a cooling and cleaning process. Ongoing research and development focus on innovative thermochemical techniques to improve the efficiency, environmental sustainability, and cost-effectiveness of hydrogen production. One such advancement is Sorption-Enhanced SMR (SE-SMR), an enhanced version of conventional SMR that integrates hydrogen production with CO_2 capture (Masoudi Soltani et al., 2021; Wu and Wey, 2021). In SE-SMR, the reforming reactor is enhanced with a CO_2 sorbent like Calcium Oxide (*CaO*) or supported amine, enabling CO_2 collection within the reactor. This modification enhances hydrogen production and reduces the required reaction temperatures.

Chemical Looping Reforming (CLR) is another thermochemical process that utilizes an oxygen carrier based on metal oxide to indirectly provide oxygen for the POX of hydrocarbon feedstock (Hill et al., 2022; Zheng et al., 2022). It involves two reactors: a fuel reactor and an air reactor. Oxygen carrier circulation between the reactors facilitates oxygen transfer from air to fuel, resulting in improved process control, increased hydrogen yields, and reduced GHGs compared with conventional POX methods.

Plasma reformation, on the other hand, utilizes non-thermal plasma, a partially ionized gas, to produce reactive species that assist in converting feedstocks containing hydrocarbons into syngas (Saleem et al., 2023). This occurs under lower pressures and temperatures than those of traditional thermochemical processes, offering energy conservation and reduced GHGs.

Supercritical Water Gasification (SCWG) is an innovative gasification technique that uses supercritical water as the medium for gasification (Houcinat et al., 2022). This method involves converting biomass or organic feedstocks into hydrogen and other gasses under extreme pressures and temperatures (Demirel et al., 2021). For detailed information on feedstocks, pressures, temperatures, energy use efficiency, CO_2 emission rate, and H_2 purity associated with each thermochemical hydrogen production technique, please refer to Table 1.

Thermochemical processes involve a diverse range of techniques used in the production of hydrogen. They are used in many sectors and offer several advantages. Hydrogen derived from thermochemical processes has the potential to be used for power production in fuel cells or by direct combustion in engines. Moreover, it functions as a raw material in several chemical processes. These techniques result in significant hydrogen quantities and demonstrate remarkable conversion efficiency (Inayat et al., 2020). The technique known as SMR has been widely used for hydrogen production for several decades (Chau et al., 2022). It is an established and fully developed technology in this field. Thermochemical techniques can seamlessly integrate with the current coal and natural gas infrastructure, thus avoiding the necessity for further capital investments (Skorek-Osikowska, 2022). Nevertheless, it is common for them to heavily depend on fossil fuels, resulting in the release of GHGs and thereby worsening the issue of climate change (Amin et al., 2022a). The methods require a substantial amount of energy, which is frequently obtained from non-renewable sources. In addition, these processes may encounter difficulties in terms of scalability to fulfill the increasing demands for hydrogen (Qureshi et al., 2022). The objective of this research

Table 1
Assessment of diverse thermochemical methods for hydrogen production (Hill et al., 2022; Zheng et al., 2022; Saleem et al., 2023; Houcinat et al., 2022; Demirel et al., 2021).

Technology	Feedstock	Operating temp.	Operating pressure	Efficiency	CO_2 rate	H_2 purity
SMR	Natural gas	700–1000 °C	Moderate	Moderate	High	High
POX	Coal, oil, heavy residues	1150–1500 °C	Moderate	Low to moderate	High	Moderate
ATR	Hydrocarb-ons	900–1100 °C	Moderate	High	High	High
Biomass gasification	Biomass	800–1000 °C	Moderate	Moderate	Low	Moderate
SE-SMR	Natural gas	600–900 °C	Moderate	Moderate	Low to high	High
CLR	Hydrocarb-ons	800–1000 °C	Moderate	Moderate	Low to high	High
Plasma reforming	Hydrocarb-ons, waste	Varies (lower than SMR)	Low to moderate	Moderate to high	Low	Moderate
SCWG	Biomass, wet feedstock	400–600 °C	High	High	Low	Moderate

is to enhance the efficiency and sustainability of thermochemical processes, such as solar-driven methodologies and the use of biomass as a feedstock. Thermochemical processes can synergize with sources of clean energy, such as solar and wind power, resulting in the production of environmentally friendly hydrogen. This integration offers a promising avenue to decrease dependence on fossil fuels and mitigate emissions. The use of Carbon Capture and Storage (CCS) technology can enhance the environmental sustainability of these operations.

Understanding the mechanisms underlying thermochemical hydrogen production methods such as SMR, POX, ATR, Biomass Gasification, and advanced techniques like SE-SMR, CLR, Plasma Reformation, and SCWG is crucial for optimizing these processes and their environmental impact.

Catalysts play a crucial role in lowering activation energy and enhancing reaction rates. For example, nickel catalysts in SMR facilitate the breaking of C—H bonds in methane, initiating the reforming process. Further exploration of catalyst interactions at the molecular level could lead to the development of more efficient catalysts, potentially reducing operational temperatures and energy consumption (Norouzi, 2022).

Temperature and pressure dynamics significantly influence thermochemical reactions. Elevated temperatures drive endothermic reactions in SMR and POX, while pressure variations affect the equilibrium of the water-gas shift reaction, thus impacting hydrogen yield (Boretti and Banik, 2021; AlHumaidan et al., 2023). A deeper understanding of these thermodynamic principles can guide the optimization of conditions for maximum efficiency and hydrogen purity.

Advanced techniques like SE-SMR and CLR demonstrate a shift toward integrating hydrogen production with environmental sustainability (Masoudi Soltani et al., 2021; Wu and Wey, 2021). Mechanistic insights into CO_2 capture in SE-SMR and oxygen transfer in CLR can inform the design of processes that enhance hydrogen production while reducing GHGs.

Material selection for reactors and catalysts is critical, considering factors like chemical stability, durability, and reactivity. Advances in material science, particularly the development of materials resistant to harsh conditions for ATR or efficient electrolytes for SCWG, can significantly impact the viability and cost-effectiveness of hydrogen production technologies (Hill et al., 2022; Houcinat et al., 2022).

Future research should focus on innovating catalyst materials and structures to enhance selectivity and longevity, thereby reducing the environmental footprint of thermochemical hydrogen production. Additionally, integrating thermochemical processes with renewable energy sources and carbon capture technologies offers a pathway to truly sustainable hydrogen production.

2.2.2. Electrochemical production

Electricity is used to split water into molecules of oxygen and hydrogen in electrochemical processes, providing a sustainable and environmentally friendly approach to hydrogen production when powered by renewable energy sources (Paul and Symes, 2021). Water electrolysis is the primary method utilized for this purpose (Anwar et al., 2021). In this process, water is dissociated into hydrogen and oxygen by passing an electric current through it using an electrolyzer. This device comprises an anode and a cathode, which are separated by an electrolyte and immersed in it to conduct electricity. At the anode, water molecules are oxidized, yielding oxygen and different ions: Hydroxide Ions (OH^-) in alkaline electrolysis, Protons (H^+) in Proton Exchange Membrane (PEM) electrolysis, or Oxygen Ions (O^{2-}) in Solid Oxide Electrolysis (SOE). These ions move through the electrolyte from the anode to the cathode, where they are reduced to form hydrogen (Al-Shara et al., 2021). The resulting hydrogen and oxygen gases are then separated, collected, and either compressed or liquefied for storage and transport.

Electrolysis methods are primarily categorized into three types: alkaline, PEM, and SOE. Alkaline electrolysis uses aqueous solutions of Sodium Hydroxide ($NaOH$) or Potassium Hydroxide (KOH) as the electrolyte and is noted for its cost-effectiveness and adaptability at different scales (de Groot et al., 2022). PEM electrolysis employs a proton-conducting membrane, offering higher energy efficiency and the ability to operate at higher current densities (Sanchez-Molina et al., 2021). SOE uses solid oxides or ceramic electrolytes that can withstand high temperatures (700–1000 °C), providing significant energy efficiency though it has less developed commercial applications due to more complex system requirements (Dey et al., 2020).

Advancements in electrochemical technology include Microbial Electrolysis Cells (MECs), Anion Exchange Membrane (AEM) electrolysis, and bipolar membrane electrolysis. AEM electrolysis, which employs an anion exchange membrane and non-precious metal catalysts, operates at lower temperatures than PEM and offers a more cost-effective alternative (Chen et al., 2021a). Bipolar membrane electrolysis uses a composite membrane with a bipolar junction that helps optimize water dissociation and hydrogen evolution, potentially increasing the overall energy efficiency of the process (Sun et al., 2022a). MECs use electroactive microorganisms to produce hydrogen from biological substrates like biomass or wastewater (Mayerhöfer et al., 2020; Amin et al., 2022b).

Electrolysis enables the transformation of surplus power from renewable sources such as solar and wind into hydrogen, which can be stored and later used to generate electricity using fuel cells (Mayyas et al., 2020). Incorporating renewable energy into electrolysis promotes hydrogen production without GHGs, enhancing environmental sustainability (Amin et al., 2022a). Electrolysis systems are customizable to meet various hydrogen production needs, generating high-purity hydrogen essential for specific applications like fuel cells (Yue et al., 2021). However, these systems are associated with high initial investments and operating costs, mainly due to the use of expensive catalysts and energy-intensive operations (Fragiacomo et al., 2022). While electrolysis is less energy efficient compared to thermochemical methods such as SMR, its environmental impact depends on the energy source used. Ongoing efforts to improve electrolysis efficiency and reduce costs are critical, especially as renewable energy becomes more prevalent, positioning electrolysis as a key technology in sustainable hydrogen production and energy storage (Younas et al., 2022).

For detailed comparisons of each electrochemical hydrogen production technology, including operating temperatures, catalysts, energy efficiency, hydrogen purity, and potential integration with renewable energy sources, please refer to Table 2.

Table 2
Assessment of diverse electrochemical methods for hydrogen production (Al-Shara et al., 2021; de Groot et al., 2022; Sanchez-Molina et al., 2021; Dey et al., 2020; Chen et al., 2021a; Sun et al., 2022a; Mayerhöfer et al., 2020; Amin et al., 2022b).

Technology	Operating temperature	Catalysts	Energy efficiency	H_2 purity	Renewable integration
Alkaline electrolysis	60–80 °C	Non-precious metals	Moderate	High	Good
PEM	50–80 °C	Precious metals (Pt)	High	High	Good
SOE	700–1000 °C	Non-precious metals	High	High	Limited
AEM	50–80 °C	Non-precious metals	Moderate to high	High	Good
Bipolar membrane electrolysis	Ambient to 80 °C	Non-precious metals	Moderate to high	High	Good
MECs	Ambient to 40 °C	Non-precious metals	Low to moderate	Moderate	Limited

2.2.3. Biological production

The production of hydrogen through biological processes utilizes microorganisms or enzymes to catalyze the conversion of various organic substrates into hydrogen (Pal et al., 2022). These techniques are generally more eco-friendly, sustainable, and environmentally benign compared to traditional thermochemical and electrochemical methods. In the field of biological hydrogen synthesis, dark fermentation and photofermentation are the two widely recognized methods. Dark fermentation uses a range of organic substances such as sugars, wastewater, organic waste, and lignocellulosic biomass as substrates (Arun et al., 2022). These substrates must contain fermentable components like organic acids and sugars, often requiring pretreatment to break down complex molecules into simpler, fermentable forms (Kucharska et al., 2020). This involves various chemical, physical, and enzymatic processes. A bioreactor is then inoculated with a mixed anaerobic bacterial culture along with the substrate. In an oxygen-free environment, these bacteria break down the organic substances, producing hydrogen and by-products like Volatile Fatty Acids (VFAs), alcohols, and CO_2. The hydrogen is then separated using techniques such as gas sparging, membrane separation, and adsorption (Rasheed et al., 2021).

Photofermentation typically uses VFAs as substrates, which are produced during dark fermentation or other anaerobic processes (Jain et al., 2022). Photosynthetic bacteria, such as purple non-sulfur bacteria, are added to a bioreactor containing the substrate (Chen et al., 2023a). This bioreactor is exposed to natural or artificial light to enable photosynthesis. Under anaerobic and illuminated conditions, these bacteria convert the substrate into hydrogen and by-products like CO_2. Similar to dark fermentation, the hydrogen produced is separated from other components and undergoes purification processes for storage and transportation.

Recent developments in biological hydrogen production include cyanobacterial dihydrogen production, which uses specific strains of cyanobacteria capable of producing hydrogen through photosynthesis, utilizing oxygen and nitrogen-fixing enzymes (Kamshybayeva et al., 2023). These strains are cultivated under controlled conditions with specific light, temperature, and nutritional parameters to maximize hydrogen production. Nitrogen depletion is used as a stress condition to induce the activation of the nitrogenase enzyme in cyanobacteria, leading to hydrogen production (Sadvakasova et al., 2020). Another approach involves enhancing hydrogen production through microbial consortia, which use organic substances like carbohydrates, wastewater, and lignocellulosic biomass as substrates (Tomasini et al., 2023). These consortia, whether naturally occurring or engineered, include diverse bacteria or microorganisms optimized to improve hydrogen production rates and yields (Joshi et al., 2023). In Bioelectrochemical Systems (BES), organic substances serve as substrates where electroactive microorganisms oxidize them at an anode, producing electrons and protons (Ergal et al., 2022; Sharma et al., 2023a). The electrons travel through an external circuit while the protons move across an ion exchange membrane to the cathode, where hydrogen is produced by reduction (Al-Mamun et al., 2023).

