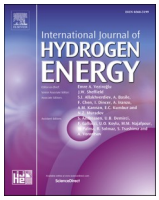
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An overview of the hydrogen value chain in energy transitioning economies: A focus on India

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ABSTRACT

India's energy sector is undergoing a major transformation as the nation targets energy independence by 2047 and net-zero emissions by 2070. With a high dependency on energy imports, a strategic shift toward renewable energy and decarbonisation is crucial. Hydrogen has emerged as a promising solution to address energy storage and sustainability challenges, prompting emerging countries to develop strong hydrogen infrastructures. This paper examines various methods involved in the hydrogen value chain, from production to utilisation, from the perspective of transitioning economies. By identifying key parameters and existing gaps, this paper aims to support policymakers and stakeholders in designing effective strategies to accelerate the development of a sustainable and secure hydrogen economy. India currently relies on carbon-intensive hydrogen from fossil fuels. Green hydrogen faces high costs and infrastructure gaps. Despite storage and safety concerns, hydrogen shows strong potential for clean energy and industry transformation.

1. Introduction

India's energy landscape is undergoing a significant transformation as the country aims to achieve energy independence by 2047. Currently, India relies heavily on imported fossil fuels and spends over $160 billion annually on energy imports, which poses a major challenge to both economic stability and energy security [1]. In response, the country is prioritising a strategic shift towards cleaner energy sources, particularly renewable energy, to meet its growing demand while aligning with its climate commitments. India has made substantial progress in expanding its renewable energy portfolio, with a cumulative installed capacity exceeding 220 GW as of March 31, 2025, positioning it among the top countries globally in renewable energy deployment [2]. However, the intermittent nature of solar and wind energy highlights the critical need for efficient and scalable energy storage solutions. In this context, hydrogen has emerged as a transformative energy carrier. Hydrogen not only addresses the challenge of energy storage but also offers a pathway to decarbonise hard-to-abate sectors such as steel, cement, chemicals, heavy-duty transport, and power generation.

Hydrogen is regenerative and can be produced through various methods. Hydrogen storage is also flexible, catering to various needs, and hydrogen can be transported over long distances. It is a versatile fuel that can be used in combustion engines, turbines, or fuel cells to generate energy. Compared with conventional fuels, it has a very high energy content (120–142 MJ/kg), making it ideal for long-distance transportation or powering heavy-duty vehicles. Some of its properties are given in Table 1 [3].

During combustion, hydrogen burns cleanly with air, releasing only water vapour as a byproduct. This makes it an environmentally friendly option, as conventional fossil fuels emit pollutants. Combustion requires a fuel to be gaseous or vapourised, and hydrogen achieves this state at very low temperatures because of its low boiling point of −252.8 °C. It is highly flammable and requires less energy to ignite. It has a high flammability range and can burn with air from 4 to 75 % by volume (for gasoline, it is 1–7.6 %). It has a high flame speed of 1.7 m/s, facilitating quicker heat release and avoiding incomplete combustion [4]. It has a high autoignition temperature of 500 °C, allowing for a higher compression ratio and thermal efficiency than conventional fuels in combustion engines. Additionally, hydrogen has an extremely high octane number, exceeding 130, which prevents unwanted autoignition.

In a fuel cell, hydrogen reacts electrochemically with oxygen from the air to produce electricity, with water and heat as the only byproducts. Fuel cells offer a clean and efficient way to generate electricity without releasing any harmful pollutants and are suitable for applications where low emissions and high efficiency are crucial.

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Abbreviations

AEC	Alkaline Electrolyser Cell
AEMEC	Anion Exchange Membrane Electrolyser Cell
BEV	Battery electric vehicles
CAPEX	Capital Expenses
CCGT	Combined-cycle gas turbines
CCH_2	Cryo-compressed hydrogen
CCHP	Combined cooling, heating, and power
CCUS	Carbon capture, utilisation, and storage
CGH_2	Compressed gas hydrogen
CNG	Compressed natural gas
COF	Covalent Organic Framework
GHG	Greenhouse gas
HFC	Hydrogen Fuel Cell
HFCV	Hydrogen fuel cell vehicles
H_2S	Hydrogen sulphide
ICE	Internal Combustion Engines
LCA	Life cycle assessment
LCOH	Levelised cost of hydrogen
LH_2	Liquefied hydrogen
$LiBH_4$	Lithium Borohydride
$LiBH_4$@Ah-BN	$LiBH_4$ with activated hexagonal boron nitride
LOHC	Liquid organic hydrogen carrier
MCH	Methylcyclohexane
MEC	Microbial Electrolysis Cell
MMT	Million Metric Tonnes
MOF	Metal Organic Frameworks
$NaBH_4$	Sodium Borohydride
NG	Natural gas
NO_x	Nitrogen oxides
OPEX	Operational Expenses
PEMEC	Proton Exchange Membrane Electrolyser Cell
PtG	Power-to-gas
PV	Photovoltaic
SCWG	Supercritical water gasification
SCWO	Supercritical water oxidation
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level
UHS	Underground hydrogen storage
US-DOE	United States – Department of Energy

Table 1
Properties of hydrogen.

Property	Value
Density (NTP)	0.08375 kg/m^3
Specific Volume (NTP)	11.94 m^3/kg
Boiling point (1 atm)	−252.8 °C
Melting point (1 atm)	−259.2 °C
Lower Calorific Value	120 MJ/kg
Higher Calorific Value	141.8 MJ/kg
Flame temperature in air	2045 °C
Flammability range	4–75 %
Ignition Energy	0.2 mJ
Autoignition temperature	500 °C

NTP (normal temperature and pressure) = 20 °C and 1 atm.

Hydrogen presents several advantages as an energy carrier, primarily in terms of environmental sustainability and energy efficiency, which significantly reduce greenhouse gas (GHG) emissions and mitigate climate change. Additionally, hydrogen is a versatile energy carrier that can be used across various sectors, including transportation, industry, and electricity generation. As a renewable and clean energy source, hydrogen is pivotal in fostering a transition towards a more sustainable and low-carbon energy landscape.

Recognising this potential, the Government of India launched the National Green Hydrogen Mission (NGHM), which sets an ambitious target of producing 5 million metric tonnes (MMTs) of green hydrogen annually by 2030 [5]. This initiative is supported by plans to install 125 GW of renewable energy capacity dedicated to hydrogen production, alongside large-scale investments in electrolyser manufacturing, hydrogen refuelling infrastructure, and research and development.

The development of a hydrogen economy necessitates a comprehensive and coordinated approach that encompasses policy frameworks, public–private partnerships, and international collaborations. The technical challenges associated with hydrogen production, storage, and transportation must also be addressed to ensure both safety and economic viability. India plans to become a global leader in hydrogen technologies by leveraging its abundant renewable resources, skilled scientific base, and increasing industrial interest. A robust hydrogen infrastructure can enhance energy security and significantly contribute to India's long-term decarbonisation goals and economic growth.

This paper is motivated by the growing need to transition to clean energy, with hydrogen emerging as a key solution for decarbonising sectors such as industry, transport, and power. While global research on hydrogen is extensive, there is an apparent lack of integrated studies tailored to the Indian context. This study addresses that gap by reviewing the technological and economic aspects of hydrogen production, storage, transportation, and applications within India's energy landscape. Its novelty lies in offering a comprehensive, context-specific analysis that identifies strategic priorities across the hydrogen value chain, serving as a valuable guide for policymakers and stakeholders shaping India's hydrogen future.

The present research work supports the Sustainable Development Goals (SDGs) 7, 11, and 13, which aim for clean energy, sustainable transportation, and a pollution-free environment, respectively.

2. Production of hydrogen

Despite being the most abundant element in the universe, hydrogen does not occur naturally in its molecular form on Earth. It needs to be produced from compounds such as water or hydrocarbons through various methods. The diverse sources, feedstocks, and processes used to produce hydrogen are shown in Fig. 1 [6]. Hydrogen production from fossil fuels remains the dominant method globally, with approximately 95 % of hydrogen being generated from feedstocks such as natural gas, oil, and coal [7]. Hydrogen is colour-coded on the basis of its production method and energy source, as shown in Fig. 2.

2.1. Reforming

Steam methane reforming (SMR) is one of the most widely used methods for producing hydrogen. It involves reacting natural gas with steam under high pressure and at temperatures of 700–1000 °C to produce hydrogen [8]. Emissions from this process range from 9 to 11 $kgCO_2/kgH_2$, limiting its environmental sustainability [9]. Hydrogen production from biomass-derived acetic acid via steam reforming has also been widely studied; however, most catalysts struggle with the acid-rich components of bio-oil [10]. Ethanol is a renewable, biodegradable, and easily transportable fuel, and catalytic steam reforming offers an effective pathway for its conversion to hydrogen. Additionally,

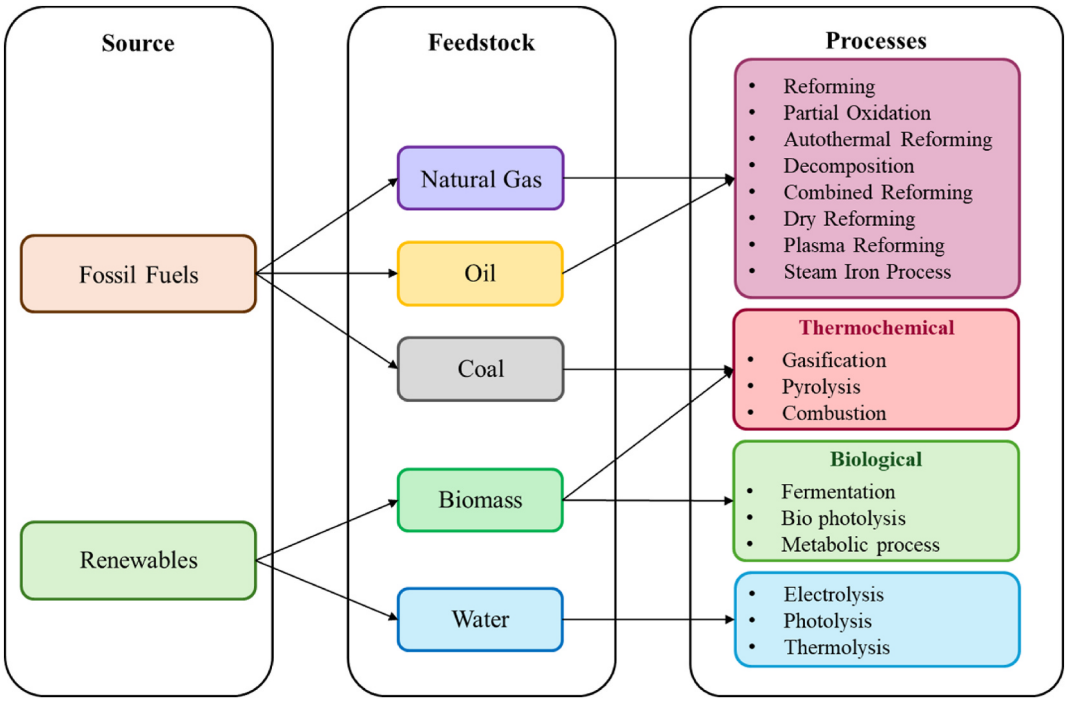


Fig. 1. Hydrogen production methods [6].

Colour	Process	Source of energy
Green	Electrolysis	Renewable energy
Blue	SMR or Gasification with carbon capture	Methane or Coal
Grey	SMR	Methane
Turquoise	Pyrolysis	Methane
Yellow	Electrolysis	Grid electricity
Brown / Black	Gasification	Fossil Fuels (Coal)
Pink / Purple / Red	Electrolysis / Thermolysis	Nuclear power
White	Naturally occurring hydrogen found in the underground	

Fig. 2. Hydrogen colour coding. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ethanol steam reforming prevents catalyst poisoning and carbon buildup. However, ensuring long-term sustainability remains a challenge [11]. Glycerol steam reforming is a sustainable hydrogen production method optimised at 900 K with a 9:1 water/glycerol ratio, costing $4.46/kg$H_2$ [12]. Steam reforming of other liquid hydrocarbons, such as heavy naphtha, kerosene, and diesel, is a promising technology for producing hydrogen at existing gas stations, enabling efficient onsite conversion [13].

Partial oxidation (PO) is a technique in which hydrocarbons are partially burned in the presence of oxygen to produce hydrogen and carbon monoxide. Autothermal reforming combines steam reforming and partial oxidation in a single reactor to increase efficiency. Dry reforming uses carbon dioxide instead of steam, offering the advantage of reducing greenhouse gas emissions. Plasma reforming and decomposition involve breaking down hydrocarbons through advanced technologies such as plasma arcs or catalytic processes.

Another hydrogen production approach combines acid gas to syngas (AG2S) and sorption-enhanced water gas shift (SEWGS) processes. AG2S converts H_2S and CO_2 into hydrogen and sulphur, followed by amine scrubbing for purification. SEWGS, operating at 350–400 °C, minimises energy losses, enables H_2S recycling, and captures CO_2 efficiently, achieving a hydrogen production efficiency of approximately 25 % [14].

2.2. *Gasification*

During gasification, coal or biomass is heated above 750 °C without combustion in a controlled oxygen environment, resulting in a series of reactions that convert the feedstock into syngas and ash/slag, producing H_2, CO, and CO_2 [15]. Gasification is also one of the most cost-effective methods for producing biohydrogen, with eucalyptus wood gasification having one of the lowest carbon footprints (−1.6 kg CO_2 eq./kg H_2) [16]. Biomass gasification using bamboo wood can achieve an efficiency of 53.6 %, producing 106.9 g/s hydrogen [17]. The bamboo in Northeast India can generate 23.92 PJ of energy, making it an economical option for localised energy solutions [18]. Biomass gasification faces barriers to commercialisation due to technological challenges, including tar formation and agglomeration, biomass variability, and gaps in implementation and policy support [19].

Steam gasification of waste plastics enables the simultaneous production of hydrogen and methanol, offering a sustainable energy alternative while mitigating the environmental impact of plastic waste [20]. Supercritical water gasification (SCWG) efficiently converts wet feedstocks without energy-intensive drying. Its hydrogen production cost is lower than that of several conventional methods, but slightly higher than that of pyrolysis and specific thermochemical water-splitting cycles [21]. Black liquor, a hazardous byproduct of the Kraft process, can be converted into hydrogen-rich gas or heat via SCWG and supercritical water oxidation (SCWO). The SCWG achieves a maximum energy efficiency of 41.53 % and a minimum hydrogen production cost of 23.28 RMB (~$3.2)/kg H_2, whereas the SCWO reaches 19.89 % efficiency [22]. However, the SCWG requires considerable thermal energy to reach high operating temperatures, reducing its overall efficiency. The selection of energy sources and process-energy configuration is crucial for making the SCWG process more economical [23].

2.3. Carbon capture, utilisation, and storage

Carbon capture, utilisation, and storage (CCUS) is a critical technology for reducing CO_2 emissions and combating climate change, with carbon mineralisation offering long-term sequestration benefits. India has substantial geological storage capacity in basaltic rocks, saline aquifers, and depleted oil reserves [24,25]. Projects such as CO_2-EOR (enhanced oil recovery) pilots have demonstrated potential for emission reduction [26]. CCUS-enabled hydrogen production, cogasification of coal and biomass, and CO_2 utilisation for green chemicals offer cost-effective, low-emission solutions. Adding CCUS to biomass-to-hydrogen (BTH) production increases energy consumption by 17 %, investment by 1.3 %, and production costs by 14.6–19.4 %, with a payback period of 5–6 years [27]. Despite a 17 % lower energy efficiency, a CO_2 capture rate of 80 % is optimal, enabling negative greenhouse gas emissions. In India, CCUS is crucial for meeting climate commitments and reducing emission intensity in accordance with the Paris Agreement. However, many CCUS technologies are at Technology Readiness Levels (TRLs) 6 and 7 globally, whereas in India, they are at TRLs 4 and 5 [28]. The future of CCUS infrastructure in India remains uncertain, but its retrofit potential for existing plants could aid in sector decarbonisation. Currently, carbon capture in India is limited to specific industries where it is an integral part of the process [29]. India needs robust policies, technological advancements, and large-scale deployment over the next decade to realise its potential and contribute to the global energy transition.

2.4. Pyrolysis

During pyrolysis, the biomass is heated above 300 °C in an anaerobic atmosphere. In the absence of oxygen, biomass thermally decomposes into combustible gases and biochar [15]. The hydrogen yield from biomass varies on the basis of its composition, with smaller particle sizes improving yield by increasing the surface area and reaction rates. High-purity hydrogen can be produced from the pyrolysis of the organic fraction of municipal solid waste, offering a carbon-negative energy recycling solution. Fast pyrolysis can generate hydrogen yields of up to 45 %, with a cost range of $1.25–$2.20 per kg [30]. Its economic feasibility depends on population density, waste resources, product price, and labour costs, making it particularly viable in developing countries [31].

Methane pyrolysis, also known as methane cracking or decomposition, thermally splits methane into hydrogen and solid carbon without generating carbon dioxide. Its zero CO_2 emissions make it a promising bridge technology for sustainable energy transition [32]. Electron beam plasma methane pyrolysis is a CO_2-free hydrogen production method, with hydrogen costs ranging from $2.55–$5.00 per kg under current economic conditions [33]. Future price trends suggest significant cost reductions, making plasma pyrolysis a more competitive option. Its carbon footprint is much lower than that of traditional hydrogen production, with emissions ranging from 1.9 to 6.4 $kgCO_2/kgH_2$ [33].

2.5. Biohydrogen

Biohydrogen is a promising zero-carbon alternative to fossil fuels, utilising various biowaste sources such as agricultural residues, food waste, and industrial and beverage wastewater [34]. Biological methods such as fermentation employ microorganisms to break down organic material, producing hydrogen. Anaerobic digestion (AD) is a sustainable microbial process that converts up to 95 % of organic matter into methane, CO_2, hydrogen, and polyhydroxyalkanoates (PHAs), and uses biowaste as feedstock for energy-rich gases and value-added products [35]. Dark fermentation is facilitated by anaerobes in the absence of light and oxygen. Gasification and fermentation are cost-effective methods for biohydrogen production. Gasification is the most developed method and has the highest technology readiness level, whereas fermentation results in the lowest greenhouse gas emissions. Dark fermentation is efficient, especially when combined with photo fermentation and microbial electrolysis cells (MECs) [36]. However, hydrogen production from biomass needs further improvement to achieve higher efficiency, and competitive scalability and large-scale production remain significant challenges. Advancing biohydrogen production requires optimising industrially viable microorganisms, innovative bioreactor designs, and hybrid methods such as dark fermentation integrated with electro fermentation [37].

Lignocellulosic biomass is a promising feedstock for biohydrogen production because of its renewable, sustainable, and abundant nature [38]. Utilising lignocellulosic waste as feedstock and dynamic membrane bioreactors can improve efficiency while coproducing biomethane and value-added chemicals, enhancing the economic feasibility of large-scale biohydrogen production [37]. Palm oil mill effluent (POME) can also be a viable raw material for biological hydrogen and methane production because of its rich composition of carbohydrates, lipids, and proteins, which can be metabolised through dark fermentation [39]. The production can be financially viable at 99.9 % purity, with a payback period of 8.5 years and an 18.48 % return on investment [40]. Converting waste such as starch-based wastewater, mango juice effluent, and sugarcane straw hemicellulose hydrolysate into hydrogen also offers an efficient way to reduce disposal costs while generating a sustainable energy source [41–43].

In India, 94 % of waste is poorly managed, and waste generation increases by 1.3 % annually [44]. Waste is increasingly viewed as a valuable feedstock for hydrogen production, with significant potential for industrial-scale innovation through scientific integration, financial support, and long-term policies promoting sustainable waste management and bioeconomic development [45]. Although hydrogen production from food waste through dark fermentation has potential, its economic feasibility remains questionable [46]. Additionally, the complex composition of food waste and interactions with microbes make enhancement challenging. However, strategies such as lactate-driven fermentation, bioaugmentation, metabolic engineering, and synthetic microbiomes offer promising solutions [47].

2.6. Electrolysis

Electrolysis splits water into hydrogen and oxygen using electricity. This method offers a clean and sustainable method for hydrogen production. The main types of water electrolyser technologies are alkaline electrolyser cells (AECs), proton exchange membrane electrolyser cells (PEMECs), solid oxide electrolyser cells (SOECs), and emerging anion exchange membrane electrolyser cells (AEMECs). Each of these systems differs in terms of materials, operating conditions, efficiency, cost, and suitability for different applications. A schematic of these systems is shown in Fig. 3 [48–50].

AECs are the most mature and widely used type, having been in use

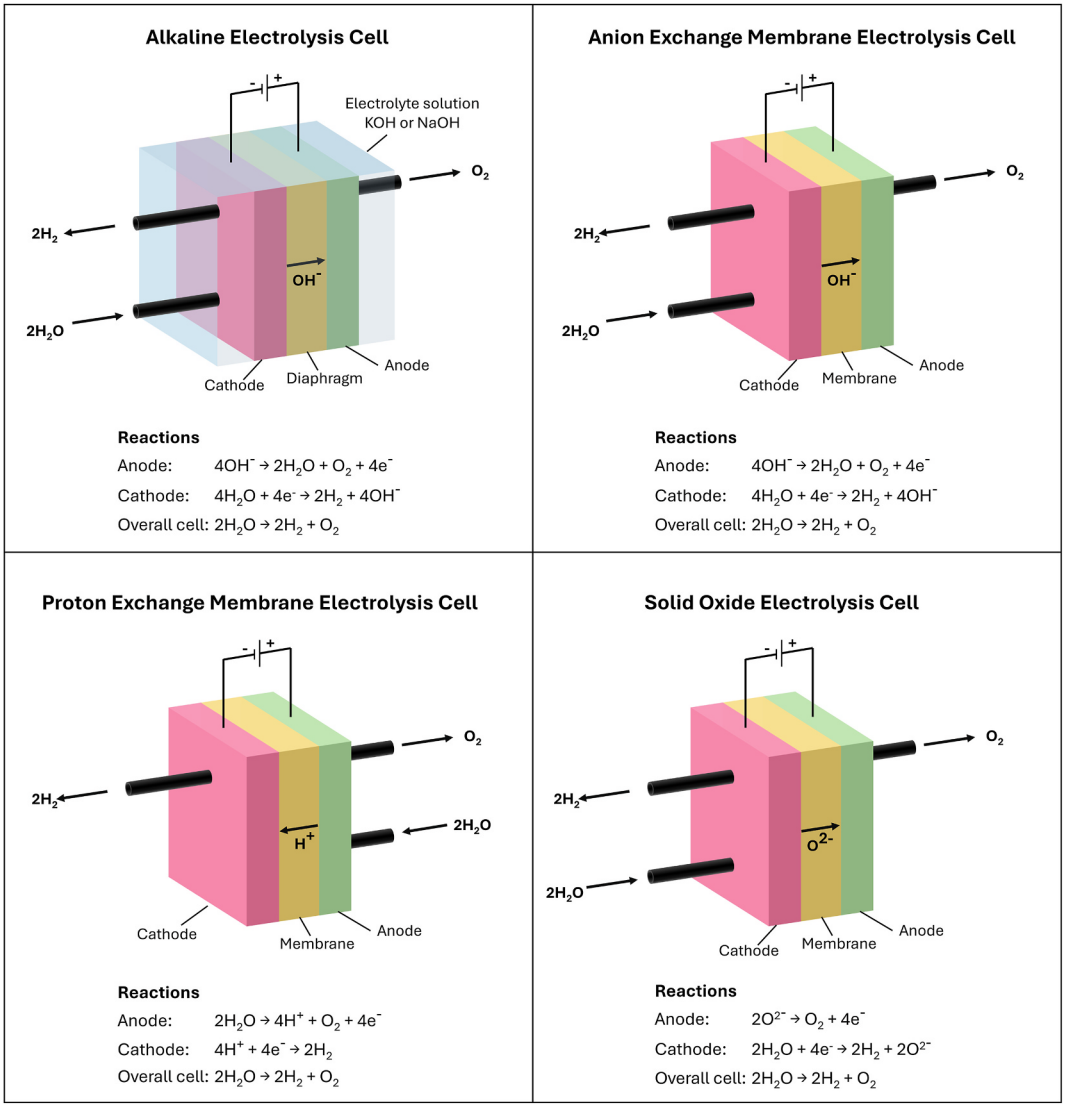


Fig. 3. Schematic of electrolyser technologies.

for over a century. They use a liquid alkaline solution, usually potassium hydroxide (KOH), as the electrolyte. The system operates at relatively low temperatures (50–80 °C) and uses nickel-based electrodes [49]. One of the key advantages of AECs is their low capital cost and long lifespan [51]. They are particularly well-suited for continuous, industrial-scale hydrogen production [50]. However, AECs are less responsive to fluctuating electricity input, making them less ideal for integration with intermittent renewable energy sources. Additionally, handling and maintaining the liquid electrolyte adds some complexity and potential corrosion challenges.

PEMECs use a solid polymer membrane that conducts protons from the anode to the cathode. PEMECs operate at temperatures 60–200 °C, achieve high current densities, and offer a fast dynamic response to changes in power input [49]. This makes them highly suitable for coupling with renewable energy sources, such as solar and wind, where the electricity supply fluctuates throughout the day [52]. PEMEC with a high-pressure cathode enhances hydrogen transmission efficiency by eliminating the need for compressors [53]. PEMECs produce very high-purity hydrogen and have a compact design [49]. However, they rely on expensive materials, including precious metal catalysts such as platinum and iridium, and require highly purified (deionised) water. These factors contribute to higher capital and operational costs; however, ongoing research is steadily improving their cost efficiency and durability. A transition from AEC to PEMEC systems is expected between 2020 and 2030, driven by reduced costs and increased operational flexibility.

SOECs represent a type of high-temperature electrolysis technology. These systems utilise a solid ceramic material as the electrolyte and conduct oxygen ions rather than protons [50]. One of the key benefits of SOECs is their high efficiency, particularly when integrated into processes that can supply the necessary heat, such as industrial waste heat systems [50]. SOECs can also perform coelectrolysis, producing syngas from water and carbon dioxide, which is useful in synthetic fuel production [54]. Reducing costs and extending lifespan are crucial factors for SOEC technologies.

AEMECs are an emerging technology that aims to combine the benefits of both AECs and PEMECs. AEMECs operate at low temperatures and utilise an alkaline solid polymer membrane, which enables the use of nonprecious metal catalysts, potentially leading to significant cost reductions [50]. They eliminate the need for liquid electrolytes and complex water purification, offering a simpler, safer, and more environmentally friendly system. While AEMEC technology has potential for decentralised and low-cost green hydrogen production, it is still in the early stages of development. Current challenges include achieving long-term durability, improving performance, and scaling up production for commercial use.

The SOCE is expected to match the AEC in terms of capital expenses (CAPEX) in the long term, whereas PEMECs are poised soon to become the most cost-effective option [55]. A combined approach of R&D investment and production expansion is recommended to drive standardisation and cost efficiency in electrolysis technologies [56]. A comparison of AEC, AEMEC, PEMEC, and SOEC electrolyser technologies is shown in Table 2 [49–51].

Producing 1 kg of hydrogen via electrolysis requires 9 L of fresh water, and meeting India's hydrogen demand would consume up to 0.05 % of the country's water supply [57]. While water use for electrolysis appears minor at the national scale, facility placement must avoid water-stressed areas, given India's increasing water scarcity. Research into seawater electrolysis and large-scale desalination offers alternative solutions, with desalination costs of approximately ₹1.5/kg for hydrogen production [57]. Seawater brine electrolysis for offshore use could be promising if impurities are effectively managed or advanced water treatment technologies are employed [58]. Compared with water electrolysis, treating nontraditional water sources, such as industrial wastewater, municipal wastewater and seawater, requires minimal energy and costs while offering vast hydrogen energy potential [59].

2.6.1. Green hydrogen

India has made substantial investments in renewable energy technologies, particularly in solar and wind power. As of March 2025, the country's installed renewable energy capacity reached 172.37 GW, representing a significant increase of approximately 331.46 % from 39.95 GW in 2014–15 [60]. Solar energy has driven much of this expansion, with installed capacity rising from 3.99 GW to 105.65 GW over the past decade. Wind power also experienced notable growth, increasing from 23.44 GW to 50.04 GW during the same period. Additionally, India's extensive 7500 km coastline offers promising prospects for tidal energy development [61]. The government has also targeted 10 GW of geothermal power generation by 2030 [62]. At the 26th UN Climate Change Conference of the Parties (COP26) in 2021, India pledged to achieve 500 GW of nonfossil fuel-based energy capacity by 2030 as part of its Panchamrit commitments [63]. Additionally, the National Green Hydrogen Mission (NGHM) aims to increase the renewable energy capacity by an additional 125 GW [5].