Biological hydrogen production methods are seen as promising due to their minimal GHGs and their use of waste materials or sunlight, making them environmentally friendly and sustainable (Gautam et al., 2023; Awasthi et al., 2022; Anjum et al., 2023). These processes typically occur at ambient or low temperatures, reducing the energy requirements for hydrogen production (Ramprakash et al., 2022). However, these systems currently offer lower hydrogen yields and conversion efficiencies compared to other hydrogen production methods. The rate of hydrogen production progresses slowly due to the inherent limitations within biological systems (Lepage et al., 2021). The field is still in early development stages, indicating the need for further research and improvement to enhance efficiency and scalability (Ferraren-De Cagalitan and Abundo, 2021). Advances in genetic manipulation and synthetic biology could improve the effectiveness of algae and microorganisms used in hydrogen production. Ongoing research and development are expected to lead to better reactor designs, optimized processes, and the integration of biological techniques with other hydrogen production methods. For a comprehensive analysis of substrates, microorganisms, light dependency, and hydrogen yield associated with each biological hydrogen production process, please refer to Table 3.

2.2.4. Photocatalytic production

Photocatalytic methods employed in hydrogen production use photocatalysts to produce hydrogen from water or alternative substrates in the presence of light (Shi et al., 2023). A widely adopted approach for hydrogen production through photocatalysis involves semiconductor photocatalysts designed for water splitting (Ishaq et al., 2021). The effectiveness of the photocatalytic process heavily depends on the choice of the photocatalyst, with common selections including Cadmium Sulfide (CdS), Titanium Dioxide (TiO_2), and various other metal oxides or sulfides (Anucha et al., 2022). Essential characteristics of photocatalyst materials are appropriate bandgap energy, high stability, and low toxicity levels. These materials undergo synthesis and processing to achieve a suitable morphology, such as nanoparticles, thin layers, or immobilization on a substrate, to enhance charge separation, light absorption, and reaction kinetics (Šuligoj et al., 2022).

The photocatalyst is placed within a photoreactor, which can be designed as either an enclosed structure or an open pond system, depending on the application and process design. The main goals of photoreactor design are to maximize light absorption, facilitate mass transfer, and prevent the reverse reaction between hydrogen and oxygen. The process initiates by introducing water into the photoreactor, which is then illuminated using a light source like artificial light or natural sunlight. This illumination activates the photocatalyst, generating electron-hole pairs. Electrons from these pairs drive the reduction of water to form hydrogen at the catalyst surface, while the holes oxidize water to produce oxygen (Lakhera et al., 2021). The oxygen and hydrogen gases produced are then isolated from one another, with the collected hydrogen undergoing processes such as purification, compression, or liquefaction for storage and transportation.

The use of semiconductor photocatalysts in water splitting offers a promising, environmentally friendly method for hydrogen production. Current developments in photocatalytic technologies focus on creating innovative materials, nanostructures, and hybrid systems to increase efficacy and functionality. Recent advancements include the development of photocatalysts with low bandgap semiconductors, doped materials, and ternary/quaternary compounds that improve light absorption, charge separation, and reaction kinetics (Zhang et al.,

Table 3
Assessment of diverse biological methods for hydrogen production (Arun et al., 2022; Kucharska et al., 2020; Rasheed et al., 2021; Jain et al., 2022; Chen et al., 2023a; Kamshybayeva et al., 2023; Sadvakasova et al., 2020; Tomasini et al., 2023; Joshi et al., 2023; Ergal et al., 2022; Sharma et al., 2023a; Al-Mamun et al., 2023).

Technology	Substrates	Microorganisms	Light dependency	H_2 Yield
Dark fermentation	Carbohydrates, organic waste, wastewater, lignocellulosic biomass	Anaerobic bacteria	No	Moderate
Photofermentation	VFAs	Photosynthetic bacteria	Yes	Low to moderate
Cyanobacterial biohydrogen production	CO_2, water	Cyanobacteria	Yes	Low
Microbial consortia for enhanced hydrogen production	Carbohydrates, organic waste, wastewater, lignocellulosic biomass	Diverse microbial consortia	No	Moderate to high
BES	Wastewater, biomass	Electroactive microorganisms	No	Low to moderate

2023a). Photocatalysts featuring diverse nanostructures like nanorods, nanowires, and quantum dots have been engineered to enhance light absorption and charge transfer, boosting overall photocatalytic efficiency (Guo et al., 2022a). Hybrid photocatalysts, combining materials such as organic-inorganic or semiconductor-metal, aim to increase both efficiency and stability by leveraging the synergistic effects from different materials, thereby improving charge separation and reducing recombination (Zhou et al., 2022a). Additionally, tandem or *Z*-scheme photocatalytic devices, which link multiple photocatalysts with optimal bandgap alignments, utilize a broader solar spectrum and reduce charge recombination to increase the overall efficiency of solar-to-hydrogen conversion (Ayodhya, 2023).

Photocatalytic hydrogen production is a sustainable method that uses solar energy and water to produce hydrogen, minimizing GHGs and significantly contributing to the renewable energy sector (Hassan et al., 2023a). This technology presents a viable option for storing solar energy, enhancing grid stability and energy management. However, the current efficiency of photocatalytic hydrogen production trails behind methods like SMR and electrolysis (Oh et al., 2022). Many photocatalytic materials suffer from autocorrosion or deactivation over time, which diminishes efficiency and requires frequent material replacement or regeneration (Priya et al., 2021). Photocatalytic hydrogen production also depends on intermittent sunlight, restricting continuous hydrogen synthesis and making it unavailable throughout the day (Rahman et al., 2022b). Ongoing research is directed toward developing novel photocatalytic materials with improved stability, efficiency, and cost-effectiveness. Future advancements can enhance reactor design, light capture efficiency, and overall system optimization, improving the effectiveness of hydrogen production through photocatalytic systems. The growing acceptance of renewable energy sources fosters interest in the potential of photocatalytic hydrogen production for producing green hydrogen, complementing existing renewable energy technologies and facilitating energy storage.

2.3. Summary of the hydrogen production technologies

In summary, hydrogen production technologies encompass a diverse array of methods and processes used to produce H_2, a crucial element for numerous industrial applications and an increasingly significant sustainable energy carrier. The discussed production technologies encompass various methodologies, including thermochemical, electrochemical, biological, and photocatalytic approaches. Table 4 provides a comprehensive analysis of these four fundamental hydrogen production technologies, outlining their respective advantages, disadvantages, current developmental stages, and potential future prospects.

Thermochemical methods employed in hydrogen production offer established and scalable solutions; however, they face challenges related to emissions and reliance on finite resources. Future advancements in hydrogen production hinge on integrating CCS methods and adopting sustainable feedstocks to enhance both the environmental impact and efficiency of this well-established technology.

The use of electrochemical methods for hydrogen production presents a viable and sustainable approach characterized by eco-friendliness. However, it remains crucial to strive for enhancements in efficiency and cost-effectiveness. With ongoing research and development efforts, electrochemical technologies can become a major and sustainable alternative for economically feasible hydrogen production.

Biological hydrogen production holds promise for achieving environmentally sustainable practices. However, challenges related to efficiency and scalability exist for this approach. Despite being in the early stages of research, advancements in biotechnology and process optimization can significantly elevate the role of biological hydrogen production, enabling sustainable and efficient hydrogen production.

Photocatalytic hydrogen production, which utilizes solar energy to produce hydrogen, is still in its early stages of advancement. Breakthroughs in material science and reaction efficiency are imperative for realizing the potential of hydrogen production as a promising avenue for clean and sustainable energy sources. As scientific research progresses, the use of photocatalytic production holds the potential to become a significant contributor to sustainable hydrogen production.

3. Hydrogen transportation technologies

3.1. Overview of hydrogen transportation technologies

The transportation of hydrogen plays a crucial role in hydrogen economic growth because it involves the movement of hydrogen between its point of production and its intended destination for usage or

Table 4
Overview and contrast of different hydrogen production methods.

Technology	Advantages	Disadvantages	Development stage	Future outlook
Thermochemical production	Well-established, easily scalable, highly efficient	Greenhouse gas emissions, dependence on finite resources	Mature	Integration of CCS, Transition to Sustainable Feedstocks
Electrochemical production	Eco-friendly, high energy conversion efficiency, versatile output	Efficiency challenges, cost considerations	Advanced	Enhanced efficiency, increased cost competitiveness
Biological production	Environmentally friendly, utilization of renewable resources, waste utilization	Lower yields, scaling challenges	Developmental	Anticipated biotechnological breakthroughs, process optimization
Photocatalytic production	Renewable, environmentally clean, sunlight-powered	Early stage of development, material constraints	Early stage	Advances in materials, enhanced reaction efficiency

storage (Faye et al., 2022). Multiple methodologies are available for the transportation of hydrogen (Noh et al., 2023). The transportation of hydrogen in its gaseous form is a commonly used technique for distributing gaseous hydrogen. This methodology involves the compression of hydrogen at increased pressures. The compressed hydrogen is subsequently stored and conveyed using specifically engineered tube trailers or high-pressure gas cylinders that possess the necessary strength to endure such elevated pressures. On the other hand, in the context of liquid hydrogen transportation, the gaseous form of hydrogen undergoes a cooling process, resulting in its conversion into a liquid state at exceedingly low temperatures. This technique enables the efficient transportation of larger quantities of hydrogen in a confined area, making it ideal for long-distance travel and the management of significant amounts of hydrogen. A different approach, referred to as hydrogen carrier transportation, involves chemically embedding hydrogen in carrier molecules. These carriers enable the storage and transfer of hydrogen at temperatures and pressures close to ambient conditions, thus streamlining the process of handling, transportation, and storage procedures in comparison to liquid or gaseous hydrogen. Fig. 3 shows the different hydrogen transportation methodologies.

3.2. *Discussion of hydrogen transportation technologies*

3.2.1. *Gaseous transportation*

The transportation of hydrogen in its gaseous state involves compressing the hydrogen under high pressures and transporting it in specialized containers to meet safety protocols and regulatory requirements (Noh et al., 2023). This method is favored for its cost-effectiveness and the availability of established infrastructure. High-pressure tube trailers and pipelines are the primary methods for transporting gaseous hydrogen. In the case of tube trailers, hydrogen is first compressed using compressors to reduce its volume, making transportation more efficient (Hassan et al., 2021b). It is then stored in pressure containers or cylinders at the production site before being loaded into specialized trucks that transport the hydrogen safely under high pressure (Hassan et al., 2021c). These trailers typically consist of multiple cylinders attached to a chassis, allowing for transport by road, ship, or rail, depending on specific needs and conditions. Upon arrival, the compressed hydrogen is transferred to appropriate storage facilities or used directly in places such as refueling stations or factories.

Similarly, the transportation of compressed hydrogen via pipelines involves injecting hydrogen into pipelines that can extend over long distances (Di Lullo et al., 2022). To prevent issues such as hydrogen embrittlement, which can degrade the materials used in pipelines due to hydrogen absorption (Wang et al., 2022), materials compatible with hydrogen must be used. Pipeline operations require systems for monitoring, leak detection, control, and emergency shutdowns to function effectively.

Advances in hydrogen compression technology have enhanced efficiency, safety, and cost-effectiveness. These advancements include various technologies such as diaphragm and piston compressors (Hassan et al., 2021b). Piston compressors work by displacing gas through the reciprocating motion of a piston within a cylinder, while diaphragm compressors use a flexible diaphragm to separate the gas from hydraulic fluids, reducing contamination and leakage risks. Centrifugal compressors, on the other hand, utilize a rotating impeller to impart kinetic energy to hydrogen, converting it into pressure energy. More sophisticated techniques like ionic liquid piston compression and electrochemical compression have also been developed. Ionic liquid piston compression uses an ionic liquid as a piston, controlled by magnetic or electric fields, to achieve nearly isothermal compression. Electrochemical compression, akin to principles used in PEM electrolysis, involves transporting gaseous hydrogen through an electrochemical cell where hydrogen ions and electrons are separated and then recombined at different pressures (Zhou et al., 2022b; Durmus et al., 2021). For a concise overview of the attributes of each compression technology, see Table 5.

The challenge of hydrogen embrittlement, which refers to the degradation of metallic materials due to hydrogen, is mitigated through research into coatings, innovative materials, and pipeline designs that enhance the efficacy and longevity of hydrogen infrastructure. Materials resistant to hydrogen embrittlement include nickel-based alloys, austenitic stainless steels, and certain aluminum alloys (Luo et al., 2020). High-entropy alloys, which have unique microstructures, show promise in effectively mitigating hydrogen embrittlement (Mohammadi et al., 2022). Non-metallic alternatives like polymer composite materials have also been successful in addressing the hazards associated with hydrogen embrittlement (Sun and Cheng, 2022). Surface treatments such as nitriding, carburizing, and shot peening can alter surface characteristics to enhance material resistance to embrittlement (Maleki et al., 2021). Protective coatings, like ceramic or metallic coatings, act as barriers to prevent hydrogen penetration, thereby reducing embrittlement risks (Laadel et al., 2022). The presence of impurities like sulfur, oxygen, or water in hydrogen can exacerbate embrittlement. Advanced purification methods such as membrane separation, pressure swing adsorption, and cryogenic distillation have proved highly effective in minimizing these impurities (Kim et al., 2022).

Gaseous hydrogen transportation is essential for the efficient delivery of hydrogen from production sites to end-users. It supports a variety of applications, including fuel cells that require high-purity hydrogen (Gordon et al., 2023). However, transporting hydrogen through pipelines can be costly due to the necessary infrastructure development and maintenance (Dehdari et al., 2022). The energy consumed in compressing hydrogen for transportation can also impact the overall efficiency of hydrogen as an energy carrier (Noh et al., 2023). Given hydrogen's high flammability and low ignition energy, stringent

(a) (b) (c)

Fig. 3. Diverse modalities of hydrogen transportation: (a) gaseous hydrogen transportation using high-pressure tube trailers, (b) Liquid hydrogen transportation via cryogenic tanker trucks, and (c) The metal hydride hydrogen storage tank used for solid hydrogen transportation.

Table 5
Assessment of different methods for compressing hydrogen gas (Noh et al., 2023; Hassan et al., 2021b; Hassan et al., 2021c; Di Lullo et al., 2022; Wang et al., 2022; Zhou et al., 2022b; Durmus et al., 2021).