The solar photovoltaic (PV)-based PEMEC achieves an energy efficiency of 16.95 %, yielding hydrogen at a rate of 2.26 g/s [17]. India's solar-based green hydrogen production potential varies between 0.008 and 0.019 kg/m^2/day [64]. Research on wind hydrogen systems is evolving from energy storage to hydrogen production for export and transportation. Wind-based electrolysis has one of the least harmful environmental impacts on climate change [65]. Using existing wind farm infrastructure and excluding the cost of the wind farm in the investment for the wind-hydrogen plant can help lower the overall hydrogen production cost [66]. By 2030, production costs could significantly decrease, making offshore hydrogen production competitive with hydrogen production from SMR [67]. The economic feasibility of renewable hydrogen production depends on optimising renewable energy sources and electrolysis types. Onshore wind power-AEC has the lowest levelised cost of hydrogen (LCOH) at \$7.25/kgH_2, whereas PV-PEM has the highest at \$13.44/kgH_2 [68]. The renewable energy capacity factor has the greatest impact on LCOH, followed by the CAPEX and OPEX of the renewable power plant. Geothermal energy-based hydrogen production systems can operate with an efficiency of 10.45 %, generating hydrogen at a rate of 32.02 g/s [17].

Green hydrogen production costs are currently high but are projected to decline by more than 50 % by 2030, positioning green hydrogen to compete with fossil-based alternatives [57]. Owing to decreasing electrolyser prices, lower net energy costs, and economies of scale, green hydrogen is becoming increasingly viable for large-scale production compared with grey, brown, or blue hydrogen pathways [69,70]. Furthermore, the commercialisation of fuel cell vehicles and the expansion of hydrogen refuelling infrastructure are expected to significantly influence production and distribution costs [71].

Expanding renewable capacity not only enhances energy access but also lowers carbon intensity and increases the cost competitiveness of green hydrogen production. India is increasingly prioritising green hydrogen as a strategic solution to reduce energy costs and dependence on oil imports, thereby enhancing long-term energy security and resilience [72]. The transition to green hydrogen offers a sustainable pathway to mitigate future energy crises and achieve energy independence and net-zero emissions. A proposed National Green Hydrogen Roadmap (Fig. 4 [1]) outlines sectoral adoption timelines and strategies for scaling hydrogen applications across industries.

Other sources include nuclear power-to-hydrogen conversion, which offers a stable and competitive alternative to renewable-based electrolysis, particularly with existing or planned nuclear infrastructure. In India, nuclear-powered electrolysers can produce 1.8–4.0 million metric tons of hydrogen annually, meeting 6 %–15 % of the demand for green hydrogen and potentially reducing CO_2 emissions by 490–570 million tons per year across various industries [73]. The cost of hydrogen is predominantly influenced by the price of nuclear electricity [74]. India's current installed nuclear power capacity is approximately 7.5 GW and is projected to increase threefold by mid-2030 [75]. Hydrogen can also be produced via reverse electrodialysis (RED), which uses the salinity gradient between two solutions to generate electrical energy, which can then drive water electrolysis, offering a sustainable and renewable method for hydrogen generation [76].

Table 2
Comparison of electrolyser technologies.

Electrolyser technologies	AEC	AEMEC	PEMEC	SOEC
Electrolyte	Alkaline/Liquid	Alkaline/Solid (polymer)	Acidic/Solid (polymer)	O_2 or H^+ conducting/Solid (ceramic)
Electrode material	Nickel-based	Nonprecious metals	Platinum group metals	Perovskites, ceramics
Operating temperature (°C)	50–80	50–60	60–200	500–1000
Operating pressure (bar)	<30	<35	<80	0–2
Start-up time	Moderate	Short	Short	Long
Required water quality	Lower-purity acceptable	High purity	High purity	High purity
Efficiency (%)	68–77	≤74	70–80	80–90.8
Durability	High	Moderate	High	Low to moderate
Scalability	Moderate to high	High	High	Low to moderate
System complexity	Low	Moderate	High	High
Hydrogen purity (%)	99.5–99.9998	99.99	99.9–99.9999	99.9–99.99
Lifetime (h)	>60,000	20,000–60,000	50,000–80,000	~20,000
CAPEX ($/kW)	500–1400	Yet to be commercialised	1100–1800	2800–5600
TRL	TRL-9	TRL-6	TRL-9	TRL-7–TRL-8
Development Status	Mature	R&D	Commercialised	R&D
Applications	Large-scale industrial	Industrial, potential for mobility	Mobility, small-scale	High-temperature industrial processes

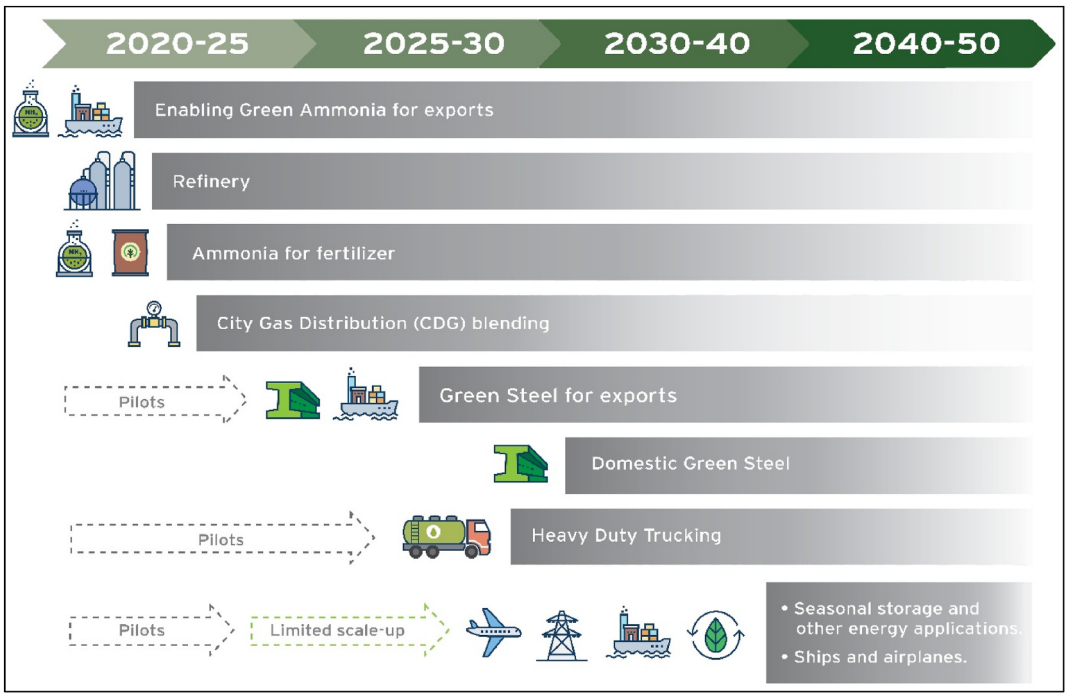


Fig. 4. Potential direction of a National Green Hydrogen Roadmap [1]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.7. Photo-driven processes

Photoelectrochemical (PEC) water splitting operates through redox reactions initiated by charge carriers produced from sunlight interacting with the catalyst's active regions. It is a simple process with minimal environmental impact; however, challenges remain in the development of suitable materials for commercial viability [77]. Photocatalysis offers advantages in terms of selectivity, biofouling resistance, and stability, with PEC processes potentially bridging the strengths for future development despite their solar dependency [78].

Hydrogen production from industrial wastewater via solar photocatalysis provides dual environmental sustainability benefits through sulphide degradation and economic advantages through the use of renewable solar energy [79]. A particulate photocatalytic hydrogen production system uses suspended photocatalyst particles in a liquid medium to harness light energy and drive water splitting into hydrogen and oxygen. High costs and design complexity hinder their large-scale application. Addressing limitations such as visible-light-responsive photocatalysts and efficient charge carrier separation could significantly improve the efficiency of photocatalyst-based hydrogen production systems, potentially achieving target costs of $1–$3.5 per kgH_2 at 10 % efficiency [80].

Bio photolysis uses the ability of photosynthetic organisms to split water molecules using sunlight, whereas metabolic processes explore natural microbial pathways to generate hydrogen. Photobioreactors have low efficiencies (1.8–5.6 %) but offer lower hydrogen production costs than biodiesel or biogas [81]. They require less land than traditional biofuels and can operate in dry regions, making them promising long-term energy solutions.

These diverse methods demonstrate the versatility of hydrogen production technologies, each tailored to specific feedstocks and energy sources. The choice of hydrogen production pathway and technology depends on the available energy source, feedstock type, and purity required for its intended application [82].

2.8. Comparative analysis of hydrogen production

Hydrogen is currently produced through SMR (48 %), partial oil oxidation (30 %), coal gasification (18 %), and electrolysis (4 %) worldwide [83]. SMR and coal gasification dominate hydrogen production because of their cost effectiveness, although they pose significant environmental challenges [84]. Even in India, most hydrogen production is sourced primarily from fossil fuels and as a byproduct in the chloralkali industry, with most of it being used at production sites [73]. Integrating carbon capture and transitioning to renewable hydrogen production offer more sustainable alternatives. Renewable methods, such as water electrolysis with proton exchange membrane (PEM) technology, are emerging as scalable solutions, with solar and wind providing the best environmental performance [85]. Biomass gasification and microbial hydrogen production offer low-carbon options, but they face challenges related to efficiency and scalability. Photonic methods are more environmentally sustainable than thermal methods, which pose greater challenges. Nuclear energy is a promising, low-cost, and low-impact option for future hydrogen production if safety and technological maturity are addressed. A balanced blue–green hydrogen decarbonisation approach can leverage fossil fuels in high-value applications while advancing renewable energy solutions [86]. A comparison of various production methods in terms of efficiency, cost, emissions, and TRL is shown in Fig. 5 [71,87–89].

The current priority is to develop large-scale, efficient, and cost-effective hydrogen production systems while reducing the initial cost, incorporating advanced novel materials, and utilising sustainable onsite production using local resources.

3. Storage of hydrogen

Owing to the low volumetric energy density of hydrogen, efficient storage is essential for transportation, grid integration, and industry applications. It can be stored in various forms, including compressed gas, liquid hydrogen, or solid-state storage via metal hydrides, chemical carriers, or adsorption materials, as shown in Fig. 6 [90,91]. Each form has certain advantages and challenges related to efficiency, safety, cost,

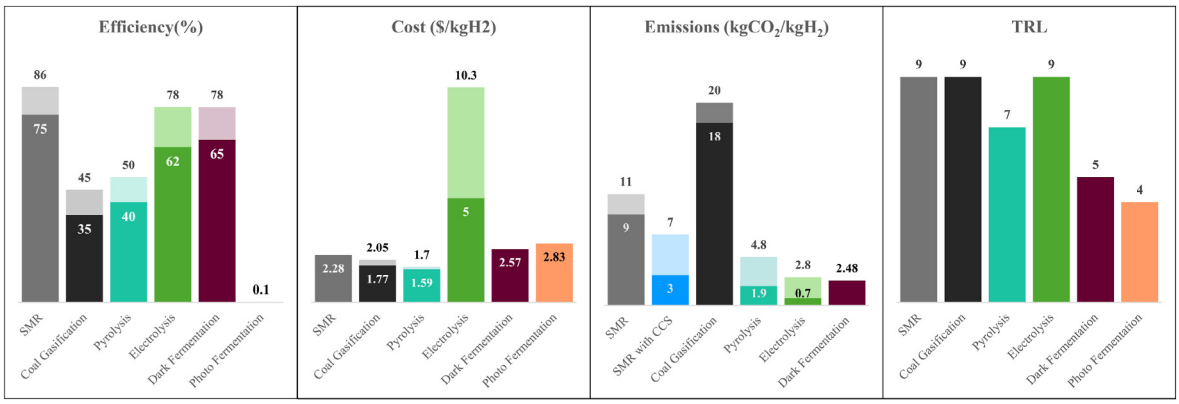


Fig. 5. Comparison of hydrogen production methods.

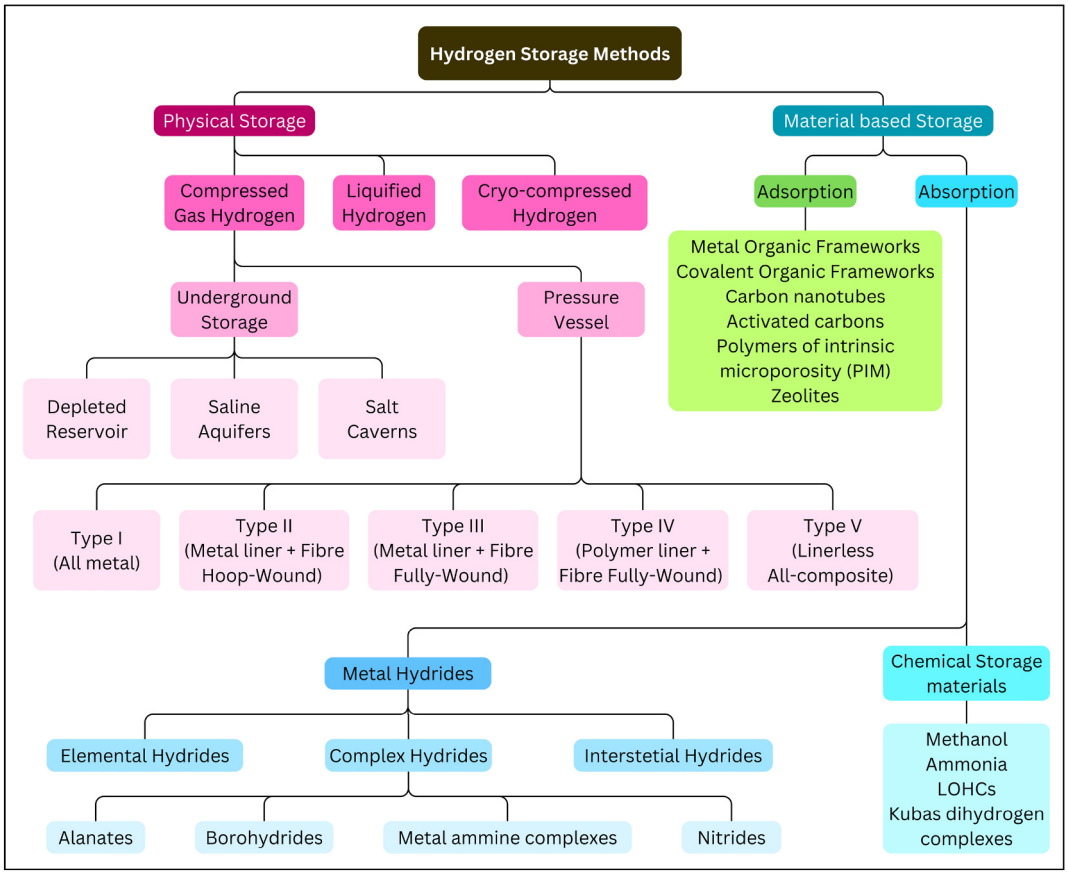


Fig. 6. Hydrogen storage methods.

and scalability.

3.1. Compressed gas hydrogen

Compressed gas hydrogen (CGH_2) is a widely used technology for both small and large-scale hydrogen storage, utilising pressure vessels and salt caverns. Type III and IV pressure vessels are commonly used in transportation and stationary applications, such as power plants, because of their ease of use, efficiency, and lightweight design. Type IV tanks can handle pressures up to 70 MPa, making them suitable for mobile applications. However, they have several drawbacks, including the need for up to 15 % of hydrogen's energy content in pressurisation, hydrogen permeation at high pressures, and the high cost of carbon fibre materials [90]. Additionally, CGH_2 at 70 MPa accounts for only 15 % of the energy density of gasoline, requiring more storage space. Durability, reliability, and safety remain concerns for long-term high-pressure storage [92]. Further research into material selection, qualification tests, and operating conditions is needed. The rapid charging and discharging of these tanks can cause temperature fluctuations due to the Joule–Thomson effect [93]. This might lead to thermal stress, microcracks, and a reduced state of charge, highlighting the importance of managing the inlet gas temperature, filling rates and precooling to avoid damage [94].

Underground hydrogen storage (UHS) is most effective in depleted reservoirs and saline aquifers because of their greater capacity, whereas salt caverns are better for cyclical storage in low-population areas [95]. However, hydrogen should not be stored at depths greater than 3700 m to prevent migration [96]. Compared with pure hydrogen, hydrogen–

methane blends can store more energy, with a 75 % blend increasing energy storage by 65 % [97]. Efficient injection and withdrawal depend on proper placement and optimised gas cycling. The internal pressure of the cavern should be between 24 % and 80 % of the overburden pressure for safety [96]. Geochemical and microbiological reactions can reduce the storage capacity over time, making quartz-rich sandstone and low-CO_2 reservoirs ideal for minimising risks. Salt caverns are cost effective, with 98 % efficiency and minimal contamination risk, and are suitable for industrial and power applications [57]. However, hydrogen storage in natural reservoirs and salt caverns is still developing, with limited knowledge of potential consequences. Additionally, because of geological conditions, salt cavern storage is not applicable in all regions [98]. India holds over 75 % of South Asia's 29,799.43 TWh UHS capacity [97]. Major UHS potential exists in the Mumbai Offshore, Krishna–Godavari, and Vindhyan Basins. The most viable basins for hydrogen storage, considering their proximity to green hydrogen sites, include the Krishna–Godavari, Mumbai Offshore, Saurashtra, Cambay, Bhima–Kaladgi, Kutch, and Rajasthan basins. The Cauvery and Krishna–Godavari basins have the capacity to store hydrogen and supply it continuously for seven years, providing long-term energy security to the southeastern region [99]. The levelised cost of hydrogen storage (LCHS) at these sites is $2.01 per kg [97]. Selecting sites for UHS requires careful analysis of geological, engineering, and safety factors, as well as addressing various technical, economic, legal, and social challenges before full-scale implementation [100,101].

3.2. Liquefied hydrogen

Liquefied hydrogen (LH_2) at −253 °C (20 K) is a traditional and advanced storage method that is ideal for large-scale storage due to minimal evaporation losses [102]. However, LH_2 requires significant energy (up to 35 % of its content) and efficient insulation, limiting its use in aerospace applications [90]. Storage of LH_2 at this temperature can cause corrosion due to ice formation, requiring specialised materials for safety and reliability [103]. Stainless steel is the most commonly used material because of its temperature performance and corrosion resistance. Researchers are also exploring aluminium, titanium alloys, and composite materials for high strength and lightweight storage, although hydrogen permeation is a challenge for composite containers [104].

Compared with CGH_2 and LH_2, cryocompressed hydrogen (CCH_2) offers higher storage densities within moderate pressure and temperature ranges. CGH_2 and LH_2 tanks are efficient (99 % efficiency) with high discharge rates, making them suitable for small-scale applications [57]. The extremely low temperatures required for liquefaction may limit the viability of LH_2 and CCH_2 for future hydrogen economy [105].

3.3. Adsorption-based storage

Metal organic frameworks (MOFs) show significant potential for hydrogen energy applications because of their high surface area, permanent and tuneable porosity, and modifiable pore surface chemistry. Several MOFs exceed the United States - Department of Energy's (US-DOE) target of gravimetric capacity at 77 K and high pressures, although only a few meet the volumetric capacity target of 40 g/L [106,107]. Balancing the volumetric and gravimetric capacities of MOFs is crucial for developing materials suitable for cryo–adsorption tanks in mobile applications.

Covalent organic frameworks (COFs) have garnered significant attention because of their low density, adjustable structure, functionalisation, and stability, making them promising materials for applications in adsorption, catalysis, membranes, sensors, and energy storage. Research on COFs is active in the USA, Germany, Japan, China, and India [108]. However, challenges remain, such as the need for better synthesis methods for mass production, limited environmental applications, and insufficient research on safety and toxicity. Adsorptive storage on high-surface-area materials is approaching its theoretical limits, making further progress unlikely [109].

Carbon materials, particularly carbon nanofibres and nanotubes, exhibit favourable hydrogen storage capacities, reaching up to 6.5 % by weight (wt%) [110]. However, they require low operating temperatures for effective hydrogen uptake [111]. The hydrogen storage capacity depends on the surface area and micropore size and can be enhanced through thermal treatments or metal doping. While theoretical studies suggest high storage capacities, experimental validation is still limited. Carbon nanorings doped with titanium (Ti) atoms are effective for hydrogen storage both below 225 K and 1 atm pressure, as well as at high pressure at room temperature, with a desorption temperature of 450 K due to stronger interactions between H_2 and the Ti-doped nanorings [112]. Carbon nanotubes and MOFs, especially when doped with transition metal particles, are considered highly promising for hydrogen storage in transportation applications [113].

3.4. Absorption-based storage

Solid-state hydrogen storage, mainly metal hydrides, is a safer and more practical alternative to high-pressure compression and cryogenic liquefaction [114]. It operates under nearly ambient conditions, making it less risky than compressed hydrogen storage. While most metal hydrides store under 2 wt% hydrogen, magnesium-based hydrides can store up to 7.5 wt%, although they require high temperatures for hydrogen release [115]. Metal hydrides offer high volumetric density, safety, and compactness and are used in applications such as solar power and thermal energy storage [90]. However, their low storage capacity, slow hydrogen release kinetics, and poor performance at low temperatures limit their use in vehicles [114]. Ongoing research aims to increase performance through catalysts, alloying, nanostructuring, and nanoconfinement [116]. Despite their potential, metal hydrides remain expensive [111]. Current technologies have not yet achieved the technoeconomic viability needed for large-scale hydrogen storage.

Complex hydrides offer high hydrogen storage capacity but suffer from slow hydrogen release and high thermodynamic stability. While adding catalysts and nanoparticles can improve kinetics, reversibility remains challenging. Large-scale production of these alloys is still limited, so advancements in production technology are needed to meet the growing demand [117]. Hydrides such as lithium borohydride ($LiBH_4$) and sodium alanates provide high storage capacities, but their practical use is hindered by slow kinetics and high desorption temperatures (e.g., over 470 °C for $LiBH_4$) [118]. $LiBH_4$ has a high gravimetric hydrogen density (18.5 wt%) and volumetric storage capacity (121 kg/m^3), but its thermodynamic limitations restrict its use [119]. A nanocomposite of $LiBH_4$ with activated hexagonal boron nitride ($LiBH_4$@Ah-BN) shows hydrogen storage of 2.3 wt% at 100 °C and dehydrogenation occurring between 110 °C and 150 °C, making it a potential candidate for fuel cell applications [120]. Sodium borohydride ($NaBH_4$) offers a high storage capacity (10.8 wt%) [121]. It is nontoxic and undergoes self-hydrolysis with water, making it suitable for hydrogen generation. Ammonia borane meets DOE vehicular targets but requires purification [90]. Interstitial hydrides offer fast kinetics and are suitable for stationary applications.

Chemical hydrogen storage technologies such as methanol, ammonia, and liquid organic hydrogen carriers (LOHCs) have lower electricity demands than hydrogen liquefaction but require more thermal energy. These thermal needs can be met in industrial applications, potentially via hydrogen carrier combustion or external fuel [98]. Methylcyclohexane (MCH) and ammonia require significant energy for hydrogenation and dehydrogenation, reducing their effective energy by 32 % [122]. Ammonia is the most feasible for widespread use, particularly when it is used directly without decomposition, due to its high hydrogen density, established technology, and CO_2-free potential [123]. However, these methods face challenges such as toxicity and the presence of ammonia residue. Advances in solid-state ammonia storage have increased safety and hydrogen density, and ammonia electrolysis may

offer clean hydrogen at low temperatures [124]. Ammonia reduces the storage tank size due to its high energy density, although its use involves energy losses and additional conversion equipment for conversion and reconversion to pure hydrogen [57]. Toluene and dibenzyl toluene are the most promising LOHCs. However, dehydrogenation requires temperatures above 300 °C [125]. Compared with fossil-based options, green formic acid is considered the most cost-effective hydrogen carrier and is safer and more affordable [126]. Liquid organic hydrides, such as methylcyclohexane and toluene, are recommended for on-board applications, whereas mixed hydride systems are suitable for stationary use [105]. LOHCs are promising for short-term storage and transportation because of their fuel-like properties; however, some LOHCs require further research before practical application [118].

Transition-metal (TM) atoms form Kubas dihydrogen complexes, which possess a strong hydrogen storage potential due to reversible H_2 adsorption at room temperature and ambient pressure. TM-decorated nanomaterials can achieve high hydrogen storage capacities (approximately 9 wt%), but clustering issues reduce their effectiveness [127]. In contrast, calcium (Ca) atoms form Kubas-like interactions with H_2, have lower cohesive energy, and are less likely to cluster, making them more suitable for hydrogen storage. Additionally, Kubas interactions enable the development of vanadium hydrazide gels, which offer a reversible storage capacity of 4.04 wt% at 77 K and 85 bar and 23.2 kgH_2/m^3 at room temperature and 85 bar, outperforming compressed gas storage [128]. These materials have minimal kinetic barriers, making them ideal for increasing hydrogen storage and vehicle range in compressed gas tanks. Kubas-interaction-based materials are becoming key intermediates between metal hydrides and physisorption materials, with increasing importance in hydrogen storage research [129].

3.5. Comparative analysis of hydrogen storage

Among the storage options, compressed hydrogen has the lowest cost, estimated at approximately ₹20–30/kg [57]. Liquid hydrogen is more expensive, costing approximately ₹50–60/kg, likely because of the energy-intensive liquefaction process. Metal hydride storage is the most expensive, exceeding ₹ 100/kg, making it the least economical option [130]. Salt cavern storage is the most cost-effective option, with a cost of ₹3.7/kg in 2020, which is projected to decrease to ₹1.5/kg by 2050 [57]. Rock cavern storage is more expensive at ₹10.4/kg in 2020, decreasing to ₹ 3.7/kg by 2050 [57]. Steel tank storage is significantly more expensive, with ₹48.1/kg in 2020 (700 kg capacity), and is expected to decrease to ₹40.0/kg by 2050 (1100 kg capacity) [57].

Despite advancements in various hydrogen storage methods, no material fully meets the US-DOE's targets for transportation applications, necessitating further research [114]. Current hydrogen storage efforts focus on achieving high gravimetric and volumetric storage densities, efficient operation at low temperatures and pressures, and the development of recyclable systems. Key challenges include high system costs, variations in efficiency on the basis of storage methods, and limitations in system weight and volume owing to containment vessels and storage media. Additionally, regulatory standards for environmental and safety concerns, durability, and operability require consistent performance and long lifetimes. Storage methods such as chemical storage and metal hydrides face trade-offs in terms of capacity, safety, and reversibility. There is a need for catalysts, alloys, and nanostructures to enhance hydrogen absorption and desorption properties [131]. Ongoing research aims to improve these aspects and develop lightweight, high-capacity, and reversible storage solutions. The ideal storage medium should provide high energy density, fast uptake and release, safety, and low cost. However, current technologies face issues such as thermal management, inefficiency, high costs, and safety risks [132]. To overcome these challenges and unlock the full potential of hydrogen in India, more focused research is urgently needed to develop efficient, safe, and scalable storage solutions.

4. Transportation of hydrogen

Efficient hydrogen transportation is a critical component of the hydrogen economy, linking production facilities with end-use applications. Owing to its low volumetric energy density, hydrogen requires a substantially greater storage volume than conventional fuels, despite being much lighter. Consequently, hydrogen must be compressed, liquefied, or converted into chemical carriers such as ammonia, methanol, or LOHCs to facilitate cost-effective and safe transportation. These methods, however, involve trade-offs between energy efficiency, capital investment, and infrastructure compatibility.

Hydrogen can be transported through pipelines, trucks, tube trailers, and maritime shipping, as illustrated in Fig. 7. The selection of a transport mode is influenced by factors such as transport distance, hydrogen quantity, pressure and temperature requirements, and regional infrastructure availability.

4.1. Pipeline transportation

Pipeline transmission is considered the most reliable and energy-efficient option for large-scale hydrogen distribution. Once constructed, pipelines offer high delivery reliability and low operating emissions, although they require significant upfront investment [133]. They are generally ideal for distances ranging from less than 100 km to approximately 1500 km [131,134]. It requires a 38–85 % lower energy footprint than other transport options [135]. Pipeline costs mainly comprise material procurement, installation, access rights, and licensing [136]. The optimum pipe diameter depends on the energy flow rate, pressure, hydrogen content, and transmission distance [137,138]. However, pipeline transportation involves safety and material challenges because hydrogen embrittlement can weaken metallic components and increase the risk of leakage [139,140]. Repurposing existing natural gas (NG) networks for hydrogen transport has been proposed as a transitional approach, yet several technical constraints exist. Steel pipelines commonly used for NG transmission are vulnerable to hydrogen-induced cracking, whereas polyethylene pipelines are suitable only for low-pressure hydrogen transport. There is also uncertainty about whether current distribution networks can meet hydrogen demand, as their capacity would be 20 % lower at the same pressures, and the storage capacity would be significantly reduced [140]. Moreover, to deliver the same energy output as NG, hydrogen requires nearly three times the volumetric flow rate, which could strain existing infrastructure [141]. In addition, safety concerns arise because hydrogen has different properties than natural gas.