Technology	Flow rate range	Cost level	Advantages	Disadvantages
Piston compression	Low to high	Moderate	High dependability, applicability across various pressure levels	High upkeep expenses, Noise and vibration
Diaphragm compression	Low to high	Moderate to high	Reduced risk of pollution and leakage, Suitable for small-scale applications	Lower flow rates, limited pressure span
Centrifugal compression	High	High	Elevated flow rates, High efficiency, Suitable for large-scale applications	Intricate design, Requires meticulous balancing, Sensitivity to changes in gas composition
Ionic liquid piston compression	Low to medium	High	Contactless operation, almost constant temperature compression, lower energy usage, minimal wear	Emerging technology, limited market availability, requires precise selection of ionic liquids, potential need for additional heat management
Electrochemical compression	Low to medium	High	Exceptionally efficient, no moving components, high-pressure output	Complex design, costly due to catalysts and membranes, susceptible to impurities in hydrogen gas

safety measures are critical during its transport, storage, and handling (Hansen, 2020). With the increasing demand for hydrogen and the growing importance of renewable energy sources, enhancing hydrogen transportation infrastructure is crucial to support efficient energy storage and distribution. Ongoing research and development are key to improving hydrogen compression and transportation technologies, ultimately boosting efficiency and cost-effectiveness in the transportation of gaseous hydrogen.

3.2.2. Liquid transportation

Liquid hydrogen transport involves a rigorous cryogenic process where gaseous hydrogen undergoes liquefaction at temperatures near −253 °C. This method, despite its high energy consumption, creates a denser energy carrier state suitable for efficient bulk movement, significantly improving the efficiency of transportation (Ratnakar et al., 2021). Once liquefied, the hydrogen is stored in well-insulated cryogenic tanks within the production facility, designed to maintain ultra-low temperatures and minimize thermal exchange (Ho Nguyen and Hoon Kim, 2022). It is then transferred to cryogenic tankers equipped with insulated tanks and pressure-relief devices to maintain necessary low temperatures and pressures during transit. These tankers, often employing road transport, facilitate the delivery of hydrogen in liquid form to its designated location, although rail or ship may also be used depending on infrastructure and requirements (Ahluwalia et al., 2023).

Upon arrival, the liquid hydrogen is transferred from the tanker to storage tanks or processing facilities at the end user's site. It is common practice to evaporate the hydrogen to ambient temperatures before usage. Strict safety protocols during transport are paramount, including monitoring temperature and pressure, employing leak detection systems, and adhering to relevant standards (Klebanoff et al., 2017; Yang et al., 2021).

Efforts to enhance the efficiency, reduce expenses, and improve safety in liquid hydrogen transport are ongoing. Innovations in tanker insulation aim to reduce heat transfer, with technologies such as vacuum insulation panels using materials like silica aerogel within a vacuum-sealed barrier and multilayer insulation, involving numerous layers of reflective materials, being key areas of development (Resalati et al., 2021; Li et al., 2021). Additionally, the use of Carbon Fiber-Reinforced Polymers (CFRPs) for tanker construction is researched for its potential to lighten tankers, potentially lowering costs and increasing payload capacity (Ekeocha et al., 2021).

Liquefaction technology advancements have led to significant reductions in energy use and costs (Massaro et al., 2023; Xu et al., 2023). The use of gases like helium or neon in the Brayton cycle and innovative refrigeration techniques like magnetic and thermoelectric refrigeration are part of these advancements (Zhang et al., 2023b; Xu et al., 2021; Abd El-Rahman et al., 2020; Qyyum et al., 2021). These developments not only reduce the energy required but also improve the overall efficiency through potential waste heat recovery measures (Su et al., 2020). Table 6 provides a comprehensive overview of these technologies.

Liquid hydrogen transportation plays a vital role in sectors like aerospace, where it is used as rocket fuel. The higher energy density of liquid hydrogen allows for more efficient transport and storage compared to its gaseous form, although the process's high energy requirements highlight the need for continued research and optimization (Noh et al., 2023; Okninski et al., 2021). The complexity and cost associated with maintaining cryogenic conditions, as well as the potential losses from boil-off gas, necessitate ongoing innovation to improve the economics and environmental impact of liquid hydrogen transport (Sotoodeh and Gudmestad, 2022).

As demand for hydrogen grows, the development and expansion of an efficient liquid hydrogen transportation infrastructure become crucial. This infrastructure not only supports the increasing hydrogen demand across various industries but also aligns with global efforts to enhance sustainability, positioning hydrogen as a key component of the renewable energy landscape.

3.2.3. Hydrogen carrier transportation

Hydrogen carriers significantly facilitate the transportation of hydrogen, providing an alternative to the complexities involved with transporting hydrogen in its gaseous or liquid forms. Common carriers include ammonia, metal hydrides, and Liquid Organic Hydrogen Carriers (LOHCs). Focusing on metal hydrides, hydrogen is combined with metal hydride-forming alloys, such as those based on magnesium or sodium, at the production site through an exothermic reaction. This reaction allows hydrogen to be absorbed and retained within the metallic hydride structure (Chen et al., 2021b). Transported to the intended destination using conventional methods like trucks, trains, or ships, the hydrogen-loaded metal hydride is then heated at the end point to release the stored hydrogen (Tong et al., 2021). The metal hydride can be recycled back to the production facility for rehydrogenation, forming a sustainable closed-loop transportation system.

Ammonia is produced through the Haber-Bosch process by reacting hydrogen with nitrogen using an iron catalyst under high pressure (Humphreys et al., 2021), while LOHCs involve the chemical combination of hydrogen with a liquid organic carrier like Dibenzyltoluene or N-Ethylcarbazole (*NEC*), typically using a catalyst under high pressure (Singh et al., 2021). These carriers provide efficient and practical solutions for hydrogen storage and transportation across various applications.

Innovative hydrogen carriers are also being explored, such as the synthesis of Magnesium Borohydride ($Mg(BH_4)_2$) through the combination of borane and magnesium, followed by hydrogenation at elevated

Table 6
Assessment of different hydrogen liquefaction methods (Ratnakar et al., 2021; Ho Nguyen and Hoon Kim, 2022; Ahluwalia et al., 2023; Klebanoff et al., 2017; Yang et al., 2021; Resalati et al., 2021; Li et al., 2021; Ekeocha et al., 2021; Massaro et al., 2023; Xu et al., 2023; Zhang et al., 2023b; Xu et al., 2021; Abd El-Rahman et al., 2020; Qyyum et al., 2021; Su et al., 2020).

Technology	Operating principle	Technical complexity	Advantages	Disadvantages
Linde-Hampson cycle	Utilizes Joule-Thomson expansion	Low	Simple design, easy to operate and maintain	Low efficiency, high energy usage
Claude cycle	Involves expansion turbine	Moderate	High efficiency, increased reliability	More intricate design, significant initial investment
Brayton cycle	Utilizes gas refrigeration	High	High efficiency, minimal energy consumption	Complex design, considerable initial investment
Magnetic refrigeration	Relies on magnetocaloric effect	High	No traditional refrigerants, high efficiency	Substantial initial investment, intricate design
Thermoacoustic	Utilizes sound wave-induced cooling	Moderate	Eco-friendly, does not use traditional refrigerants	Moderate efficiency, complex design
Two-stage mixed refrigerant cycles	Utilizes optimized mixed refrigerants	High	High efficiency, minimal energy consumption	Complex design, considerable initial investment

pressures. This substance boasts a high gravimetric hydrogen density, making it an effective hydrogen transporter (Wang et al., 2021a). Additionally, reactions between hydrogen and CO_2 may produce formic acid with the aid of catalysts (Mardini and Bicer, 2021). Research continues into enhancing LOHCs like *NEC* for their hydrogen storage capacity and improved thermodynamic properties (Dong et al., 2021). The exploration of reversible hydrogenation-dehydrogenation mechanisms in carriers like Dibenzyltoluene and Perhydro-Dibenzyltoluene (H18-DBT) supports their application in efficient hydrogen storage and release, suitable for transportation and other uses (Sisakova et al., 2021; Jorschick et al., 2020). Table 7 presents a detailed comparison of these hydrogen carriers.

Hydrogen carriers offer higher energy densities than gaseous or liquid hydrogen, enabling more efficient storage and transportation (Viteri et al., 2023). Additionally, many carriers present lower risks of flammability and explosion, enhancing safety during transport and storage. Some carriers, such as ammonia and LOHCs, can utilize existing infrastructure like pipelines, reducing the need for significant new investments (Di Lullo et al., 2022). However, releasing hydrogen from these carriers generally requires additional energy, potentially leading to conversion inefficiencies that impact overall energy efficiency (Otto et al., 2022). The deployment of hydrogen carrier technologies often involves complex chemical processes and specialized equipment for storage and release, necessitating substantial financial investment, particularly for the development of new materials or technologies (Usman, 2022; Cloete et al., 2022).

Hydrogen carriers mitigate the logistical challenges associated with transporting hydrogen in more traditional forms. By chemically binding hydrogen in forms that are easier to manage, carriers like metal hydrides provide an effective mechanism for the reversible storage and release of hydrogen, while ammonia and LOHCs offer versatile alternatives for long-distance transport (Chen et al., 2021b; Tong et al., 2021; Humphreys et al., 2021; Singh et al., 2021). Continued advancements in hydrogen carrier technologies aim to improve storage capacities, reduce costs, and enhance safety features, making hydrogen transport more efficient and viable. These efforts are critical as the demand for hydrogen grows, supporting the wider adoption of hydrogen as a clean energy source and enhancing the flexibility and resilience of the hydrogen supply chain.

3.3. Summary of hydrogen transportation technologies

In summary, hydrogen transportation technologies encompass various techniques and methodologies used for the distribution and conveyance of hydrogen from production facilities to storage sites or end users. This element is a crucial part of the overall hydrogen supply chain. The main methods for transporting hydrogen include gaseous hydrogen transportation, liquid hydrogen transportation, and the use of hydrogen carriers. Table 8 offers a comprehensive analysis of the main methods employed for hydrogen transportation, presenting a thorough examination of their respective advantages and disadvantages.

The transportation of hydrogen in its gaseous state is widely recognized as an established and economically efficient method for distributing hydrogen. Nevertheless, it is faced with obstacles of significant energy requirements and comparatively limited energy density. The future of hydrogen transportation is contingent on advancements in storage materials and the establishment of infrastructure to facilitate widespread use and efficient distribution.

Table 8
Overview and contrast of different methods for transporting hydrogen (Viteri et al., 2023; Otto et al., 2022; Usman, 2022; Cloete et al., 2022).

Technology	Advantages	Disadvantages
High-pressure tube trailers	Convenient deployment and scalability, flexible routing	Limited capacity, higher transportation expenses, safety concerns due to the high-pressure aspect
Pipelines	Substantial capacity, cost-efficiency, reliability	Significant initial investment, restricted geographic coverage, susceptibility to leaks and sabotage
Liquid transportation	Elevated energy content, established technology	Cryogenic storage needs, increased energy usage
Hydrogen carriers transportation	Convenient handling, transportation, and storage	Intricate chemical processes, high energy consumption

Table 7
Assessment of different methods for transporting hydrogen carriers (Chen et al., 2021b; Tong et al., 2021; Humphreys et al., 2021; Singh et al., 2021; Wang et al., 2021a; Mardini and Bicer, 2021; Dong et al., 2021; Sisakova et al., 2021; Jorschick et al., 2020).

Technology	H_2 storage capacity	Volumetric energy density	Storage state	Storage pressure	Storage temperature
Metal hydrides	Moderate	Moderate	Solid	Low	Ambient
Ammonia	High	High	Liquid	Moderate	Low
LOHCs	Moderate to high	Moderate	Liquid	Atmospheric	Ambient
$Mg(BH_4)_2$	High	Moderate to high	Solid	Low	Ambient
Formic acid	Moderate	Moderate	Liquid	Atmospheric	Ambient

Liquid hydrogen transportation, characterized by its heightened energy density, is an established method for hydrogen distribution. However, it necessitates cryogenic storage and involves substantial energy consumption. The future outlook for liquid hydrogen transportation centers on the advancement of improved insulating materials and the adoption of more energy-efficient processes. These advancements are poised to enhance the overall efficiency and viability of this approach within the hydrogen supply chain.

The adoption of hydrogen carriers for transportation presents a promising alternative because of their streamlined transportation, handling, and storage capabilities, which surpass those of gaseous and liquid hydrogen. This approach holds significant potential for enhancing the flexibility and efficiency of hydrogen transportation in the future. However, the current methodology involves complex chemical processes and requires significant energy usage. The eventual course of hydrogen-powered transportation is contingent on advancements in the efficient design of carriers and the optimization of hydrogen release procedures. These developments can enhance the feasibility of using hydrogen as a widely distributed energy source.

4. Hydrogen storage technologies

4.1. Overview of hydrogen storage technologies

Hydrogen storage technologies encompass a diverse range of approaches and procedures used to securely and efficiently store hydrogen, facilitating its application across a broad spectrum of uses (Speigel, 2020). These storage technologies can be categorized into three primary categories: gaseous storage, liquid storage, and solid-state storage. Gaseous storage is predominantly achieved using two principal methods: compressed hydrogen storage and subsurface hydrogen storage. Compressed hydrogen storage involves storing hydrogen in its gaseous state under heightened pressure. High-pressure H_2 is stored in specialized high-pressure gas cylinders or large storage tanks, which are purposefully constructed to endure these substantial pressures (Chen et al., 2021b). Subsurface hydrogen storage, on the other hand, revolves around the concept of storing H_2 in geological formations or structures situated beneath the Earth's surface. These formations or structures encompass depleted oil reserves, salt caverns, gas reserves, and aquifers (Kumari and Ranjith, 2023). Liquid storage, the second major classification, necessitates the application of cryogenic temperatures to cool and convert gaseous hydrogen into compact liquid form. The storage of liquefied hydrogen involves the use of well-insulated cryogenic tanks meticulously designed to endure extremely low temperatures and effectively contain liquid hydrogen in a secure manner (Yatsenko et al., 2022). Liquid storage offers a higher energy density than its gaseous counterpart. Solid-state storage techniques involve confining hydrogen within solid materials like metal hydrides, chemical hydrides, or adsorption onto porous materials such as carbon (Kumari and Ranjith, 2023; Yatsenko et al., 2022). This methodology enables hydrogen storage at reduced pressures and temperatures, which is different from conventional gaseous or liquid storage methods. Consequently, it has the potential to augment energy density and mitigate infrastructure requirements. These technologies collectively play a pivotal role in enabling the efficient utilization and dissemination of hydrogen across a myriad of applications. Fig. 4 shows an overview of the different hydrogen storage technologies.