Hydrogen blending into NG pipelines, typically at 5–15 % volume, is emerging as a feasible short-term strategy [142]. India currently lacks cross-country hydrogen pipelines but operates approximately 12,654 km of high-pressure NG pipelines, with an additional 13,680 km under construction [143]. Even a 3–5 % blend can enable meaningful hydrogen delivery without significantly affecting NG transport. H_2 blending into NG pipelines is expected to start in India at low concentrations and increase over time as necessary modifications are made [144]. Nevertheless, issues related to pipeline integrity, leak detection, ignition risk, and safety remain critical. Hydrogen flows nearly twice as fast as NG because of its lower molecular weight and viscosity, which can influence friction loss and operational control [145]. High hydrogen concentrations can degrade steel pipelines over prolonged exposure, depending on the steel grade used [146]. However, pipe coatings and linings can help address these challenges [145]. Low hydrogen blends ($\leq$5 %) are not expected to pose major safety hazards [144]. However, concentrations above 17 % typically necessitate pipeline retrofitting and appliance upgrades [147]. Additionally, repurposing CNG stations is costly, and blend limits make large-scale hydrogen delivery challenging, emphasising the need for dedicated H_2 infrastructure [142]. Establishing dedicated hydrogen pipelines is estimated to cost approximately 10 % more than new NG pipelines, and is therefore essential for long-term

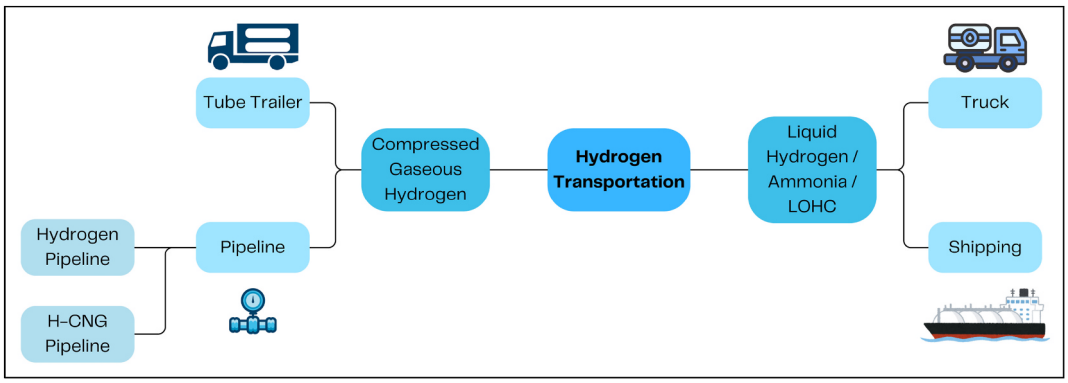


Fig. 7. Hydrogen transportation methods.

hydrogen infrastructure development [148].

Developing an integrated network of hydrogen refuelling stations, similar to existing gasoline stations, is another vital step toward enabling the hydrogen economy [149]. The simultaneous development of fuelling station networks and the introduction of commercial hydrogen vehicles are essential for achieving significant market penetration in the transport sector [150]. Hydrogen refuelling processes involve large pressure gradients (from 35 MPa storage pressure to approximately 0.16 MPa at the fuel cell), which present challenges in designing efficient and safe pressure-reducing systems [151]. Fuelling station costs vary according to geographical location, storage capacity, and station type, directly influencing the overall hydrogen supply chain economics [136].

4.2. Road transportation

Road transportation provides flexibility and accessibility, particularly for small-to medium-scale hydrogen distribution. CGH_2 and LH_2 are the predominant forms transported by trucks. CGH_2 transport is technically mature and cost-effective for short distances (up to 100 km) and medium capacities, although it is limited by low volumetric energy density and large vessel requirements [133,134]. In contrast, compared with CGH_2, LH_2 enables 4–6 times higher mass delivery per trip, making it more efficient for medium-range distribution [145]. However, the liquefaction process is energy-intensive and requires advanced insulation systems to prevent boil-off losses. LOHC-based transport becomes competitive for distances exceeding 100 km, provided that the capital costs of hydrogenation and dehydrogenation reactors remain manageable [152]. Nevertheless, LOHC transport has greater environmental impact than CGH_2 because of additional processing energy requirements [153]. Alternative hydrogen storage media, including metal hydrides and MOFs, offer advantages such as high hydrogen density and enhanced safety. However, these technologies are still in the early stages of commercialisation and currently incur high costs [133]. MOF-based systems are estimated to be 3–10 times more expensive than CGH_2 and LH_2 transportation; however, cost reductions are expected with improvements in material capacity and cycle stability [154]. Overall, truck-based transportation involves significant operational and fuel costs but remains an attractive option for distributed production systems or regions lacking pipeline infrastructure. The economic feasibility depends primarily on the transport distance, loading efficiency, and storage configuration.

4.3. Maritime transportation

For intercontinental and long-distance exports, maritime shipping is the most viable transport option. Shipping LH_2 is more suitable for long-distance delivery of smaller hydrogen quantities [155]. LH_2 offers high energy density and has a small CO_2 footprint [156]. However, it suffers from high liquefaction energy demand, boil-off losses, and limited storage duration [133]. The substantial capital investment required for liquefaction and cryogenic systems makes LH_2 shipping cost-prohibitive in the near term, with costs expected to remain high even by 2050 [57,157].

As alternatives, chemical hydrogen carriers such as ammonia, methanol, and LOHCs such as MCH, toluene, and dibenzyl toluene, enable hydrogen transport in liquid form under ambient conditions [93,133]. These carriers can leverage existing petrochemical infrastructure, making them attractive for long-distance trade. Ammonia shipping is estimated to be ~28 % less costly than LH_2 transport over intercontinental routes [158]. For smaller-scale systems (<2 tonne H_2/h), methanol is preferred because of its lower dehydrogenation energy demand [159]. The viability of LOHC-based transport depends on the heat source for dehydrogenation; if waste heat is available, the toluene and dibenzyl toluene systems offer superior efficiency [160]. However, the internal heat supply significantly reduces their competitiveness, except in the case of methanol. Ammonia transport benefits from economies of scale, whereas toluene-based systems face technical challenges related to high vapour pressure and hydrogen release kinetics [161]. Dibenzyl and benzyl toluenes are commercially used as LOHCs in Germany, whereas the toluene-based system is established in Japan [162]. Among potential LOHCs, N-ethylcarbazole provides good handling characteristics and high theoretical storage density (5.8 wt%), but its high cost limits commercial applicability [160,163]. The utilisation of existing mineral oil logistics infrastructure for LOHC transport could provide additional cost benefits by enabling the return and reuse of carrier materials.

4.4. Comparative analysis of hydrogen transportation

The cost of hydrogen transport is influenced by factors such as fuel, labour, logistics, CAPEX, and storage configuration, all of which vary with transport distance and capacity [136]. Levelised transport costs decline with increasing throughput but rise sharply with longer distances [164]. Centralised production systems lower hydrogen generation costs but increase distribution expenses, whereas decentralised systems have the opposite effect.

Pipeline transport involves high CAPEX but low OPEX, whereas road transport requires lower initial investment but higher operational costs [131]. At a distance of 1000 km, ammonia, LOHC, and truck-based transport are approximately twice as expensive as pipeline transport, and at 3000 km, they remain ~1.5 times costlier [165]. Truck and trailer systems cost between €150,000 and €860,000, whereas LOHC and LH_2 ships require approximately €35 million and €146 million, respectively [160]. OPEX is 12 % for trucks and 2 % for trailers [160]. The depreciation periods are typically 8 years for trucks, 12 years for trailers, and 25 years for ships. Annual utilisation averages 3500 h for trucks/trailers and 8000 h for ships, with payload capacities ranging from 720 kg (CGH_2 trailers) to 12,658 kg (LH_2 ships) [160]. The payload capacity

differs widely, from 720 kg for CGH_2 trailers to 12,658 kg for LH_2 ships [160]. Loading times vary from 1.5 to 3 h for trucks to approximately 48 h for maritime systems [160]. From an environmental perspective, pipeline and ammonia transport yield comparable greenhouse gas (GHG) emissions, whereas other transport modes emit roughly twice as much [165]. Hence, the integration of renewable energy in compression, liquefaction, and dehydrogenation operations is crucial to achieve low-carbon hydrogen logistics. Continuous improvements in pipeline materials, storage media, and process efficiency will be instrumental in reducing both costs and lifecycle emissions in the evolving hydrogen supply chain.

5. Applications of hydrogen

India currently consumes approximately 6 million metric tonnes (MMTs) of H_2 annually, which are mainly used in refineries and fertiliser production [73]. Hydrogen has diverse applications across multiple sectors, making it a key element in the transition to clean energy. Hydrogen can replace fossil fuels in various applications and provide immediate benefits if it is produced from renewable sources [166]. Some of the important applications of hydrogen are presented below.

5.1. Transportation

Hydrogen in internal combustion engines (ICE) and hydrogen fuel cells (HFC) can power vehicles, including cars, buses, trucks, trains, and ships, offering a zero-emission alternative to fossil fuels. Hydrogen can be used as a fuel with few modifications to traditional gasoline-powered engines [167]. Additionally, hydrogen-gasoline dual injection can increase the lean-burn limits [168]. Adding 5 % hydrogen to a diesel engine shortens the ignition lag, reduces the pressure rise, improves engine smoothness, and enhances durability [169]. Injecting H_2 into NG lowers unburned hydrocarbon and CO emissions. A 10 % hydrogen blend cuts CO_2 emissions by 5 %, whereas a 50 % blend achieves a 30 % reduction [170]. However, more than 30 % H_2 leads to knocking, backfiring, and increased NO_x [171]. Delhi is exploring H-CNG blends to reduce emissions, with the recommendation of NITI Aayog. Research has shown reductions in pollutants compared with diesel, CNG, and gasoline. The total biohydrogen supply chain cost is ₹149.6 ($3.39) per kg, with H-CNG priced similarly to CNG per mile [172]. The regions near Delhi have 20 times more biomass residue than needed to support an 18–82 % H-CNG mix for its CNG vehicle fleet, offering a significant opportunity to improve air quality and lower GHG emissions [172].

With the implementation of Euro-VI, diesel engine costs are rising, whereas shipping and aviation have limited low-carbon fuel alternatives [131]. Shifting 72.3 % of fossil fuel demand in the transportation sector to electricity is technically feasible today [173]. However, achieving carbon neutrality in road transport is difficult with battery electric vehicles (BEVs) alone [174]. Additionally, some modes require chemical fuels in addition to electricity, such as aeroplanes, which are not economically viable with electricity alone [175]. A mix of BEVs and hydrogen fuel cell vehicles (HFCVs) can significantly reduce air pollution, with HFCVs potentially reducing road transport CO_2 emissions by more than 96 % [174]. Additionally, HFCVs offer longer ranges and shorter refuelling times than traditional batteries [176]. HFC light-duty vehicles are expected to achieve 2.5–2.7 times the fuel economy of conventional gasoline ICE vehicles on the same platform [177]. HFCVs have greater energy storage in a more compact space than batteries used in battery electric vehicles (BEVs) [178]. Testing of the Toyota Mirai HFCV in India has shown a potential range of 482 km with a 7 kg H_2 capacity [179]. Daimler's fourth-generation GLC F-CELL features a 147 kW fuel cell stack with a lithium-ion battery, offering a 478 km range in H_2 mode [180]. Hyundai's fourth-generation Tucson ix35, launched in 2012, had a 100 kW fuel cell stack operating at 250–450 V [180]. The fifth-generation Hyundai Nexo boasts a 120 kW fuel cell stack, a 395 Nm torque electric motor, and a 756 km range [180].

However, HFCV development is hindered by the lack of safe, lightweight, and efficient onboard hydrogen storage and challenges related to low volumetric density and high tank costs for compressed gas storage [181]. Additionally, consumers are concerned about the cost of HFCVs, hydrogen prices, and the availability of refuelling stations [179]. The government and manufacturers should collaborate to highlight the benefits of HFCVs and address perceived risks to gain user support. The practicality of HFCVs in India depends on the development of hydrogen infrastructure and addressing issues related to production, transportation, and storage [182]. India lags in the development of efficient fuel cell infrastructure and needs greater collaboration among scientists, technologists, policymakers, and industries to compete in the global market [180]. The introduction of hydrogen to the transportation sector can be cost-effective by using large vehicles on limited routes, with heavy-duty freight modes helping advance technology for broader use in light-duty vehicles [183]. Additionally, to make HFCVs cost-competitive, the government should draw lessons from countries such as Japan, the USA, and South Korea, offering financial incentives such as subsidies and tax benefits [179]. A modest government incentive program can help initiate a market for HFCVs [184]. The success of H_2-powered hypersonic aircraft depends on various social, political, and economic factors, including mass versus elite air travel, global economic trends, military propulsion advancements, and the commitment to hydrogen aviation [185]. In space exploration, LH_2 is also a high-energy rocket fuel [104].

5.2. Energy

In the energy sector, hydrogen can be used for energy storage and stationary power generation. Batteries are suitable for short-term grid stabilisation but not large-scale energy storage [186]. In contrast, hydrogen can enable industrial-scale power-to-X solutions for the transportation, industry, and electricity sectors [187]. Grid-integrated hydrogen storage can mitigate seasonal power fluctuations by reducing curtailment, replacing peak capacity, and improving transmission. Hydrogen storage with a two-week discharge duration is expected to be viable by 2050 [188]. Electrolysers and fuel cells help stabilise wind and solar power fluctuations, enabling more efficient electric system operation [189]. However, hydrogen re-electrification (power-H_2-power) is unsuitable for short-term storage because of its high cost and low efficiency compared with batteries and diesel generators, but it becomes viable when seasonal storage is needed, PV space is limited, and nighttime electricity demand is high [190]. India may require such storage only in extreme scenarios involving variable renewable energy by the 2040s, where alternative solutions could emerge, making its role uncertain [57].

Hydrogen can also be used in engines, combustion turbines, and heat generation [191–193]. Hydrogen can enhance electricity generation efficiency through combined-cycle gas turbines (CCGTs) and fuel cells in large-scale power plants and smaller applications [178]. HFCs provide reliable backup for critical facilities, such as banking, telecommunications, and airports, as well as portable power for remote areas, disaster relief, and military use [178]. However, they have higher initial costs than traditional generators. Fuel cell systems can generate power for port microgrids, supporting electrical loads such as cranes, lighting, refrigeration, and buildings [194]. They can also balance renewable energy sources for cargo handling equipment, with or without battery storage. Fuel cells can also meet thermal demands when integrated with combined cooling, heating, and power (CCHP) [194]. Hydrogen-based micro-combined heat and power (mCHP) devices can improve energy efficiency by 22 % and reduce carbon emissions by 18 % in the office and residential sectors [195]. Currently, approximately 1 % of the world's energy demand is met by hydrogen produced from renewable sources [195].

Hydrogen can also be used for long-distance energy transport instead of high-voltage direct current (HVDC) transport by converting

renewable electricity to hydrogen, transporting it via pipelines, and reconverting it at demand centres. By 2050, this method will be cost-competitive with HVDC systems above 350 km for a 1 GW system, offering lower storage costs and 15–20 % lower investment costs [196]. Compared with power cables, which have an energy capacity of 1–2 GW, hydrogen pipelines offer a significantly higher capacity of 15–30 GW [144].

5.3. Industry

Hydrogen currently plays a vital role in the chemical industry, supporting refinery processes such as hydrocracking and hydrodesulphurisation, as well as petrochemical production of materials such as alpha alcohols and polyolefins, and chemical manufacturing, including ammonia and methanol synthesis [175]. The Indian fertiliser industry, one of the world's most efficient, currently accounts for more than 50 % of India's hydrogen demand (~3 MMT), which is expected to increase to 7.5 MMT by 2050 [57]. Hydrogen is essential for refining crude oil and desulphurisation. India has the world's fourth-largest refinery capacity and aims to double its refining capacity from 254 MMT to 500 MMT annually by 2030 [57]. The growing need for ultralow-sulphur fuels is anticipated to be the key driver of future hydrogen demand in refineries. India can meet global ammonia demand at the lowest costs, estimated at 723 €/tonne-NH_3 for domestic use and 765 €/tonne-NH_3 for exports [197]. Hydrogen can also be used to produce ethanol, methanol, gasoline, and other high-value chemicals [198]. Hydrogen can help mitigate carbon emissions in iron-making plants by acting as a reductant in the blast furnace during smelting [199]. Hydrogen can be used directly in steelmaking or to convert steel mill byproduct gases into methanol or methane [200]. Hydrogen can replace coking coal, noncoking coal, and natural gas in iron and steel production. India and China play major roles in global steel production, contributing to Asia's dominant share of 73.9 % of the total output in 2022 [201]. India, the world's second-largest steel producer and third-largest consumer, is expected to see its steel sector drive future hydrogen demand, accounting for more than a third of total demand [57]. However, H_2-based steelmaking is costlier in India than in China, the USA, Russia, and South Korea because of the absence of a CO_2 allowance market.

Hydrogen is also essential in material processing, serving as a heat treatment agent, shielding gas in welding, and semiconductor production. In the glass industry, hydrogen can be used in high-temperature cutting torches, polishing glass surfaces, heat treating optical fibres, and creating a reductive atmosphere for the float–glass process [102]. Hydrogen is used in food processing for hydrogenation, converting unsaturated fats into solid fats to increase shelf life [178]. Hydrogen is also gaining importance in heating applications, where it can be blended with natural gas or used in pure form for industrial heating [202]. In India, industrial heat is generated mainly from fossil fuels. Hydrogen serves as an alternative where electrification is unfeasible.

Given its versatility and potential, hydrogen can play a vital role in India's transition to clean energy. As hydrogen applications continue to expand across various sectors, ensuring robust safety measures becomes increasingly critical to support their widespread adoption and build public confidence in hydrogen technologies.

6. Hydrogen economy

A hydrogen economy signifies a system where hydrogen functions as a key energy carrier to drive decarbonisation across industries, transportation, and power sectors. The hydrogen value chain, which encompasses production, storage, transportation, distribution, and end-use applications, forms the backbone of this emerging economy (Fig. 8) [203]. Each stage involves the specific technologies mentioned in sections 2, 3, 4, and 5. The economic considerations and infrastructure requirements collectively determine the viability and scalability of

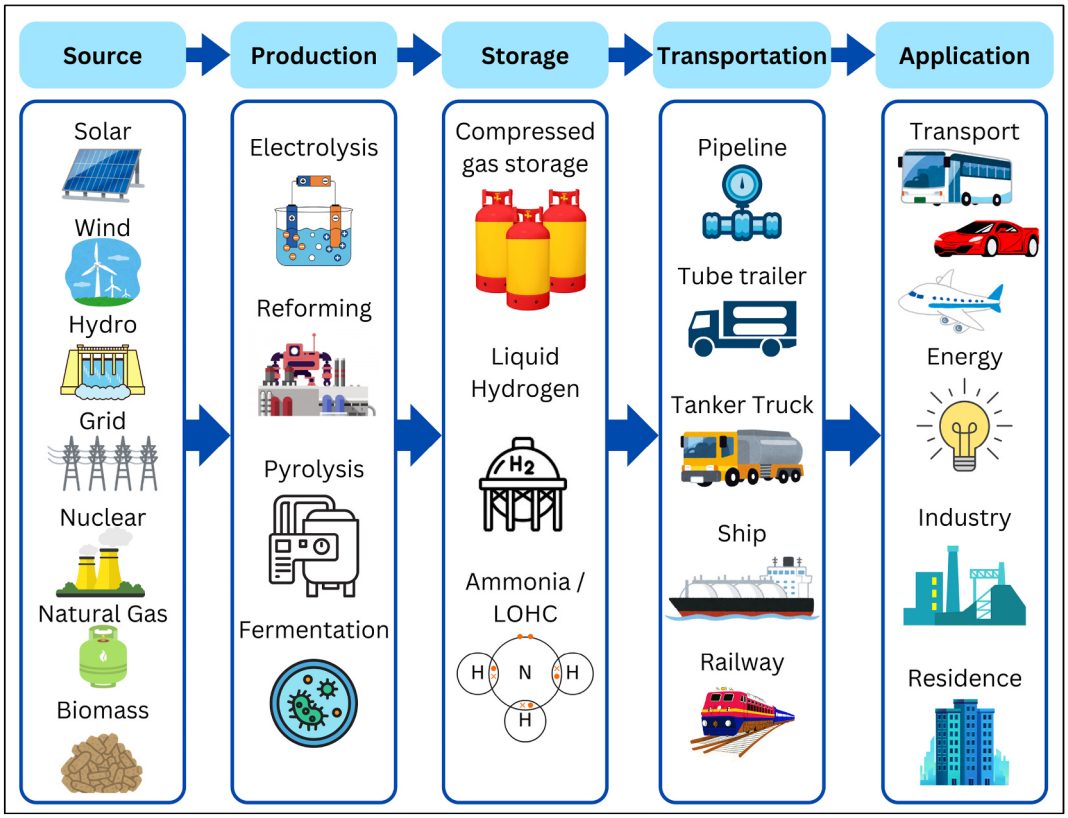


Fig. 8. Hydrogen value chain.

hydrogen as an energy carrier. The successful deployment of the hydrogen value chain depends not only on technological advancements but also on safety protocols across all stages.

While selecting a method for hydrogen production, several key parameters must be considered to ensure better efficiency, sustainability, and economic viability. These include the energy source, production cost, carbon footprint, and technology scalability. The availability of feedstock, such as water, natural gas, or biomass, is also critical. Environmental impacts, particularly greenhouse gas emissions, also play a significant role. Technological maturity and infrastructure requirements must be evaluated to determine feasibility. Additionally, safety, operational reliability, and regulatory compliance are essential factors, particularly for large-scale or long-term deployment. The choice of production method should align with national energy goals, resource availability, and intended end-use applications.

Choosing an appropriate hydrogen storage method involves evaluating several critical parameters to ensure safety, efficiency, and suitability for the intended application. Key considerations include gravimetric and volumetric energy densities, which determine the amount of hydrogen that can be stored by weight and volume. The operating temperature of the method and pressure requirements influence both energy consumption and system complexity. Storage system weight, size, and portability are crucial, especially for mobile applications such as fuel cell vehicles. Safety is a primary concern due to the high flammability and leakage risk of hydrogen. Therefore, hydrogen storage requires robust containment and handling systems. Reversibility and storage kinetics are important for usability and efficiency. Cost factors, including material, manufacturing, and lifecycle expenses, also play a significant role. Compatibility with existing infrastructure, environmental impact, and compliance with regulatory standards must be considered to ensure reliable and scalable deployment.

The selection of a suitable hydrogen transportation method requires careful consideration of several parameters, including distance, volume, cost, and infrastructure availability. The physical form of hydrogen affects storage and handling requirements, influencing safety, energy efficiency, and cost. CAPEX and OPEX, including fuel, labour, and maintenance, must be evaluated alongside the levelised cost of transport. Energy loss during compression, liquefaction, or conversion into carriers such as ammonia or methanol also impacts overall efficiency. Regulatory compliance, environmental impact, and compatibility with existing energy infrastructure are vital for ensuring a reliable and scalable hydrogen supply chain.

Several interrelated factors influence hydrogen applications, including production costs, purity requirements, storage and transportation infrastructure, and the specific energy needs of various sectors. Purity is critical for certain applications, such as fuel cells, which require high-purity hydrogen to operate efficiently. The availability of reliable storage and transport options affects the feasibility of hydrogen in sectors such as mobility, power generation, and industrial processes. Technical maturity and compatibility with existing infrastructure also determine how easily hydrogen can be integrated into current systems. Furthermore, environmental regulations and decarbonisation targets are driving interest in hydrogen as a clean energy alternative, especially in hard-to-abate sectors such as steel, refining, and heavy transport.

The future of hydrogen as an energy carrier will depend on various factors, including technological, economic, environmental, social, and political considerations [175]. Beyond the hydrogen value chain, key indicators such as population, GDP, CO_2 emissions, and renewable energy sources are also essential for analysing the feasibility of hydrogen as an energy carrier [204]. In addition, factors such as generation, leakage management, storage efficiency, and risk assessment shape the socioeconomic impact [205]. Financial aspects such as discount rates, inflation, and project lifespan influence the net present value (NPV) and levelised cost of energy (LCOE) [206]. Hydrogen pricing varies by location, driven by technology and raw material costs, with industrial clusters serving as early hubs for deployment [130]. To increase cost-effectiveness and sustainability, techno-economic analysis (TEA) and life cycle assessment (LCA) are crucial [207]. While TEA evaluates financial metrics such as simple payback period (SPP), internal rate of return (IRR), and return on investment (ROI), LCA assesses environmental impact through indicators such as global warming potential (GWP), energy payback time (EPBT), and cumulative energy demand (CED), ensuring a comprehensive evaluation of both economic feasibility and sustainability.

Building a robust hydrogen economy requires a coordinated strategy across technology, infrastructure, policy, and finance. Significant investments, scaling up green hydrogen production through renewable-powered electrolysers, reducing costs, and incentivising domestic manufacturing are crucial to reducing reliance on fossil-based hydrogen. On the demand side, targeted subsidies and tax incentives can spur demand and growth, but should be phased out as technology matures and markets stabilise [208]. The development of safe and efficient storage solutions, along with the expansion of pipeline infrastructure and hydrogen refuelling stations, will ensure effective distribution. Strengthening research, development, and demonstration through dedicated centres and pilot projects can drive innovation in fuel cells, hydrogen carriers, and storage materials. Cross-sectoral collaboration is needed to align hydrogen applications with the needs of industry, transportation, power generation, and residential sectors. Safety remains a paramount concern in hydrogen deployment. Unlike conventional fuels, hydrogen has different handling requirements because of its low density, high diffusivity, and wide flammability range of 4–75 %. Therefore, risk mitigation strategies, including advanced leak detection systems, proper ventilation, and reinforced safety regulations, are essential. The standardisation of safety protocols, certification systems, and public awareness are also critical for widespread adoption. Policy support through clear regulations such as green hydrogen mandates, carbon pricing, incentives, and long-term roadmaps is essential to attract private investment and drive innovation. Mobilising finance through public–private partnerships, green bonds, and international collaborations can help derisk investments. Building skilled human capital and fostering global partnerships are essential to accelerate adoption across different domains. Finally, integrating hydrogen into industrial clusters and launching sector-specific pilot projects such as hydrogen valleys can demonstrate scalable, real-world applications. A holistic approach is crucial for advancing the hydrogen economy [209]. A holistic view of the hydrogen economy is shown in Fig. 9. Realising the full potential of hydrogen will require coordinated efforts across technology development, policy support, infrastructure expansion, and public awareness to ensure a sustainable and economically viable hydrogen ecosystem.

This study offers a comprehensive understanding of the hydrogen ecosystem, encompassing the entire value chain from production to end-use. As India embarks on an ambitious journey toward energy independence and net-zero emissions, hydrogen is poised to play a transformative role in decarbonising key sectors such as industry, transport, and power. However, the transition is hindered by high costs, technological uncertainties, storage limitations, and safety concerns. This study offers valuable insights to guide evidence-based policymaking and foster innovation by synthesising current developments, identifying critical gaps, and evaluating strategic options. Ultimately, it aims to contribute to building a resilient, efficient, and low-carbon hydrogen economy aligned with India's long-term energy and climate goals.

7. Conclusions

The present paper reviews various methods of hydrogen production, storage, transportation, and application in the Indian context. Currently, most hydrogen production in India relies on fossil fuels, particularly steam methane reforming (SMR) and coal gasification, which contribute up to 9–11 kg of carbon emissions per kg of hydrogen produced. Green hydrogen, produced via electrolysis using renewable energy, remains

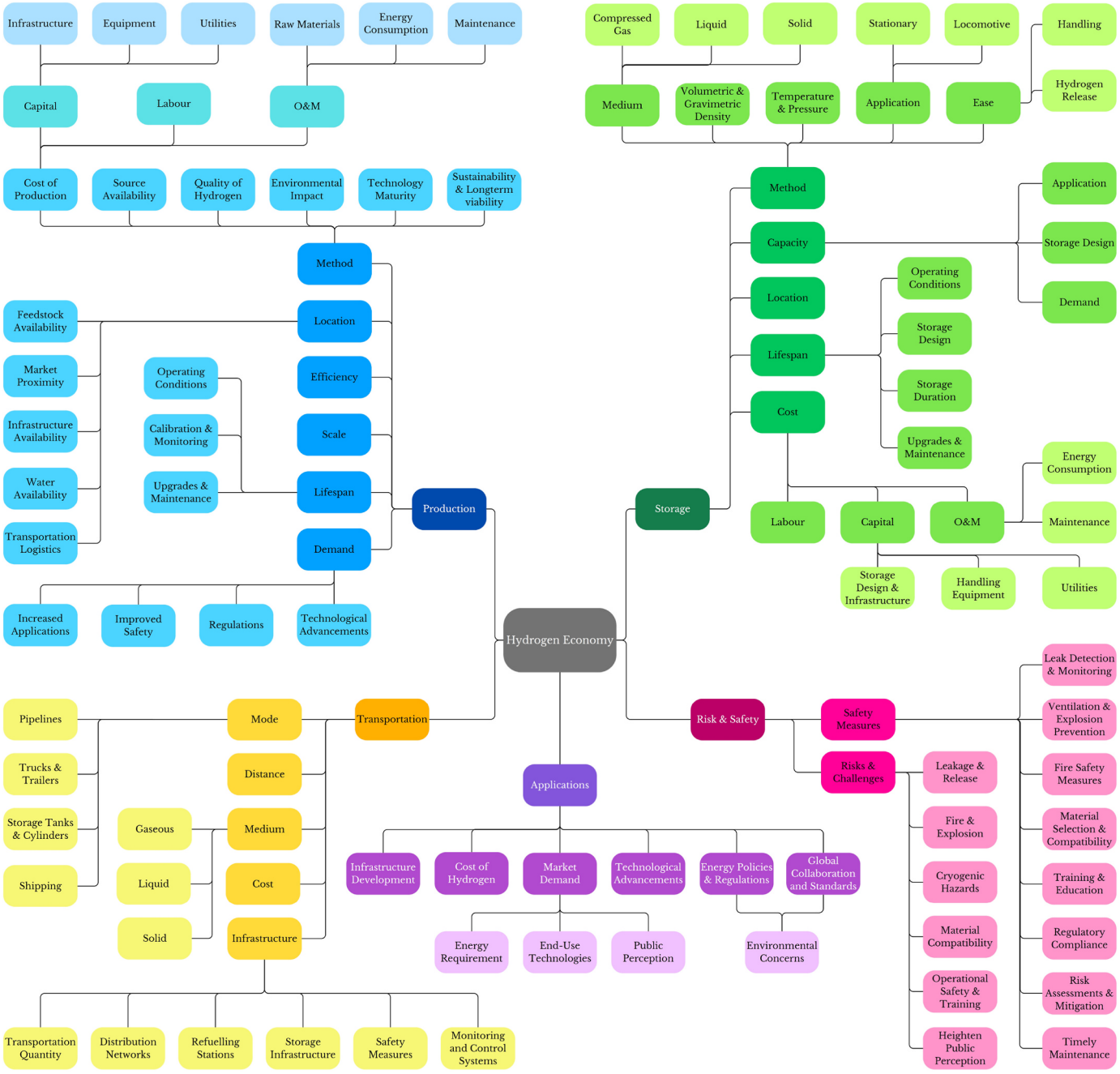


Fig. 9. Holistic view of hydrogen economy.