4.2. Discussion of hydrogen storage technologies

4.2.1. Gaseous storage

The concept of gaseous hydrogen storage involves various techniques to safely store hydrogen in its gaseous state, which generally requires specialized containment systems designed to withstand high pressures while adhering to established safety standards (Hydrogen and Fuel Cell Technologies Office, 2023; Dewangan et al., 2022a). Gaseous

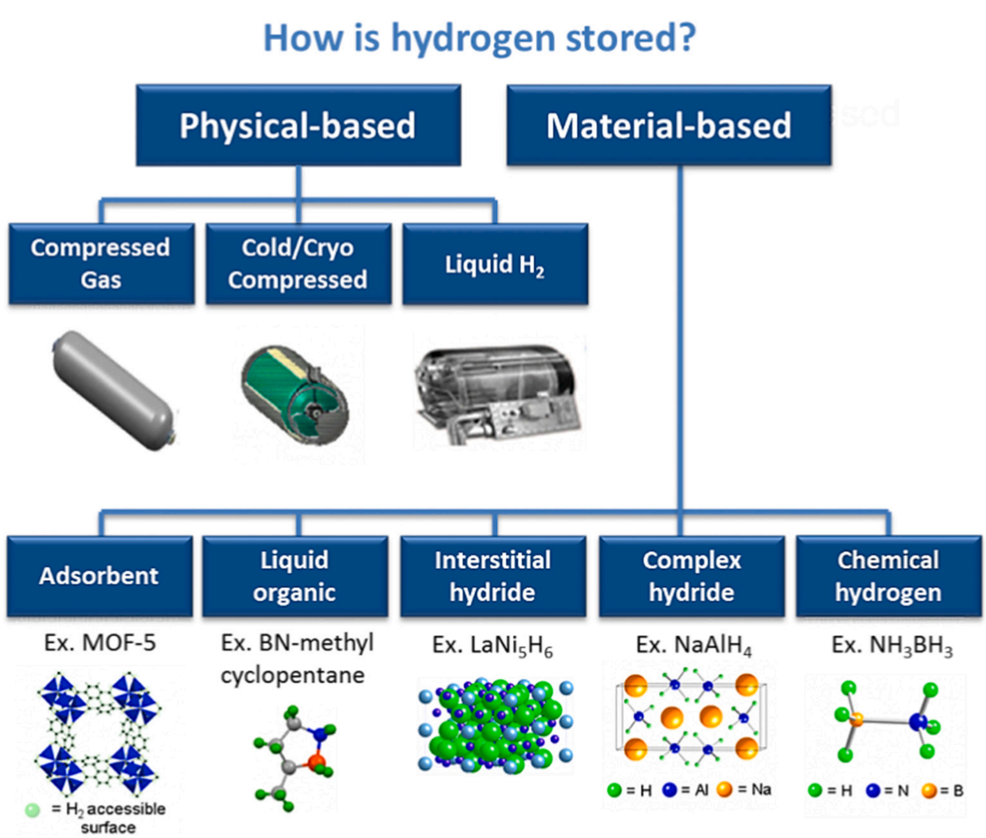

Fig. 4. Comprehensive overview of hydrogen storage technologies. Reprinted with permission from Ref. (Hydrogen and Fuel Cell Technologies Office, 2023).

hydrogen storage is primarily categorized into compressed hydrogen storage and subsurface hydrogen storage.

In compressed hydrogen storage, hydrogen is subjected to elevated pressures, typically between 200 and 700 bar, to reduce its volume and increase its storage capacity (Chen et al., 2021b). This type of storage usually employs high-pressure cylinders, which come in various types based on their construction materials and design (Azeem et al., 2022). Type I cylinders are made from robust metallic materials like steel or aluminum. Type II cylinders combine a metallic liner with a composite wrap of carbon fiber or glass fiber, enhancing structural integrity while reducing weight. Type III cylinders feature a metallic liner surrounded by composite materials, significantly lightening the cylinder without compromising structural integrity. Type IV cylinders use a polymer liner, such as high-density polyethylene, providing a lightweight yet durable alternative, though they may be costlier (Barthelemy et al., 2017; Li et al., 2024; Kis and Kökai, 2024).

Recent research in compressed hydrogen storage technology includes the development of cascade storage systems, which utilize multiple sets of high-pressure cylinders at different pressures to facilitate efficient refueling or supply, particularly useful in stationary applications (Yu et al., 2022). Advances in materials science, such as the exploration of nanocomposites and carbon fiber composites, are aimed at creating lighter and stronger high-pressure hydrogen storage tanks (Zhang and Xu, 2022). Another innovative area is the development of conformable tanks, designed to better fit within the spatial limitations of vehicles or other platforms, enhancing energy density and storage efficiency (Dong et al., 2022).

Subsurface hydrogen storage involves storing hydrogen in geological formations below the Earth's surface, such as salt caverns or depleted gas reservoirs (Zhong et al., 2024; Hosseini et al., 2022; Lankof and Tarkowski, 2020; Lankof et al., 2022). Salt caverns are created through solution-mining techniques that inject water into underground salt deposits to dissolve the salt and form controlled caverns. Depleted gas and oil reservoirs are also considered for hydrogen storage due to their proven ability to contain gases over geological timeframes (Muhammed et al., 2023; Kanaani et al., 2022). Another potential method involves using aquifers, where confined aquifers are preferred over unconfined ones due to their natural barriers that prevent gas migration (Mahdi et al., 2021).

Ongoing research and development in subsurface hydrogen storage is focused on optimizing the efficiency and precision of salt cavern creation and employing advanced technologies like 3D seismic imaging for better management of hydrogen storage in geological formations (Tackie-Otoo and Haq, 2024; Wu et al., 2023; Khayer et al., 2023). The use of cushion gases like N_2, CO_2, or CH_4 to enhance hydrogen recovery from geological stores is an example of how gas recovery strategies are being advanced (Zamehrian and Sedaee, 2022; Heinemann et al., 2021).

Gaseous hydrogen storage is crucial for a wide range of applications, including electricity production, industrial processes, and energy systems integration, helping to buffer against fluctuations in renewable energy production and contributing to grid stabilization (Sambo et al., 2022; Tahan, 2022; Abdellatif et al., 2023). While the storage of gaseous hydrogen presents challenges due to its lower energy density compared to other fuels, necessitating larger storage volumes or higher pressures, the development of advanced storage materials and technologies continues to improve the viability and efficiency of hydrogen storage solutions (Elberry et al., 2021; Zivar et al., 2021).

The evolution of gaseous hydrogen storage, from high-pressure cylinder innovations to the strategic use of geological formations, demonstrates its vital role in supporting the hydrogen economy, offering reliable and scalable options for the clean energy sector. The continuous advancement in technologies and materials for hydrogen storage is pivotal in maximizing the effectiveness and sustainability of hydrogen as a key energy carrier.

4.2.2. Liquid storage

Storing hydrogen in liquid form involves specialized tanks designed to maintain hydrogen at cryogenic temperatures, typically below −253 °C. These tanks are crucial for both storing and transporting liquid hydrogen, emphasizing the need for maintaining specific temperature and pressure conditions (Yatsenko et al., 2022; Ali et al., 2024). For safe storage, specialized tanks or insulated containers are necessary to minimize heat transfer and maintain the extremely low temperatures required. Safety is paramount, with strict adherence to safety laws and guidelines necessary to mitigate risks associated with cryogenic properties and potential reactivity of liquid hydrogen (Yatsenko et al., 2022).

Technological advancements in insulation materials and techniques used to maintain low temperatures in storage tanks often find applications in transportation systems as well. These include vacuum-insulated tanks, vacuum insulation panels, aerogels, cryogenic insulation foams, double-walled tanks, and multilayer insulation (Zhang et al., 2023b). Advanced composite materials, such as CFRPs, provide both insulation and structural support, enhancing the safety and efficiency of liquid hydrogen storage tanks and transportation systems (Ekeocha et al., 2021; Zhang et al., 2020).

Active cooling systems, such as cryogenic refrigeration cycles, are used in both storage and transportation to maintain the low temperatures necessary for liquid hydrogen (Zhang et al., 2023b). Research on materials resistant to hydrogen embrittlement compatible with liquid hydrogen is vital for improving both storage and transportation systems (Okonkwo et al., 2023).

While the technologies and methods overlap, the storage and transportation of liquid hydrogen serve distinct purposes within the hydrogen supply chain. Storage primarily focuses on preserving hydrogen for future use or distribution, whereas transportation involves moving hydrogen from production sites to storage facilities or end users. Each process requires specific infrastructure; storage involves fixed insulated tanks at sites like production facilities, distribution hubs, or refueling stations, while transportation uses mobile containers such as cryogenic tanker trucks, ships, or rail carriages (Speigel, 2020; Noh et al., 2023; Yatsenko et al., 2022; Dewangan et al., 2022a).

Liquid hydrogen storage allows for the preservation of hydrogen in a highly condensed and pure form, useful in industries that require high-purity hydrogen, such as semiconductor fabrication (Guo et al., 2022b). It also boasts a higher volumetric energy density than gaseous hydrogen, reducing the volume required for storage and making transportation more efficient (Tashie-Lewis and Nnabuife, 2021). However, the liquefaction of hydrogen requires significant energy input, which can lead to energy losses during the storage phase (Niermann et al., 2021). Maintaining cryogenic temperatures also requires additional energy, contributing to boil-off losses during storage and transit (Meng et al., 2021).

The safety challenges of managing liquid hydrogen under cryogenic conditions include risks of frostbite and material embrittlement, limiting its use to specific industries. Innovations in insulation materials and storage processes are critical for mitigating evaporation losses and enhancing the efficiency of liquid hydrogen storage. The adoption of new liquefaction techniques and improvements in procedural aspects could reduce the energy consumption and associated costs of converting hydrogen from its gaseous state to a liquid state (Niermann et al., 2021).

Looking forward, integrating liquid hydrogen storage into renewable energy systems could provide efficient energy distribution and storage solutions, particularly in scenarios requiring high energy density. Liquid hydrogen continues to play a pivotal role in space exploration and the growing commercial space industry, where its properties as a rocket propellant are invaluable.

In summary, liquid hydrogen storage involves specialized practices and technologies to maintain hydrogen at cryogenic temperatures, requiring advanced materials and cooling systems that overlap with transportation needs. While sharing technical requirements, storage and transportation differ in purpose, infrastructure, and operational duration, necessitating ongoing innovation to enhance efficiency, reduce costs, and improve safety in both domains (Tables 9 and 10).

4.2.3. Solid-state storage

Solid-state hydrogen storage involves preserving hydrogen within solid materials through physical or chemical bonding mechanisms, which typically offer improved safety and increased volumetric energy density compared to gaseous or liquid storage (Hydrogen and Fuel Cell Technologies Office, 2023). In this storage method, hydrogen interacts with metals or metal alloys to form stable and reversible bonds, creating metal hydrides that trap hydrogen within their lattice and release it upon heating or pressure reduction (Shi et al., 2022).

Metal hydrides are classified based on their composition and properties. Alloy-based metal hydrides, such as AB5 and AB2 types, are prevalent due to their efficient performance characteristics. AB5 alloys, which include rare-earth and transition metals like lanthanum and nickel combinations (e.g., $LaNi_5$), are versatile due to their admirable hydrogen storage capacities and ability to operate at moderate temperatures (Joubert et al., 2021). AB2 alloys, typically comprising zirconium- or titanium-based compounds (e.g., $ZrMn_2$, TiFe), often possess higher storage capacities but may require higher temperatures for hydrogen release (Loh et al., 2023).

Magnesium Hydride (MgH_2), recognized for its substantial storage capacity, faces challenges such as slow absorption and desorption kinetics and the need for high temperatures to release hydrogen. These limitations are being addressed by applying nanostructuring techniques to enhance surface area and kinetics (Li et al., 2023; Cho et al., 2023).

Complex hydrides, which include materials bonded with hydrogen and elements like aluminum, boron, or nitrogen, offer higher gravimetric storage capacities. Notable examples are metal alanates like Sodium Aluminum Hydride ($NaAlH_4$) and Lithium Aluminum Hydride ($LiAlH_4$), which store hydrogen efficiently and have lower breakdown temperatures (Le et al., 2023; Pratthana and Aguey-Zinsou, 2022). Borohydrides, such as Lithium Borohydride ($LiBH_4$) and Sodium Borohydride ($NaBH_4$), can hold significant amounts of hydrogen, with sodium borohydride known for its considerable regenerability and gravimetric storage capacity, releasing hydrogen via hydrolysis in the presence of a catalyst (Le et al., 2021; Ozerova et al., 2020). Ammonia Borane (NH_3BH_3) is another example, releasing hydrogen through hydrolysis or thermolysis (Kim et al., 2020).

Nitrogen-containing amides and imides such as Magnesium Amide ($Mg(NH_2)_2$), Lithium Amide ($LiNH_2$), and Lithium Imide (Li_2NH) also exhibit significant hydrogen storage capabilities, although they require high temperatures for hydrogen release (He et al., 2021). Lithium Magnesium Borohydride ($Li_2Mg(BH_4)_4$) and bimetallic borohydrides like Calcium Lithium Borohydride ($CaLi_2(BH_4)_4$) demonstrate enhanced hydrogen storage properties (Chen et al., 2021c; Ji et al., 2023).

Table 9
Assessment of different hydrogen underground storage methods (Kanaani et al., 2022; Zamehrian and Sedaee, 2022; Heinemann et al., 2021).

Technology	Storage capacity	Storage pressure	Costs	Geological availability
Solution-mined caverns	High	Moderate to high	Moderate to high	Limited
Mined caverns (rock salt)	High	Moderate to high	High	Limited
Depleted gas reservoirs	Moderate to high	Moderate to high	Low to moderate	Moderate
Depleted oil reservoirs confined	Moderate to high	Moderate to high	Low to moderate	Moderate
Aquifers (water-bearing)	Moderate to high	Low to moderate	Moderate	Widespread
Unconfined aquifers (water-bearing)	Moderate to high	Low to moderate	Moderate	Widespread

Adsorbent materials store hydrogen through physisorption, where hydrogen molecules adhere to the outer layer of a solid material due to their high surface areas. These include activated carbon, which is effective due to its large surface area and capacity for physical absorption at high pressures and low temperatures (Hirscher et al., 2023; Doğan et al., 2020). Metal-Organic Frameworks (MOFs), with their enhanced surface areas and customizable pore widths, and Carbon Nanotubes (CNTs), known for their extensive surface area, are also utilized for hydrogen storage (Yousaf et al., 2023; Mahmodi et al., 2020; Karki and Chakraborty, 2023; Ullah et al., 2022). Porous Aromatic Frameworks (PAFs), porous Boron Nitride (*p-BN*), and nanostructured graphene materials are newer materials being explored for their potential in hydrogen storage (Li et al., 2022; Zu et al., 2022; Khossossi et al., 2022; Liu et al., 2023).

Research continues to focus on enhancing the kinetics, operating temperatures, and storage capacities of solid-state materials to make them more practical and efficient for applications like hydrogen fuel cell vehicles and remote power generation (Yao et al., 2022; Jansen et al., 2021). The goal is to achieve higher volumetric energy densities, which reduces the space required for hydrogen storage and addresses safety issues related to cryogenic liquid storage or high-pressure gaseous storage (Dewangan et al., 2022a). Challenges such as slow hydrogen absorption and release kinetics, unfavorable thermodynamic properties, and potentially high costs and complex synthesis processes are areas of ongoing improvement (Salehabadi et al., 2023; Kumar et al., 2022).

Overall, solid-state hydrogen storage is a promising approach for the efficient and safe storage of hydrogen, facilitating advancements in hydrogen technology and its integration into various energy systems. As research progresses, these materials are expected to play a crucial role in the evolving hydrogen economy.

4.3. Summary of hydrogen storage technologies

In essence, hydrogen storage is a crucial element in advancing and harnessing hydrogen as a sustainable energy source. The hydrogen storage landscape encompasses various systems, notably gaseous hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage. Each of these technologies has distinct advantages and challenges, rendering them suitable for specific applications and operating conditions. For a concise overview of hydrogen storage systems, see Table 11 (Kumar et al., 2022).

Gaseous hydrogen storage comprises compressed hydrogen storage and underground hydrogen storage, offering advantages like low energy requirements, high purity hydrogen, and ample storage capacity. However, challenges such as low energy density, high-pressure system requirements, and geological limitations persist. Ongoing advancements and optimizations position gaseous hydrogen storage as a mature technology that is likely to remain popular for stationary and short-distance travel. In regions with suitable geological formations, it can complement other hydrogen storage systems.

Liquid hydrogen storage boasts adaptability for long-distance travel, a high volumetric energy density, and has established utility in the aerospace industry. However, it faces obstacles like cryogenic temperature requirements, energy-intensive liquefaction, and losses from boil-off and evaporation. Expected to retain relevance in specific applications, especially in long-distance travel and aerospace, further research can address constraints, enhancing its efficiency and applicability.

Solid-state hydrogen storage offers notable volumetric and gravimetric energy density (dependent on the material), safer storage with reduced pressure needs, and compact storage options. Challenges include intricate material fabrication, slow hydrogen uptake and release kinetics (dependent on the material), and temperature sensitivity for specific materials. Despite being a developing industry, solid-state hydrogen storage holds promise, and ongoing advancements in material performance, cost reduction, and system integration are key to realizing its potential in diverse hydrogen storage applications.

Table 10
Assessment of different solid-state hydrogen storage technologies (Li et al., 2023; Yao et al., 2022; Jansen et al., 2021; Salehabadi et al., 2023; Kumar et al., 2022).

Technology feature	Kinetics	Volumetric capacity	Operating temperature	Cycling stability	Energy requirement
Metal hydrides	Moderate	Moderate to high	Low to medium	Good	Moderate
Complex hydrides	Moderate to slow	Moderate to high	Medium to high	Moderate to poor	Moderate to high
Adsorbent materials	Fast	Low to moderate	Low	Good	Low

Table 11
Overview and contrasting analysis of different hydrogen storage technologies (Kumar et al., 2022).

Technology	Advantages	Disadvantages
Compressed hydrogen storage	Low energy demand, mature technology, high-purity hydrogen	Low energy density, requirement for high-pressure storage systems, large and cumbersome storage tanks
Underground hydrogen storage	Large-scale storage capability, minimal environmental impact, long-term storage potential	Dependent on geological formations, potential initial high capital cost, necessitates monitoring and maintenance
Liquid hydrogen storage	High energy density per volume, suitable for extended transportation, established technology in aerospace applications	Cryogenic temperature demands, substantial energy usage for liquefaction, losses due to boil-off and evaporation
Solid-state hydrogen storage	Elevated energy density in volume and weight, enhanced safety due to reduced pressure requirements, compact storage alternatives	Complex material synthesis and handling, slow hydrogen absorption and release kinetics, temperature sensitivity in certain materials

5. Hydrogen use technologies

5.1. Overview of hydrogen usage technologies

The application of hydrogen in various sectors for different purposes involves leveraging its versatility as either an energy carrier or a fuel source. This extends across diverse domains, including transportation, heating, electrical generation, and industrial operations. Various technologies are regularly employed to use hydrogen, such as fuel cells, industrial processes, hydrogen combustion, grid management, and energy storage. These technologies collectively facilitate the integration of hydrogen into multiple sectors, thereby aiding the shift toward a more environmentally friendly and sustainable energy system. Fuel cells, which are characterized as electrochemical devices, have the capability to transform the chemical energy present in a fuel source like hydrogen into both electrical energy and heat through a chemical reaction, without involving combustion. This chemical reaction within a fuel cell involves the interaction of hydrogen and oxygen, resulting in the generation of electrical, water, and thermal energy. Conversely, hydrogen combustion entails a chemical reaction between hydrogen and oxygen, usually facilitated by a flame or heat. This reaction leads to the production of water and the release of energy in the form of heat and light. Hydrogen can directly undergo combustion within Internal Combustion Engines (ICEs) or gas turbines, yielding simultaneous thermal energy and mechanical work. Hydrogen plays a critical role in a wide spectrum of industrial operations, functioning as a crucial reducing agent or feedstock in industrial processes. Industrial processes encompass a series of steps or operations that facilitate the conversion of components, raw materials, or energy into finished goods or services. These processes frequently involve modifications in chemical, physical, or biological properties and are typically intended for large-scale production. Energy storage encompasses the process of capturing and preserving energy generated during a specific period for subsequent use, thereby enhancing the adaptability and resilience of energy systems. Grid balancing, also referred to as grid management or load balancing, is a fundamental task aimed at ensuring synchronization between the electrical supply generated by power plants and other sources and the corresponding demand from consumers and enterprises. Effective coordination of various components is of utmost importance for maintaining the stability and reliability of the electrical grid.

5.2. Discussion of hydrogen usage technologies

5.2.1. Fuel cells

Fuel cells are electrochemical devices that convert the chemical energy stored in hydrogen into electrical energy through a process involving oxygen (Rashidi et al., 2022; Kim et al., 2021; Lopes et al., 2021; Daneshvar et al., 2021). Various types of fuel cells are categorized based on the electrolyte material used and their operating conditions. For instance, PEM fuel cells use a polymer membrane, such as Nafion, as the electrolyte, operating at relatively lower temperatures ranging from 50 °C to 100 °C. This makes them suitable for rapid start-up and deployment in applications like fuel cell electric vehicles, small-scale stationary power generation, and portable power sources (Lan et al., 2023).

Solid Oxide Fuel Cells (SOFCs) utilize solid ceramic materials such as Yttria-Stabilized Zirconia (YSZ) for the electrolyte, functioning at higher temperatures between 600 °C and 1000 °C. These are ideal for extended stationary power generation, Combined Heat and Power (CHP) systems, and Auxiliary Power Units (APUs) (Mankour et al., 2022). Alkaline Fuel Cells (AFCs) employ a liquid alkaline solution such as *KOH* as the electrolyte, with an operating temperature range of 60 °C–250 °C, making them applicable in spaceflight, limited stationary power generation, and submarines (Kapoor et al., 2020).

Molten Carbonate Fuel Cells (MCFCs) use a molten carbonate salt mixture like lithium and potassium carbonates as the electrolyte, operating at temperatures from 600 to 700 °C. This suits them for large-scale power generation in stationary settings and CHP systems (Ghorbani et al., 2021). Phosphoric Acid Fuel Cells (PAFCs) use liquid phosphoric acid as the electrolyte and operate within a temperature range of 150 °C–220 °C, suitable for stationary power production and CHP systems (Oh et al., 2023).

Protonic Ceramic Fuel Cells (PCFCs) utilize proton-conducting ceramic materials such as barium zirconate or barium cerate as electrolytes. These systems are designed to operate at temperatures ranging from 500 to 700 °C, making them highly suitable for use in stationary power production and CHP systems (Tsvetkov et al., 2022). Bio-electrochemical fuel cells, or Microbial Fuel Cells (MFCs), employ various electrolytes including ionic liquids and polymer membranes to generate electrical energy. These devices operate within a range of ambient to relatively high temperatures and find applications in wastewater treatment, small-scale power generation, and remote sensing (Yaqoob et al., 2023).

Fig. 5 provides detailed schematic diagrams of various fuel cells, illustrating the unique design and component arrangement of each type. In addition, Table 12 offers a comprehensive comparative analysis that highlights the distinct characteristics, performance metrics, and applications of different fuel cell types.

Fuel cells offer a diverse range of opportunities for using hydrogen in power generation, transportation, and other domains. Unlike traditional combustion-based power production systems, fuel cells achieve higher energy efficiency by directly converting chemical energy into electrical energy (Chehrmonavari et al., 2023). Additionally, using hydrogen as a

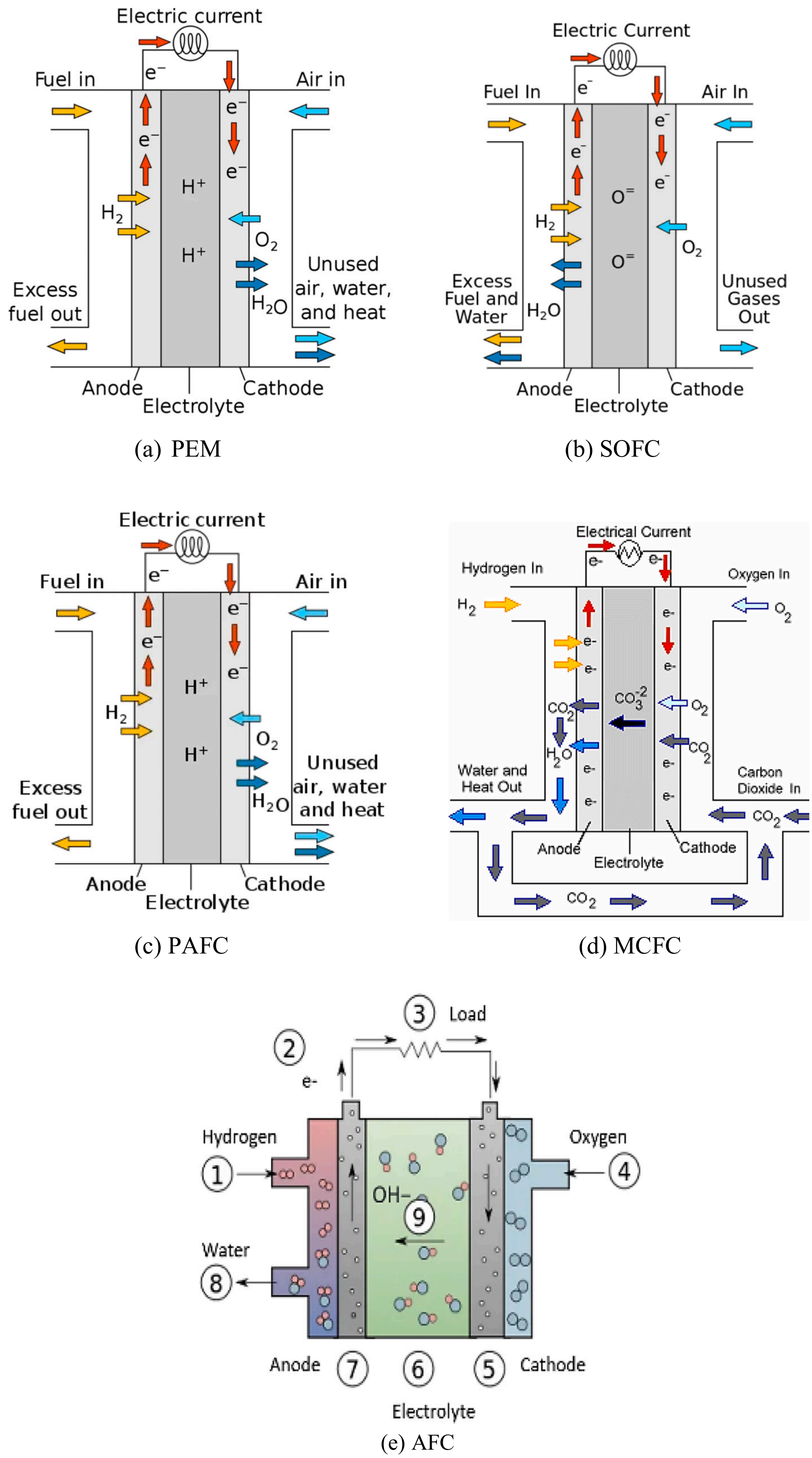

Fig. 5. Schematic diagrams of different fuel cell types: (a) PEM, (b) SOFC, (c) PAFC, (d) MCFC, and (e) AFC.