uneconomical at $5–10.3/kg because of high CAPEX and the need for infrastructure development. Hydrogen storage is another challenge, with compressed hydrogen being the most widely used method; however, it requires more space, high energy input, and raises safety concerns. Research on solid-state hydrogen storage materials, such as metal hydrides, remains limited despite their potential for safer and more efficient storage. For transportation, pipelines are the most cost-effective solution for large-scale hydrogen distribution. Blending less than 15 % hydrogen with natural gas in existing pipelines is a promising strategy to increase hydrogen adoption while minimising infrastructure costs. Hydrogen applications extend across the transport, energy, and industrial sectors, offering decarbonisation potential for hard-to-abate industries such as steel and cement. The emergence of green steel, which replaces coal with hydrogen in steelmaking, highlights the transformative potential of hydrogen in reducing emissions from one of the most polluting industries.

Selecting optimal methods across the hydrogen value chain requires balancing the technical, economic, environmental, and regulatory factors. For production, considerations include feedstock availability, energy sources, emissions, cost, and scalability. Storage solutions must ensure safety, efficiency, and portability, especially for mobile applications. Transportation methods, on the other hand, depend on factors such as distance, quantity, available infrastructure, and the form of hydrogen. The applications of hydrogen vary by sector and demand high purity, infrastructure compatibility, and cost competitiveness. The future of hydrogen also hinges on broader socioeconomic indicators such as population growth, emission targets, and economic trends. Realising a robust hydrogen economy will demand large-scale investments in renewables and infrastructure, along with strong policy frameworks, safety standards, and public awareness. Cross-sectoral

collaboration and global partnerships are crucial for scaling up deployment, reducing costs, and fostering innovation throughout the hydrogen value chain.

CRediT authorship contribution statement

Deepak D. Adiga: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **B. Satish Shenoy:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Pramod B. Salunkhe:** Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Data curation. **Suresh Sampath:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization.

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Declaration of competing interest

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

Data availability

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

References

[1] NITI Aayog. Government of India. Harnessing Green Hydrogen. https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf. [Accessed 7 September 2022].
[2] Ministry of New and Renewable Energy. Physical achievements. https://mnre.gov.in/en/physical-progress/. [Accessed 12 April 2025]. n.d.
[3] Hydrogen Tools. Basic hydrogen properties chart. https://h2tools.org/basic-hydrogen-properties-chart. [Accessed 3 March 2024]. n.d.
[4] Guarco J, Langstine B, Turner M. Practical considerations for firing hydrogen versus natural gas. Combust energy assoc. 2021. Available at: https://cea.org.uk/wp-content/uploads/2021/06/Zeeco-Hydrogen-Article.pdf. [Accessed 3 March 2024].
[5] Ministry of New and Renewable Energy. National green hydrogen mission. https://mnre.gov.in/en/national-green-hydrogen-mission/. [Accessed 3 October 2024]. n.d.
[6] Swayam - National Programme on Technology Enhanced Learning. Hydrogen energy - production, storage, transportation and safety - course. https://onlinecourses.nptel.ac.in/noc22_ch66/preview. [Accessed 24 April 2024]. n.d.
[7] Ferraren-De Cagalitan DDT, Abundo MLS. A review of biohydrogen production technology for application towards hydrogen fuel cells. Renew Sustain Energy Rev 2021;151:111413. https://doi.org/10.1016/j.rser.2021.111413.
[8] Gunawardane K. Evolution of hydrogen energy and its potential opportunities around the globe. Elsevier Inc.; 2023. https://doi.org/10.1016/B978-0-443-15329-7.00007-7.
[9] Chisalita DA, Cormos CC. Techno-economic assessment of hydrogen production processes based on various natural gas chemical looping systems with carbon capture. Energy 2019;181:331–44. https://doi.org/10.1016/j.energy.2019.05.179.
[10] Chen G, Tao J, Liu C, Yan B, Li W, Li X. Hydrogen production via acetic acid steam reforming: a critical review on catalysts. Renew Sustain Energy Rev 2017;79:1091–8. https://doi.org/10.1016/j.rser.2017.05.107.
[11] Sharma YC, Kumar A, Prasad R, Upadhyay SN. Ethanol steam reforming for hydrogen production: latest and effective catalyst modification strategies to minimize carbonaceous deactivation. Renew Sustain Energy Rev 2017;74:89–103. https://doi.org/10.1016/j.rser.2017.02.049.
[12] Lee B, Heo J, Kim S, Kim CH, Ryi SK, Lim H. Integrated techno-economic analysis under uncertainty of glycerol steam reforming for H2 production at distributed H2 refueling stations. Energy Convers Manag 2019;180:250–7. https://doi.org/10.1016/j.enconman.2018.10.070.
[13] Katikaneni SP, Al-Muhaish F, Harale A, Pham TV. On-site hydrogen production from transportation fuels: an overview and techno-economic assessment. Int J Hydrogen Energy 2014;39:4331–50. https://doi.org/10.1016/j.ijhydene.2013.12.172.
[14] Bassani A, van Dijk HAJ, Cobden PD, Spigno G, Manzolini G, Manenti F. Sorption enhanced water gas shift for H2 production using sour gases as feedstock. Int J Hydrogen Energy 2019;44:16132–43. https://doi.org/10.1016/j.ijhydene.2019.04.199.
[15] Yukesh Kannah R, Kavitha S, Preethi Parthiba Karthikeyan O, Kumar G, Dai-Viet NV, et al. Techno-economic assessment of various hydrogen production methods – a review. Bioresour Technol 2021;319:124175. https://doi.org/10.1016/j.biortech.2020.124175.
[16] Ganeshan P, Vigneswaran VS, Gowd SC, Kondusamy D, Sanjay kumar C, Krishnamoorthy N, et al. How does techno-economic analysis and lifecycle assessment help in commercializing the biohydrogen supply chain? Fuel 2023;341:127601. https://doi.org/10.1016/j.fuel.2023.127601.
[17] Ishaq H, Dincer I. Comparative assessment of renewable energy-based hydrogen production methods. Renew Sustain Energy Rev 2021;135:110192. https://doi.org/10.1016/j.rser.2020.110192.
[18] Kakati U, Sakhiya AK, Baghel P, Trada A, Mahapatra S, Upadhyay D, et al. Sustainable utilization of bamboo through air-steam gasification in downdraft gasifier: experimental and simulation approach. Energy 2022;252:124055. https://doi.org/10.1016/j.energy.2022.124055.
[19] Narnaware SL, Panwar NL. Biomass gasification for climate change mitigation and policy framework in India: a review. Bioresour Technol Rep 2022;17:100892. https://doi.org/10.1016/j.biteb.2021.100892.
[20] Al-Qadri AA, Ahmed U, Jameel AGA, Ahmad N, Zahid U, Zein SH, et al. Process design and techno-economic analysis of dual hydrogen and methanol production from plastics using energy integrated system. Int J Hydrogen Energy 2023;48:10797–811. https://doi.org/10.1016/j.ijhydene.2022.11.266.
[21] Chen J, Liang J, Xu Z, E J. Assessment of supercritical water gasification process for combustible gas production from thermodynamic, environmental and techno-economic perspectives: a review. Energy Convers Manag 2020;226:113497. https://doi.org/10.1016/j.enconman.2020.113497.
[22] Liang J, Liu Y, Chen J, E J, Leng E, Zhang F, et al. Performance comparison of black liquor gasification and oxidation in supercritical water from thermodynamic, environmental, and techno-economic perspectives. Fuel 2023;334:126787. https://doi.org/10.1016/j.fuel.2022.126787.
[23] Onigbajumo A, Taghipour A, Ramirez J, Will G, Ong T, Couperthwaite S, et al. Techno-economic assessment of solar thermal and alternative energy integration in supercritical water gasification of microalgae. Energy Convers Manag 2021;230:113807. https://doi.org/10.1016/j.enconman.2020.113807.
[24] Datta A, Krishnamoorti R. Opportunities for a low carbon transition-deploying carbon capture, utilization, and storage in northeast India. Front Energy Res 2019;7. https://doi.org/10.3389/fenrg.2019.00012.
[25] Shaw R, Mukherjee S. The development of carbon capture and storage (CCS) in India: a critical review. Carbon Capture Sci Technol 2022;2:100036. https://doi.org/10.1016/j.ccst.2022.100036.
[26] Chen P, Bose S, Selveindran A, Thakur G. Application of CCUS in India: designing a CO2 EOR and storage pilot in a mature field. Int J Greenh Gas Control 2023;124:103858. https://doi.org/10.1016/j.ijggc.2023.103858.
[27] Ma Z, Liu X, Li G, Qiu X, Yao D, Zhu Z, et al. Energy consumption, environmental performance, and techno-economic feasibility analysis of the biomass-to-hydrogen process with and without carbon capture and storage. J Environ Chem Eng 2021;9:106752. https://doi.org/10.1016/j.jece.2021.106752.
[28] Gupta NC, Tanwar R, Dipesh Kaushik A, Singh R, Patra AK, et al. Perspectives on CCUS deployment on large scale in India: insights for low carbon pathways. Carbon Capture Sci Technol 2024;12:100195. https://doi.org/10.1016/j.ccst.2024.100195.
[29] NITI Aayog. Carbon capture, utilization and storage (CCUS). https://www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf. [Accessed 8 October 2024]. n.d.
[30] Nemitallah MA, Alnazha AA, Ahmed U, El-Adawy M, Habib MA. Review on techno-economics of hydrogen production using current and emerging processes: status and perspectives. Results Eng 2024;21:101890. https://doi.org/10.1016/j.rineng.2024.101890.
[31] Wang S, Yang H, Shi Z, Zaini IN, Wen Y, Yang W. Renewable hydrogen production from the organic fraction of municipal solid waste through a novel carbon-negative process concept. Energy 2022;252. https://doi.org/10.1016/j.energy.2022.124056.
[32] Weger L, Abánades A, Butler T. Methane cracking as a bridge technology to the hydrogen economy. Int J Hydrogen Energy 2017;42:720–31. https://doi.org/10.1016/j.ijhydene.2016.11.029.
[33] Kerscher F, Stary A, Gleis S, Ulrich A, Klein H, Spliethoff H. Low-carbon hydrogen production via electron beam plasma methane pyrolysis: techno-Economic analysis and carbon footprint assessment. Int J Hydrogen Energy 2021;46:19897–912. https://doi.org/10.1016/j.ijhydene.2021.03.114.
[34] Osman AI, Deka TJ, Baruah DC, Rooney DW. Critical challenges in biohydrogen production processes from the organic feedstocks. Biomass Convers Biorefinery 2023;13:8383–401. https://doi.org/10.1007/s13399-020-00965-x.
[35] Patel SKS, Das D, Kim SC, Cho BK, Kalia VC, Lee JK. Integrating strategies for sustainable conversion of waste biomass into dark-fermentative hydrogen and value-added products. Renew Sustain Energy Rev 2021;150:111491. https://doi.org/10.1016/j.rser.2021.111491.
[36] Hosseinzadeh A, Zhou JL, Li X, Afsari M, Altaee A. Techno-economic and environmental impact assessment of hydrogen production processes using bio-waste as renewable energy resource. Renew Sustain Energy Rev 2022;156:111991. https://doi.org/10.1016/j.rser.2021.111991.
[37] Ramprakash B, Lindblad P, Eaton-Rye JJ, Incharoensakdi A. Current strategies and future perspectives in biological hydrogen production: a review. Renew