Table 12
Assessment of different hydrogen utilization technologies using various fuel cell types (Rashidi et al., 2022; Kim et al., 2021; Lopes et al., 2021; Daneshvar et al., 2021; Lan et al., 2023; Mankour et al., 2022; Kapoor et al., 2020; Ghorbani et al., 2021; Oh et al., 2023; Tsvetkov et al., 2022; Yaqoob et al., 2023).

Fuel cell type	Electrolyte	Advantages	Disadvantages
PEMFC	Polymer membrane	Rapid startup, high power output, low operating temperature	Susceptibility to impurities, need for humidification, high material expenses
SOFC	Solid ceramic material	High efficiency, fuel adaptability, potential for combined heat and power generation	Elevated operating temperature, material degradation, extended startup duration
AFC	Liquid alkaline solution	High efficiency, cost-effective materials, long-standing technology	Sensitivity to CO_2, requirement for pure hydrogen and oxygen, restricted commercial availability
MCFC	Molten carbonate salt mixture	High efficiency, fuel adaptability, potential for combined heat and power generation	Elevated operating temperature, intricate system design, material degradation (corrosion)
PAFC	Liquid phosphoric acid	Moderate operating temperature, good tolerance to impurities, commercially accessible	Lower efficiency compared to other types, limited fuel adaptability, relatively higher cost
PCFC	Proton-conducting ceramic material	Lower operating temperature compared to SOFC, high efficiency, fuel adaptability	Less established technology, limited commercial availability, challenges in material durability
MFC	Various types	Direct conversion of waste to electricity, utilization of renewable energy	Low power density, restricted commercial availability, system intricacy

fuel source in fuel cells results in only heat and water as secondary byproducts, significantly reducing GHGs emissions and air pollution levels. Fuel cells can be designed in various sizes and capabilities, suitable for a broad spectrum of applications from compact electronic devices to large-scale power production (Zakaria et al., 2021). They are known for their low noise levels, which enhances their suitability for urban and residential settings (Acha et al., 2020).

However, certain types of fuel cells, particularly PEMs, may incur high costs due to the use of expensive materials like platinum and the requirement for specialized components (Sajid et al., 2022). Some fuel cell types may also have limited lifespans or experience performance deterioration over time, affecting their long-term reliability and cost-effectiveness (Saadabadi et al., 2021).

The widespread adoption of fuel cells depends on the development of a comprehensive hydrogen infrastructure that includes manufacturing, storage, and distribution (Mohideen et al., 2023). Future advancements in materials science are expected to yield new materials with improved capabilities for hydrogen storage. Further research efforts can optimize the integration of solid-state materials for hydrogen storage with fuel cells and other energy conversion devices, potentially increasing the commercial viability of solid-state hydrogen storage technologies and fostering innovative applications and industries (Table 13).

5.2.2. Hydrogen combustion

The hydrogen combustion process involves initiating hydrogen ignition with the aid of an oxidizing agent like oxygen or air, resulting in the release of energy (Kim et al., 2021). This method of energy harnessing has significant implications across a wide array of applications, including ICEs and gas turbines. In hydrogen ICEs, which operate similarly to traditional gasoline or diesel engines but use hydrogen as the primary fuel, there are two main configurations: spark-ignition and

Table 13
Assessment of different hydrogen utilization technologies involving hydrogen combustion (Boretti, 2020; Gong et al., 2020; Kurien and Mittal, 2022; Escamilla et al., 2022; Khoshgoftar Manesh et al., 2022; Shi et al., 2021; Wang et al., 2021b; Chen et al., 2023b; Sharma et al., 2023b; Sun et al., 2023; Gültekin and Ciniviz, 2023; Kusuma et al., 2022).

Technology	Efficiency	Emissions reduction	Key benefits	Main drawbacks
Spark-ignition engines	Moderate efficiency	Moderate emissions reduction	Easy transition from gasoline engines, rapid response	Lower efficiency, NO_x emissions
Compression-ignition engines	Higher efficiency than spark-ignition engines	Moderate to low emissions reduction	Better efficiency, enhanced fuel economy, reduced emissions compared to spark-ignition engines	Less common, NO_x emissions, more intricate design
Gas turbines	Moderate to high efficiency	Moderate to low emissions reduction	Scalable, high power output, versatile fuel usage, integration into combined cycles	Complex systems, NO_x emissions, high initial cost
Hydrogen-rich gas turbines	High efficiency	Low emissions reduction	Increased efficiency, reduced emissions, versatile fuel usage	High initial cost, complex systems
Fuel cell gas turbines	High efficiency	Low emissions reduction	Exceptional efficiency, minimal emissions, adaptable fuel usage, potential cogeneration	High initial cost, complex systems, limited availability
Rotating detonation engines	High efficiency	Low emissions reduction	Enhanced efficiency, diminished emissions, compact design	Less established technology, limited commercial availability, complex design

compression-ignition engines (Boretti, 2020). Spark-ignition engines, using a spark plug to initiate combustion, resemble conventional gasoline engines (Gong et al., 2020), while compression-ignition engines rely on the heat from compressing the hydrogen-air mixture to ignite, similar to diesel engines (Kurien and Mittal, 2022). Though spark-ignition engines are more common, compression-ignition engines are noted for higher efficiency and fewer pollutant emissions.

Hydrogen is also utilized in gas turbines for generating electricity or mechanical power, often in power plants where they may be part of combined-cycle systems that enhance overall efficiency (Escamilla et al., 2022). A notable advancement in hydrogen combustion technology is the development of fuel cell gas turbines, which integrate the high-temperature exhaust from SOFC to drive a gas turbine. This system combines efficiency with minimal emissions, making it ideal for stationary power generation (Khoshgoftar Manesh et al., 2022).

In hydrogen ICEs, recent advancements focus on enhancing efficiency, reducing emissions, and optimizing engine design to better facilitate hydrogen combustion (Shi et al., 2021; Wang et al., 2021b). These improvements include technologies like direct injection, lean burn techniques, advanced ignition systems, and intelligent control systems. Furthermore, the concept of flameless hydrogen combustion, which burns hydrogen fuel in an oxygen-deficient atmosphere to achieve uniform and low-temperature combustion, is gaining attention. This method promises to reduce NO_x emissions, improve efficiency, and enhance safety due to its low flame temperature and gradual combustion kinetics (Chen et al., 2023b; Sharma et al., 2023b).

Another emerging technology in this field is rotating detonation engines, which utilize continuous detonation waves to burn fuel, including hydrogen, offering increased efficiency and reduced emissions compared to traditional combustion methods (Sun et al., 2023).

Hydrogen combustion is not only applicable in ICEs and turbines but also in boilers and furnaces where it generates heat for various industrial processes such as steel production, glassmaking, and chemical processing (Gültekin and Ciniviz, 2023; Kusuma et al., 2022). Additionally, hydrogen can replace conventional heating sources like natural gas or oil in building heating applications, providing a cleaner option for space heating.

The combustion of hydrogen primarily produces water vapor, resulting in relatively low levels of GHGs and air pollution compared to fossil fuels. Hydrogen's high energy density per unit mass enables efficient combustion and reduced fuel consumption (Ramesh et al., 2023). Integrating hydrogen combustion into existing power generation and heating systems usually requires minimal modifications, reducing the need for substantial infrastructure investments (Von Mikulicz-Radecki et al., 2023).

However, challenges remain in the storage and delivery of hydrogen due to its lower volumetric energy density compared to traditional fuels (Yu et al., 2020). Hydrogen's wide flammability range also raises safety concerns during transportation, handling, and use in combustion-based applications (Abohamzeh et al., 2021). As infrastructure develops and the demand for hydrogen increases, hydrogen combustion is expected to play a significant role in the transition to clean energy. Ongoing research and development are directed toward improving the efficiency, cost-effectiveness, and safety of hydrogen combustion technologies, enhancing their competitiveness against other power generation and heating methods.

5.2.3. Industrial processes

The use of hydrogen in industrial processes encompasses a diverse range of methods and applications, employing hydrogen as a feedstock, energy carrier, or fuel across various industrial settings (Lopes et al., 2021). These methods have been strategically developed to achieve multiple objectives, including the reduction of industries' environmental footprint, enhancement of energy security, and facilitation of the transition toward a more environmentally friendly energy system.

Hydrogen utilization technologies span a wide array of key industrial processes across various sectors, such as steel production, methanol production, ammonia formation, chemical synthesis, petroleum refining, and the semiconductor industry. In the steel manufacturing process, hydrogen serves as a reducing agent, replacing carbon-based reductants like coke that result in CO_2 emissions, thereby significantly reducing GHGs and presenting an eco-friendlier approach to steel production (Palone et al., 2022). Hydrogen is critical in ammonia production, which is a fundamental component of fertilizer formulation. The Haber-Bosch process synthesizes ammonia by subjecting nitrogen and hydrogen to high pressure and temperature, and using green hydrogen from renewable sources can mitigate the environmental impact associated with ammonia production (Yüzbaşıoğlu et al., 2022).

Methanol, an essential chemical precursor, can be synthesized by combining hydrogen with either CO_2 or carbon monoxide. "Green methanol production" uses hydrogen from renewable sources and captured CO_2 to form methanol, thus reducing GHGs (Sollai et al., 2023). In the petroleum refining sector, hydrogen is extensively used in processes like hydrocracking, hydrodesulfurization, and hydrotreating to improve product quality and reduce harmful pollutant emissions (van Dyk et al., 2022a). Hydrogen also acts as a feedstock or reactant in various chemical production processes, including the formation of hydrochloric acid, hydrogen peroxide, and specialized chemicals (Wan et al., 2023). Furthermore, hydrogen plays a crucial role in the semiconductor industry, serving as a carrier gas and cleaning agent for the fabrication of high-purity silicon wafers and impurity elimination during manufacturing (Elgarahy et al., 2022).

The use of Hydrogen Direct Reduction (H-DRI) employs hydrogen as a reducing agent to produce Direct Reduced Iron (DRI) using iron ore, resulting in a substantial reduction in GHGs compared to the conventional blast furnace steel production process (Galitskaya and Zhdaneev, 2022). Incorporating hydrogen into industrial operations offers reduced GHGs, enhanced energy efficiency, and improved product quality, such as reduced sulfur content during petroleum refining (Ajanovic et al., 2022). However, the expenses associated with hydrogen production, storage, and transportation can pose constraints, especially considering the continued availability of low-cost fossil fuels (Tashie-Lewis and Nnabuife, 2021; Van Dyk et al., 2022b). The integration of hydrogen-based industrial processes often requires new infrastructure or modifications to existing facilities (Swennenhuis et al., 2022). Hydrogen's distinct characteristics necessitate safety considerations in handling, storage, and usage within industrial operations because of its low ignition energy, high flammability, and propensity to induce embrittlement in metal components (Abohamzeh et al., 2021).

The anticipated growth in hydrogen applications for industrial processes is expected to contribute to decarbonization in energy-intensive industries as efforts to minimize GHGs escalate. Research and development efforts primarily focus on enhancing hydrogen production methods, storage technology, and process integration to improve effectiveness and affordability in industrial applications. The integration of hydrogen in industrial operations aligns with the principles of a circular economy, reducing resource consumption and emissions on a global scale by using waste streams from one process as raw materials for another process.

5.2.4. Energy storage and grid balancing

The use of hydrogen in energy storage and grid balancing involves a spectrum of methods and applications aimed at storing surplus energy and maintaining electrical network stability (Daneshvar et al., 2021). Power-to-Gas (P2G), hydrogen blending, and methanation are key methods employed for these purposes. In the P2G process, surplus renewable electricity is converted to hydrogen through electrolysis, allowing the hydrogen to be stored and used as an eco-friendly fuel or blended with natural gas for use in existing gas infrastructure (Sun et al., 2022b; Colombo et al., 2020). Methanation involves combining hydrogen generated through electrolysis with CO_2 to produce synthetic methane or Synthetic Natural Gas (SNG), which can utilize captured CO_2 from industrial activities or directly from the atmosphere, contributing to GHGs reduction (Katla et al., 2021). This synthetic methane can then be injected into existing natural gas infrastructure, used for power generation, or employed as a fuel for heating and transportation.

Furthermore, hydrogen produced through P2G technology can be blended with natural gas within the current gas infrastructure, serving applications in power generation, transportation, and heating, with minimal modifications to existing systems (Erdener et al., 2023). However, cautious use of hydrogen in the mixture is necessary to avoid adverse effects on the operational efficiency and safety of the pre-existing gas infrastructure.

Cutting-edge energy storage and grid balancing technologies explore hydrogen's versatility in integrating renewable energy sources, enabling long-term energy storage, and interconnecting multiple sectors like gas, electricity, transportation, and industry. P2G is part of the broader Power-to-X framework, which transforms excess renewable electricity into various energy carriers, chemicals, and fuels, thereby expanding potential applications for storing and using renewable energy (Baldry et al., 2022).

Recent advancements in electrolysis technologies enhance the efficiency, affordability, and scalability of hydrogen production for P2G applications, contributing to the integration of hydrogen production, storage, and usage systems into existing energy infrastructure components, including renewable energy generation, smart grid technologies, and energy storage (Yuan et al., 2020). These integrated energy systems strive to optimize the efficiency and adaptability of renewable energy use while improving the stability and resilience of the power grid.

Energy storage and grid balancing technologies are crucial in mitigating the challenges posed by the intermittent nature of renewable energy sources. Hydrogen acts as a medium for storing surplus energy from renewable sources, converting it back to electricity when needed, significantly contributing to grid stability by offering flexibility in power generation and consumption (Mayyas et al., 2020; Hou et al., 2023). This enables the seamless integration of intermittent renewable sources by efficiently storing excess energy for future use.

However, the energy losses incurred during the conversion of electricity to hydrogen and its subsequent reconversion to electricity reduce the overall efficiency of the system (Oliveira et al., 2021). The initial and operational costs of P2G technology may pose challenges, potentially impacting its competitiveness compared with alternative energy storage solutions (Jafari et al., 2022). Continuous research and development efforts are expected to enhance the efficiency and reduce the costs of P2G systems, increasing their competitiveness and widespread adoption.

P2G technology holds the potential to significantly contribute to sector coupling, facilitating the smooth integration of energy systems encompassing electricity, heating, gas, and transportation. It provides extended energy storage solutions, enhancing flexibility and reliability in effectively managing energy supply and demand dynamics. The proliferation of P2G technology can strongly support the development of a hydrogen-centric economy, elevating hydrogen's position as a key player in the global energy landscape.

5.3. Summary of hydrogen usage technologies

In general, technologies related to hydrogen usage encompass a broad spectrum of applications and methodologies that leverage hydrogen as a fuel, energy carrier, or fundamental resource in various sectors. These technological approaches hold considerable promise in reducing GHGs, bolstering energy security, and supporting the transition toward a more sustainable and environmentally mindful energy framework. Table 14 furnishes an extensive summary of the key technologies pivotal in harnessing hydrogen, encompassing fuel cells, industrial processes, hydrogen combustion, energy storage, and grid balancing.

Fuel cells represent a promising technology for hydrogen utilization, marked by high efficiency, minimal emissions, and a versatile range of potential applications. However, challenges including financial implications, susceptibility to contaminants, and reliance on costly catalysts made of precious metals need to be overcome. Despite these challenges, fuel cells are currently available in the commercial market, and their future potential lies in broader acceptance, cost reduction, and exploration of novel applications, paving the way for a more environmentally friendly and carbon-neutral energy infrastructure.

Hydrogen combustion is a viable and versatile energy solution known for its cleanliness. This technology offers advantages such as flexibility in using various fuel sources and significant reduction in emissions. However, its efficiency is lower than that of fuel cells. Hydrogen combustion has already achieved commercial viability, and its future trajectory involves striving for improved efficiency and wider implementation. With the increasing sustainability of hydrogen production, hydrogen combustion will play a crucial role in transitioning to an energy system with reduced carbon emissions.

Utilization of hydrogen in industrial processes holds promise for emission reduction, carbon capture, and the advancement of an environmentally friendly energy system. However, challenges like significant infrastructure investments and efficient CO_2 control strategies need to be addressed. Presently, these processes are economically feasible and are continually advancing. The future of industrial hydrogen usage envisions a surge in demand, the emergence of innovative applications, and improved integration into other energy systems, all of which play a pivotal role in constructing a low-carbon economy.

The application of hydrogen technologies for grid balancing and energy storage offers significant benefits. However, ongoing challenges, such as enhancing storage efficiency and requiring infrastructure investments, need to be resolved. Currently, this sector is characterized as an emerging technology undergoing continuous development efforts. Future prospects for hydrogen-based energy storage and grid balancing involve the expansion of hydrogen infrastructure and increased adoption, fortifying a more resilient and environmentally sustainable energy system.

6. Integrated sustainability analysis

As the quest for low-carbon energy solutions intensifies, hydrogen-based systems have emerged as sustainable alternatives. Essential to this transition is a comprehensive sustainability analysis that weighs both environmental and economic factors. This analysis spans the entire hydrogen energy lifecycle from production to end use and examines the intricate balance between technological readiness and financial feasibility. Through these lens, this section presents a clear assessment that guides informed decisions on the deployment of hydrogen as a cornerstone of a greener future.

6.1. Environmental and economic assessment

Conducting a comprehensive assessment of the environmental impact of a hydrogen-based renewable energy system involves evaluating its entire lifecycle, which includes hydrogen production, transportation, storage, and end-user consumption. A thorough environmental analysis underscores the lower GHGs of hydrogen systems compared with those of fossil fuel-based systems. However, it is essential to consider the emissions associated with hydrogen's complete lifecycle, including manufacturing, transportation, and storage processes. Moreover, hydrogen production is water-intensive and requires careful consideration of its impacts on water resources. Assessing land

Table 14
Overview and contrasting analysis of different technologies for hydrogen utilization.

Technology	Advantages	Disadvantages	Development stage	Future outlook
Fuel cells	High efficiency, low environmental impact, wide range of uses	Cost challenges, vulnerability to impurities	Currently accessible	Anticipated increased adoption, cost minimization, exploration of new use cases
Hydrogen combustion	Environmentally clean combustion, fuel versatility	Slightly lower efficiency compared to fuel cells	Currently accessible	Improved efficiency, growing adoption
Industrial processes	Emission reduction, potential for carbon capture	Requires substantial infrastructure investment, challenges in CO_2 management	Currently accessible	Escalating demand, diversification of applications, enhanced integration
Energy storage and grid balancing	Integration of renewable sources, enhanced grid stability, Storage efficiency	Requires infrastructure investments	An emerging field	Expansion of hydrogen infrastructure, increased adoption

use is also critical for understanding the potential impacts on habitat degradation and biodiversity loss. Additionally, the evaluation of air quality is paramount because of the pollutants that can be emitted during hydrogen production and transportation processes (Sinigaglia et al., 2017; Balat and Balat, 2009; Nadaleti et al., 2017).

Performing an economic assessment of a hydrogen-based renewable energy system requires a detailed analysis of its costs and benefits and comparison with alternative energy sources. This includes analyzing capital expenditures that are crucial for understanding the initial costs related to hydrogen infrastructure and evaluating operating expenses to assess long-term economic sustainability. Moreover, potential revenue streams from hydrogen sales provide insights into the economic benefits of these systems. External factors such as the financial implications of carbon emissions and environmental damage also play a significant role in economic evaluation (Tozlu, 2022; Muresan et al., 2013; Zhiznin et al., 2023; Peramanu, 1999). These comprehensive assessments are vital for policymakers and investors, aiding informed decisions regarding the development and implementation of hydrogen-based renewable energy systems.

The Life Cycle Assessment (LCA) of a hydrogen-based renewable energy system begins with the production phase, employing methods such as electrolysis, reforming, and biomass gasification. Electrolysis, which uses electrical energy to split water into hydrogen and oxygen, is particularly promising when powered by renewable sources like wind or solar, as it produces minimal GHGs. In contrast, reforming involves a chemical reaction that emits CO_2, while biomass gasification depends on the availability of organic materials (Swennenhuis et al., 2022). Subsequent phases of storage and transportation are critical for evaluating the environmental impacts of the system. Hydrogen can be stored as gas or liquid and transported via pipelines or tankers, each with distinct environmental footprints. The application of hydrogen in fuel cells or combustion engines for power generation also needs to be evaluated to identify potential areas for environmental impact reduction (Li and Cheng, 2020; Liu et al., 2020; Liu et al., 2021; He et al., 2024).

Technological readiness is a key factor in the development of hydrogen-based systems. The Technological Readiness Level (TRL) helps assess the maturity of these technologies from basic research to commercial application. Hydrogen production technologies, particularly electrolysis using renewable sources, have reached a high TRL, indicating their advanced development stage. Storage and transportation technologies have also evolved significantly, employing methods like compressed gas cylinders and liquid hydrogen for various applications, including industrial uses and fuel cells. Fuel cells have found widespread commercial applications in areas such as backup power systems and automotive industries. However, challenges such as improving the efficiency and cost-effectiveness of hydrogen systems compared with traditional fossil fuels and increasing fuel cell durability remain. These issues underscore the need for ongoing research and development to enhance the viability and reliability of hydrogen technologies (Petrovic and Hossain, 2020; Shahbaz et al., 2022; Boretti, 2021; Kampker et al., 2020; Pinsky et al., 2020; Lindorfer et al., 2020; Riemer et al., 2023; Dovichi Filho et al., 2021).

In summary, a comprehensive environmental and economic assessment along with a detailed life cycle and technological readiness evaluation illustrates the potential and challenges of hydrogen-based renewable energy systems. These assessments provide essential insights that help optimize environmental benefits while addressing economic and technological hurdles, paving the way for sustainable energy solutions.

6.2. Market trends and policy impact

Utilization of hydrogen energy is increasingly recognized as an environmentally friendly and sustainable source of energy. The growth of the hydrogen and green energy industry has been significantly influenced by a range of commercial and policy-related factors, notably accelerating in the aftermath of the COVID-19 pandemic. Several governments globally have demonstrated substantial support by investing in the development of hydrogen energy, which has been pivotal. For instance, the European Union (EU) has developed a Hydrogen Strategy aimed at fostering an environmentally sustainable hydrogen-based economy, with plans to allocate €40 billion toward the hydrogen industry over the next decade. Similarly, Japan has set a visionary goal to become a hydrogen-reliant society by 2050, offering financial incentives such as subsidies and tax advantages to enterprises investing in hydrogen technologies (Hoang et al., 2021a; Nguyen et al., 2021; Pingkuo and Xue, 2022; Li and Taghizadeh-Hesary, 2022; Kar et al., 2022).

The demand for hydrogen is surging, particularly in industries where it serves as a crucial feedstock for processes such as chemical refining, synthesis, and steel manufacturing. This increasing industrial demand is partly driven by the global push to reduce carbon emissions, with clean hydrogen being touted as a viable replacement for fossil fuels (Zhao et al., 2020; Zhang et al., 2022). Concurrently, there have been significant advancements in fuel cell technology, which converts hydrogen into energy. These improvements not only enhance the efficiency of fuel cells but also broaden the scope of hydrogen applications in sectors such as transportation and stationary power generation (Yaqoob et al., 2023).

Moreover, the costs associated with hydrogen production are decreasing because of continuous technological and procedural advancements. This reduction in costs makes hydrogen a more competitive alternative to fossil fuels (Ji and Wang, 2021). Additionally, partnerships and collaborations play a crucial role in the sector's expansion. These alliances, which often involve hydrogen producers, automakers, and utility companies, help share knowledge and resources, thereby accelerating infrastructure development and adoption of hydrogen-based technologies (Lindner, 2023).

Countries worldwide have adopted comprehensive hydrogen roadmaps that project substantial installations of electrolysis capacities to ramp up green hydrogen production. Over 25 nations, including those in the EU, have detailed strategic plans calling for significant infrastructure establishment to support a transition toward hydrogen-based economies. The EU, for instance, installs at least 40 GW of electrolyzer by 2030, enhancing their existing capabilities significantly (Wappler et al., 2022).

To meet the escalating demand, the global manufacturing capacity for electrolyzer is projected to grow exponentially. The current capacity stands at a modest base; however, to achieve Net Zero goals by 2030, it is estimated that over 700 GW of water electrolysis installations will be necessary. This would require a 200 % increase in electrolyzer manufacturing capacities within the next decade, indicating a robust industrial scale-up (Wappler et al., 2022).

Fig. 6 illustrates the comparative analysis of projected green hydrogen demand against the anticipated growth in electrolyzer production capacities from 2021 to 2030. The graph depicts a rapid increase in green hydrogen demand alongside the growth of electrolyzer production capacity over the decade. Demand is expected to rise sharply to 75 MT by 2030, mirrored by a surge in electrolyzer capacity to 500 GW, highlighting the industry's expansion to support a low-carbon energy transition (Wappler et al., 2022). The scale-up reflects global efforts to integrate sustainable energy solutions and the impact of the policy measures designed to bolster the hydrogen economy. The alignment between demand and production capacity growth underscores the market's readiness to meet future sustainability targets.

In conclusion, the accelerating growth in hydrogen demand and the simultaneous expansion of electrolyzer capacity signal a pivotal shift toward sustainable energy practices globally. This trend, reinforced by strong policy frameworks and strategic investments, is steering the energy industry toward a future where green hydrogen plays a central role in meeting global energy needs while addressing climate change imperatives. The proactive approach of governments and industries in supporting hydrogen infrastructure and technology development is

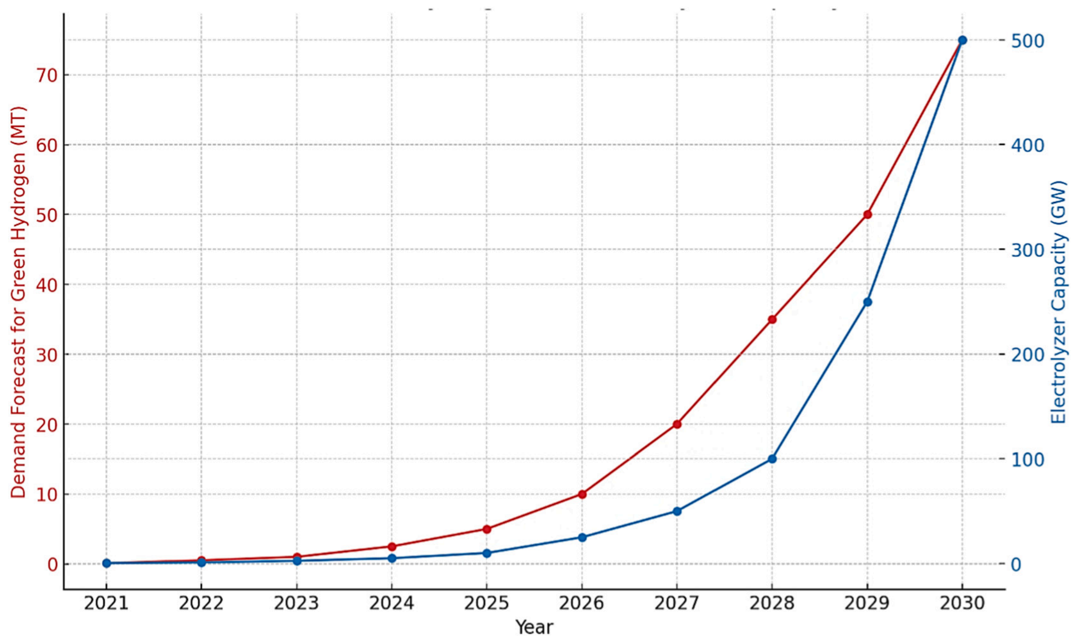

Fig. 6. Projected growth of global green hydrogen demand and electrolyzer manufacturing capacity from 2021 to 2030, adapted from Ref. (Wappler et al., 2022).

laying the groundwork for an innovative and sustainable energy landscape (Hoang et al., 2023). As we approach 2030, concerted efforts to scale up the hydrogen economy are expected to yield substantial environmental benefits, making it a cornerstone of global energy transformation.

6.3. Public perception and societal acceptance

In recent times, hydrogen energy has garnered substantial interest and excitement as a potential alternative to traditional fossil fuels. Using hydrogen as a sustainable energy resource holds the promise of significantly reducing GHGs emissions, offering a prospective solution to mitigate the impacts of climate change. However, the level of acceptance and adoption of hydrogen energy by the general population is still evolving and is influenced by various factors such as geographical location, national regulations, and cultural differences (Itaoka et al., 2017; Chen et al., 2016).

Several countries, including Japan, the Republic of Korea, and Germany, have taken prominent roles in researching and adopting hydrogen energy technology, while others are beginning to explore its potential. Public perceptions of hydrogen energy are shaped by several issues, including environmental concerns, energy stability, economic considerations, and advancements in scientific knowledge. A significant challenge in the widespread implementation of hydrogen energy lies in the lack of the necessary infrastructure to support its use, particularly the absence of hydrogen recharging stations for vehicles. In addition, there is a common perception that hydrogen energy is still too expensive and that its production methods have yet to achieve the required standards of reliability and safety (Schonauer and Glanz, 2022; Gordon et al., 2022).

Despite these limitations, there has been a noticeable increase in public awareness and enthusiasm regarding the integration of hydrogen with renewable energy. Governments and organizations are dedicating significant resources to exploring, developing, and implementing hydrogen energy. This trend has experienced significant acceleration, especially in the aftermath of the COVID-19 pandemic (Hoang et al., 2021b). The potential of hydrogen energy to play an essential role in the global energy mix and significantly contribute to mitigating the impacts of climate change depends on sustained research and development efforts, as well as the establishment of the necessary infrastructure to facilitate its use (Lozano et al., 2022).

6.4. Challenges and future opportunities in sustainability

The push for hydrogen energy as a solution to global energy challenges introduces complex hurdles. Financial viability remains a significant barrier, with the production and storage of hydrogen currently being more expensive than conventional fossil fuels. This cost gap presents a critical research direction in developing more economical catalysts and efficient electrolyzer that could bridge this discrepancy (Dewangan et al., 2022b). Additionally, the nascent state of supporting infrastructure, such as refueling stations and storage facilities, demands urgent attention to enable a seamless hydrogen economy (Olabi et al., 2021).

Safety concerns, particularly the flammability of hydrogen and risks associated with its high-pressure storage and transport, mandate the creation of stringent safety protocols and robust containment methods (Jafari Raad et al., 2022; Agaton et al., 2022). Furthermore, the high energy density of hydrogen necessitates innovative storage solutions to effectively manage the substantial physical space requirements. The environmental footprint of hydrogen production, primarily when derived from fossil fuels, also calls for a strategic focus on optimizing renewable-driven electrolysis and biogas-based methods (Zhao et al., 2022; Hassan et al., 2023b).

Looking forward, the integration of renewable energy sources in hydrogen production presents a bright prospect for a sustainable energy matrix that minimizes GHGs and leverages the cyclical nature of resources like solar and wind power. The advancement of fuel cell technology, particularly for transportation, can revolutionize the sector, with a pivot toward hydrogen fuel cell vehicles offering a greener alternative to gasoline-powered transport (Baeyens et al., 2020).

Table 15 presents a comparative analysis of production costs, CO_2 emissions, technological readiness, and future market potential for each method (Hassan et al., 2023b). Such a juxtaposition not only aids in understanding the current landscape of hydrogen production but also in discerning the trajectory of market adoption and technological evolution, which is crucial for strategizing future developments in sustainable hydrogen energy solutions.

These data underscore the importance of pursuing advanced, low-emission hydrogen production technologies. Despite the higher cost,

Table 15
Comparative analysis of hydrogen production methods.

Method	Production cost ($/kg)	CO_2 emissions (kg CO_2/kg H_2)	TRL	Future market potential
SMR	1.5	10	9	Stable
Coal gasification	2.5	20	8	Declining
Biomass gasification	3.5	2	7	Growing
Water electrolysis	5.0	0	8	Rapid growth

methods like water electrolysis powered by renewable energy represent the most sustainable option, signifying a rapidly growing sector with the potential to reshape the global energy market.

In summary, the landscape of hydrogen energy is at a crossroads where its inherent challenges are pronounced as the opportunities it presents. As the world leans into a future where sustainability is not just preferred but also required, hydrogen energy stands as a beacon of potential. The transition toward hydrogen as a key energy carrier will involve surmounting the outlined economic and technological barriers, yet the rewards promise a cleaner, more resilient energy paradigm. The drive toward innovation, bolstered by the insights from Table 15, must continue unabated, focusing on developing scalable, efficient, and safe hydrogen solutions. Ultimately, the commitment to overcoming these challenges will determine the role of hydrogen in the sustainable energy portfolio of tomorrow.

7. Conclusions

This review comprehensively assessed the current advancements and the broader context of hydrogen energy technology, encapsulating its essential technological components, extensive real-world applications, and envisioning potential future trajectories. It highlighted the multifaceted role of hydrogen as a cornerstone in the transition toward sustainable energy systems, evaluated the challenges and innovations within the sector, and explored the synergistic potential of hydrogen with other renewable technologies.

7.1. Principal conclusions and insights

Hydrogen stands out as a sustainable energy carrier with a high energy density of 120 MJ/kg, surpassing traditional fuels in efficiency and emitting only water vapor upon consumption. This position hydrogen as a formidable ally in the global effort to mitigate climate change, particularly through the decarbonization of critical sectors such as transportation, industry, and residential heating.

In the transportation sector, hydrogen can replace diesel in heavy vehicles, offering a reduction in carbon emissions by up to 70 % compared with conventional fuels. In the industrial sector, particularly in steel manufacturing, hydrogen can serve as a reducing agent instead of coking coal, which could lower carbon emissions by over 30 %. For residential heating, integrating hydrogen with natural gas could achieve a 7 % reduction in CO_2 emissions nationally, assuming adaptation of existing infrastructure.

Technological advancements in hydrogen production are significant, with current electrolysis systems achieving efficiencies of up to 70 %. Innovations increase this efficiency beyond 80 %, making hydrogen production more economically viable. In terms of storage, research is focused on developing solid-state materials that could provide safer and more efficient storage solutions than high-pressure tanks.

Economically, hydrogen faces challenges, particularly in terms of production costs, which currently stand at approximately $5 per kilogram for green hydrogen. The goal is to reduce these costs below $2 per kilogram to compete with conventional fuels (Zun and McLellan, 2023). Infrastructure development is also critical, with projections suggesting the need for over 10,000 hydrogen refueling stations by 2030 to support the widespread adoption of hydrogen-powered vehicles (Genovese and Fragiacomo, 2023).

Government policies and economic measures, including carbon pricing and subsidies for low-carbon technologies, are vital for bridging the cost gap between hydrogen and fossil fuels. A carbon price of $50 per ton of CO_2, for example, could significantly enhance the economic viability of hydrogen. Supportive regulatory frameworks are necessary to facilitate market growth and consumer acceptance.

Public perception and acceptance of hydrogen as an energy source will play a crucial role in its adoption. Educational programs designed to improve public understanding and mitigate skepticism could accelerate the acceptance and integration of hydrogen technologies.

Overall, the environmental benefits of hydrogen, which include the potential to reduce energy-related carbon outputs by up to 30 %, confirm its potential as a key component of a low-carbon future. However, achieving this potential requires overcoming the persistent challenges of high production costs, technological innovation in storage and production, and the development of a comprehensive supporting infrastructure. Collaboration across governmental, industrial, and academic sectors is essential to effectively address these challenges.

7.2. Implications for safety and practice

The review highlighted the immense potential of hydrogen energy as an environmentally friendly and enduring energy source that can significantly mitigate the impacts of climate change. Hydrogen energy offers a high energy yield per unit mass (three times that of conventional gasoline) and could drastically reduce global dependence on fossil fuels while curbing GHGs by up to 830 million tons of CO_2 annually. However, the extensive adoption of hydrogen energy is currently impeded by a range of technological and infrastructure challenges that require comprehensive attention.

Given these challenges, it is advisable for authorities to allocate substantial resources toward research and development efforts aimed at overcoming these barriers and promoting the adoption of hydrogen energy. This entails supporting the advancement of innovative technologies, such as improved electrolysis processes that could enhance efficiency and reduce production costs currently estimated at $5 per kilogram for green hydrogen. Additionally, enhancing infrastructure is crucial, including the expansion of hydrogen transport and distribution networks. Over 5000-km hydrogen pipelines by 2030 would significantly improve supply efficiency across various regions.

Furthermore, implementing robust safety regulations is essential to enable the safe and efficient production, storage, and transportation of hydrogen. These regulations would help manage the risks associated with hydrogen handling, particularly in its compressed or liquefied forms, which are prone to high-pressure risks and require stringent safety protocols.

Policymakers should consider implementing regulatory measures and incentive mechanisms, such as tax incentives for enterprises investing in hydrogen energy and grants for hydrogen infrastructure development. This becomes especially crucial in areas where the existing infrastructure is inadequate. Such measures would not only accelerate infrastructural development but also promote industrial investment in hydrogen technologies.

The review also suggests that practitioners prioritize the development of cost-effective and environmentally sustainable methods for hydrogen production while improving the essential infrastructure for its transportation and use. This includes the establishment of new infrastructure like hydrogen refueling stations and advancements in technologies related to hydrogen production and storage.

In summary, although hydrogen energy can be a transformative factor in addressing climate change, its widespread integration faces obstacles due to various technological and infrastructure limitations. To effectively address these challenges and promote the adoption of hydrogen energy as an eco-friendly and sustainable energy solution for the future, close collaboration between policymakers and practitioners is crucial. This collaborative approach would ensure that hydrogen energy becomes a cornerstone of the global effort to create a sustainable and low-carbon future.

7.3. Directions for future research

Future research on hydrogen energy systems is essential to enhance their efficiency, sustainability, and economic viability and to address the various technological and infrastructural challenges currently impeding their widespread adoption. Investigating more economically viable and efficient electrolysis methods is critical. Current methods showcase energy efficiencies ranging from 60 % to 80 %, but with innovations in catalyst technologies, particularly those facilitating hydrogen production from alternative sources like biomass, it is possible to both lower costs and reduce environmental impacts. Presently, the cost of producing green hydrogen is approximately $5 per kilogram, highlighting the need for breakthroughs in reducing these expenses.

Innovative storage solutions and infrastructure improvements are also vital. The development of cost-effective, secure, and lightweight materials for hydrogen storage would address the current challenges associated with high-pressure and cryogenic storage methods. In addition, expanding the hydrogen distribution network, including the establishment of refueling stations, is essential. To meet growing demands, the number of hydrogen refueling stations must increase tenfold by 2030.

Addressing safety and regulatory issues is paramount for integrating hydrogen systems into the current energy landscape. This includes the formulation of robust safety protocols and standards that enhance system integrity and public trust. Future studies should also explore the development of regulatory frameworks that could effectively govern hydrogen production, storage, and transportation activities, ensuring safety and efficiency.

Moreover, integrating hydrogen energy systems with other renewable sources, such as electricity and natural gas, presents an opportunity to stabilize and diversify energy supplies. Research should focus on developing hybrid systems that effectively combine hydrogen with these energies, which will be crucial for building resilient and sustainable energy infrastructures.

Finally, improving the economic viability of hydrogen energy systems is essential. This entails not only lowering the costs associated with production and storage but also developing innovative business models and financial strategies that encourage broader adoption and market penetration. Exploring new market mechanisms and subsidies could help mitigate the substantial initial costs associated with hydrogen infrastructure development.

Overall, to fully realize the potential of hydrogen as a sustainable and environmentally friendly energy source, it is crucial to overcome existing barriers through enhanced research collaboration among policymakers, industry stakeholders, and researchers. This collaborative approach will ensure that hydrogen energy plays a transformative role in the global energy landscape.

CRediT authorship contribution statement

Abdellatif M. Sadeq: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Raad Z. Homod:** Conceptualization, Formal analysis, Investigation, Supervision, Validation. **Ahmed Kadhim Hussein:** Conceptualization, Formal analysis, Supervision, Validation. **Hussein Togun:** Conceptualization, Formal analysis, Supervision, Validation, Visualization. **Armin Mahmoodi:** Conceptualization, Formal analysis, Investigation, Supervision. **Haytham F. Isleem:** Conceptualization, Formal analysis, Supervision, Validation. **Amit R. Patil:** Conceptualization, Supervision, Validation. **Amin Hedayati Moghaddam:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Abdellatif M. Sadeq reports article publishing charges and writing assistance were provided by Qatar University. Abdellatif M. Sadeq reports a relationship with Qatar University that includes: board membership. Abdellatif M. Sadeq has patent pending to None. 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. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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