Sustain Energy Rev 2022;168:112773. https://doi.org/10.1016/j.rser.2022.112773.
[38] Soares JF, Confortin TC, Todero I, Mayer FD, Mazutti MA. Dark fermentative biohydrogen production from lignocellulosic biomass: technological challenges and future prospects. Renew Sustain Energy Rev 2020;117. https://doi.org/10.1016/j.rser.2019.109484.
[39] Garritano AN, Faber M de O, De Sà LRV, Ferreira-Leitão VS. Palm oil mill effluent (POME) as raw material for biohydrogen and methane production via dark fermentation. Renew Sustain Energy Rev 2018;92:676–84. https://doi.org/10.1016/j.rser.2018.04.031.
[40] Wee ANCH, Erison AE, Edward Anyek EH, Pakpahan GR, Lim JR, Tiong ANT. Techno-economic assessment of hydrogen production via steam reforming of palm oil mill effluent. Sustain Energy Technol Assessments 2022;53:102575. https://doi.org/10.1016/j.seta.2022.102575.
[41] Yu H, Zhu Z, Hu W, Zhang H. Hydrogen production from rice winery wastewater in an upflow anaerobic reactor by using mixed anaerobic cultures. Int J Hydrogen Energy 2002;27:1359–65. https://doi.org/10.1016/S0360-3199(02)00073-3.
[42] Penislus Shiyan S, Krishnaveni M. Hydrogen production by Pseudomonas stutzeri JX442762 isolated from thermal soil at mettur power station, Salem district, Tamil Nadu, India. J Pharm Res 2013;6:112–6. https://doi.org/10.1016/j.jopr.2012.11.024.
[43] Tomasini M, Faber M de O, Ferreira-Leitão VS. Sequential production of hydrogen and methane using hemicellulose hydrolysate from diluted acid pretreatment of sugarcane straw. Int J Hydrogen Energy 2023;48:9971–87. https://doi.org/10.1016/j.ijhydene.2022.11.276.
[44] Sharma S, Basu S, Shetti NP, Aminabhavi TM. Waste-to-energy nexus for circular economy and environmental protection: recent trends in hydrogen energy. Sci Total Environ 2020;713:136633. https://doi.org/10.1016/j.scitotenv.2020.136633.
[45] Vm S, Chiranjeevi P, Dahiya SANK. Waste derived bioeconomy in India: a perspective. N Biotech 2018;40:60–9. https://doi.org/10.1016/j.nbt.2017.06.006.
[46] Yun YM, Lee MK, Im SW, Marone A, Trably E, Kim DH. Biohydrogen production from food waste: current status, limitations, and future perspectives. Bioresour Technol 2018;248:79–87. https://doi.org/10.1016/j.biortech.2017.06.107.
[47] Villanueva-Galindo E, Vital-Jácome M, Moreno-Andrade I. Dark fermentation for H2 production from food waste and novel strategies for its enhancement. Int J Hydrogen Energy 2023;48:9957–70. https://doi.org/10.1016/j.ijhydene.2022.11.339.
[48] Sharma I, Shah V, Shah M. A comprehensive study on production of methanol from wind energy. Environ Technol Innov 2022;28:102589. https://doi.org/10.1016/j.eti.2022.102589.
[49] Wang J, Wen J, Wang J, Yang B, Jiang L. Water electrolyzer operation scheduling for green hydrogen production: a review. Renew Sustain Energy Rev 2024;203:114779. https://doi.org/10.1016/j.rser.2024.114779.
[50] Akyüz ES, Telli E, Farsak M. Hydrogen generation electrolyzers: paving the way for sustainable energy. Int J Hydrogen Energy 2024;81:1338–62. https://doi.org/10.1016/j.ijhydene.2024.07.175.
[51] Wei X, Sharma S, Waeber A, Wen D, Sampathkumar SN, Margni M, et al. Comparative life cycle analysis of electrolyzer technologies for hydrogen production: manufacturing and operations. Joule 2024;8:3347–72. https://doi.org/10.1016/j.joule.2024.09.007.
[52] Mucci S, Mitsos A, Bongartz D. Power-to-X processes based on PEM water electrolyzers: a review of process integration and flexible operation. Comput Chem Eng 2023;175:108260. https://doi.org/10.1016/j.compchemeng.2023.108260.
[53] Hancke R, Holm T, Ulleberg Ø. The case for high-pressure PEM water electrolysis. Energy Convers Manag 2022;261. https://doi.org/10.1016/j.enconman.2022.115642.
[54] Kazempoor P, Braun RJ. Hydrogen and synthetic fuel production using high temperature solid oxide electrolysis cells (SOECs). Int J Hydrogen Energy 2015;40:3599–612. https://doi.org/10.1016/j.ijhydene.2014.12.126.
[55] Böhm H, Zauner A, Rosenfeld DC, Tichler R. Projecting cost development for future large-scale power-to-gas implementations by scaling effects. Appl Energy 2020;264:114780. https://doi.org/10.1016/j.apenergy.2020.114780.
[56] Schmidt O, Gambhir A, Staffell I, Hawkes A, Nelson J, Few S. Future cost and performance of water electrolysis: an expert elicitation study. Int J Hydrogen Energy 2017;42:30470–92. https://doi.org/10.1016/j.ijhydene.2017.10.045.
[57] Hall W, Spencer T, Renjith G, Dayal S. The Potential Role of Hydrogen in India: a pathway for scaling-up low carbon hydrogen across the economy, 49. New Delhi Energy Resour Inst; 2020.
[58] Meier K. Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials: techno-economic assessment for an offshore-based hydrogen production approach with state-of-the-art technology. Int J Energy Environ Eng 2014;5:1–12. https://doi.org/10.1007/s40095-014-0104-6.
[59] Winter LR, Cooper NJ, Lee B, Patel SK, Wang L, Elimelech M. Mining nontraditional water sources for a distributed hydrogen economy. Environ Sci Technol 2022;56:10577–85. https://doi.org/10.1021/acs.est.2c02439.
[60] Ministry of New and Renewable Energy. Renewable Energy Statistics 2024. https://mnre.gov.in/en/renewable-energy-statistics/. [Accessed 22 January 2025]. n.d.
[61] Mukhopadhyay R, Karisiddaiah SM. The Indian coastline: processes and landforms. Dordrecht: World Geomorphol Landscapes Springer; 2014. p. 1397. https://doi.org/10.1007/978-94-017-8029-2_8. 1397.
[62] Puppala H, K Jha S, Singh AP, Madurai Elavarasan R, Elia Campana P. Identification and analysis of barriers for harnessing geothermal energy in India. Renew Energy 2022;186:327–40. https://doi.org/10.1016/j.renene.2022.01.002.
[63] Ministry of Science & Technology. India is committed to achieve the net zero emissions target by 2070. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1961797#:~:text=Dr%20Jitendra%20Singh%20said%2C%20India,1%20billion%20tons%20by%202030%3B. [Accessed 15 February 2024]. n.d.
[64] Sareen K, Panigrahi BK, Shikhola T, Nagdeve R. Deep learning solar forecasting for green hydrogen production in India: a case study. Int J Hydrogen Energy 2024;50:334–51. https://doi.org/10.1016/j.ijhydene.2023.08.323.
[65] Von Der Assen N, Voll P, Peters M, Bardow A. Life cycle assessment of CO2 capture and utilization: a tutorial review. Chem Soc Rev 2014;43:7982–94. https://doi.org/10.1039/c3cs60373c.
[66] Olateju B, Kumar A, Secanell M. A techno-economic assessment of large scale wind-hydrogen production with energy storage in Western Canada. Int J Hydrogen Energy 2016;41:8755–76. https://doi.org/10.1016/j.ijhydene.2016.03.177.
[67] Giampieri A, Ling-Chin J, Roskilly AP. Techno-economic assessment of offshore wind-to-hydrogen scenarios: a UK case study. Int J Hydrogen Energy 2024;52:589–617. https://doi.org/10.1016/j.ijhydene.2023.01.346.
[68] Shin H, Jang D, Lee S, Cho HS, Kim KH, Kang S. Techno-economic evaluation of green hydrogen production with low-temperature water electrolysis technologies directly coupled with renewable power sources. Energy Convers Manag 2023;286:117083. https://doi.org/10.1016/j.enconman.2023.117083.
[69] Praveenkumar S, Agyekum EB, Ampah JD, Afrane S, Velkin VI, Mehmood U, et al. Techno-economic optimization of PV system for hydrogen production and electric vehicle charging stations under five different climatic conditions in India. Int J Hydrogen Energy 2022;47:38087–105. https://doi.org/10.1016/j.ijhydene.2022.09.015.
[70] Al-Ghussain L, Ahmad AD, Abubaker AM, Hassan MA. Exploring the feasibility of green hydrogen production using excess energy from a country-scale 100% solar-wind renewable energy system. Int J Hydrogen Energy 2022;47:21613–33. https://doi.org/10.1016/j.ijhydene.2022.04.289.
[71] Mohideen MM, Subramanian B, Sun J, Ge J, Guo H, Liu Y. Techno-economic analysis of different shades of renewable and non-renewable energy-based hydrogen for fuel cell electric vehicles. Renew Sustain Energy Rev 2023;174:113153. https://doi.org/10.1016/j.rser.2023.113153.
[72] Pudukudy M, Yaakob Z, Mohammad M, Narayanan B, Sopian K. Renewable hydrogen economy in Asia - opportunities and challenges: an overview. Renew Sustain Energy Rev 2014;30:743–57. https://doi.org/10.1016/j.rser.2013.11.015.
[73] Bhattacharyya R, Singh KK, Bhanja K, Grover RB. Leveraging nuclear power-to-green hydrogen production potential in India: a country perspective. Int J Energy Res 2022;46:18901–18. https://doi.org/10.1002/er.8348.
[74] Bhattacharyya R, Singh KK, Bhanja K, Grover RB. Assessing techno-economic uncertainties in nuclear power-to-X processes : the case of nuclear hydrogen production via water electrolysis. Int J Hydrogen Energy 2023;48:14149–69. https://doi.org/10.1016/j.ijhydene.2022.11.315.
[75] Bhattacharyya R, Singh KK, Grover RB, Bhanja K, Bhattacharyya R, Singh KK, et al. Estimating minimum energy requirement for transitioning to a net-zero, developed India in 2070. Curr Sci 2022;122:517–27. https://doi.org/10.18520/cs/v122/i5/517-527.
[76] Ranade A, Singh K, Tamburini A, Micale G, Vermaas DA. Feasibility of producing electricity, hydrogen, and chlorine via reverse electrodialysis. Environ Sci Technol 2022;56:16062–72. https://doi.org/10.1021/acs.est.2c03407.
[77] Tayebi M, Lee BK. Recent advances in BiVO4 semiconductor materials for hydrogen production using photoelectrochemical water splitting. Renew Sustain Energy Rev 2019;111:332–43. https://doi.org/10.1016/j.rser.2019.05.030.
[78] Dingenen F, Verbruggen SW. Tapping hydrogen fuel from the ocean: a review on photocatalytic, photoelectrochemical and electrolytic splitting of seawater. Renew Sustain Energy Rev 2021;142:110866. https://doi.org/10.1016/j.rser.2021.110866.
[79] Preethi V. Solar hydrogen production in India, 25. Netherlands: Springer; 2023. https://doi.org/10.1007/s10668-022-02157-1.
[80] Lakhera SK, Rajan A, T PR, Bernaurdshaw N. A review on particulate photocatalytic hydrogen production system: progress made in achieving high energy conversion efficiency and key challenges ahead. Renew Sustain Energy Rev 2021;152:111694. https://doi.org/10.1016/j.rser.2021.111694.
[81] Holtermann T, Madlener R. Assessment of the technological development and economic potential of photobioreactors. Appl Energy 2011;88:1906–19. https://doi.org/10.1016/j.apenergy.2010.11.018.
[82] Dawood F, Anda M, Shafiullah GM. Hydrogen production for energy: an overview. Int J Hydrogen Energy 2020;45:3847–69. https://doi.org/10.1016/j.ijhydene.2019.12.059.
[83] Kar SK, Sinha ASK, Harichandan S, Bansal R, Balathanigaimani MS. Hydrogen economy in India: a status review. Wiley Interdiscip Rev Energy Environ 2023;12:1–26. https://doi.org/10.1002/wene.459.
[84] Ji M, Wang J. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. Int J Hydrogen Energy 2021;46:38612–35. https://doi.org/10.1016/j.ijhydene.2021.09.142.
[85] Acar C, Dincer I. Review and evaluation of hydrogen production options for better environment. J Clean Prod 2019;218:835–49. https://doi.org/10.1016/j.jclepro.2019.02.046.
[86] Cloete S, Arnaiz del Pozo C, Jiménez Álvaro Á. System-friendly process design: optimizing blue hydrogen production for future energy systems. Energy 2022;259. https://doi.org/10.1016/j.energy.2022.124954.

[87] Chaurasia AK, Mondal P. Hydrogen production from waste and renewable resources. Hydrog Fuel Cell Technol Station Appl 2021:22–46. https://doi.org/10.4018/978-1-7998-4945-2.ch002.

[88] Lepage T, Kammoun M, Schmetz Q, Richel A. Biomass-to-hydrogen: a review of main routes production, processes evaluation and techno-economical assessment. Biomass Bioenergy 2021;144:105920. https://doi.org/10.1016/j.biombioe.2020.105920.

[89] Lee JY, Sim YB, Jung JH, Pandey AK, Kyung D, Kim SH. Greenhouse gas emissions and net energy production of dark fermentation from food waste followed by anaerobic digestion. Energy 2024;312. https://doi.org/10.1016/j.energy.2024.133559.

[90] Hassan IA, Ramadan HS, Saleh MA, Hissel D. Hydrogen storage technologies for stationary and mobile applications: review, analysis and perspectives. Renew Sustain Energy Rev 2021;149:111311. https://doi.org/10.1016/j.rser.2021.111311.

[91] Su Y, Lv H, Zhou W, Zhang C. Review of the hydrogen permeability of the liner material of type iv on-board hydrogen storage tank. World Electr Veh J 2021;12:1–18. https://doi.org/10.3390/wevj12030130.

[92] Barthelemy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. Int J Hydrogen Energy 2017;42:7254–62. https://doi.org/10.1016/j.ijhydene.2016.03.178.

[93] Muthukumar P, Kumar A, Afzal M, Bhogilla S, Sharma P, Parida A, et al. Review on large-scale hydrogen storage systems for better sustainability. Int J Hydrogen Energy 2023;48:33223–59. https://doi.org/10.1016/j.ijhydene.2023.04.304.

[94] Li M, Bai Y, Zhang C, Song Y, Jiang S, Grouset D, et al. Review on the research of hydrogen storage system fast refueling in fuel cell vehicle. Int J Hydrogen Energy 2019;44:10677–93. https://doi.org/10.1016/j.ijhydene.2019.02.208.

[95] Safari A, Zeng L, Nguele R, Sugai Y, Sarmadivaleh M. Review on using the depleted gas reservoirs for the underground H2 storage: a case study in Niigata prefecture, Japan. Int J Hydrogen Energy 2023;48:10579–602. https://doi.org/10.1016/j.ijhydene.2022.12.108.

[96] Navaid H Bin, Emadi H, Watson M. A comprehensive literature review on the challenges associated with underground hydrogen storage. Int J Hydrogen Energy 2023;48:10603–35. https://doi.org/10.1016/j.ijhydene.2022.11.225.

[97] Guha Roy D, Goyal J, Talukdar M. Capacity assessment and economic analysis of geologic storage of hydrogen in hydrocarbon basins: a South Asian perspective. Int J Hydrogen Energy 2024;92:917–29. https://doi.org/10.1016/j.ijhydene.2024.10.282.

[98] Andersson J, Grönkvist S. Large-scale storage of hydrogen. Int J Hydrogen Energy 2019;44:11901–19. https://doi.org/10.1016/j.ijhydene.2019.03.063.

[99] Nikhil P, Prakash GB, Kavyasri K, Sivasankar P. Analysis on CO2 emissions, green hydrogen requirement and geo-storage potential of hydrogen for decarbonization of industrial operations in southeastern coast of India. Int J Hydrogen Energy 2024;52:1507–21. https://doi.org/10.1016/j.ijhydene.2023.08.235.

[100] Shahriar MF, Khanal A, Khan MI, Pandey R. Current status of underground hydrogen storage: perspective from storage loss, infrastructure, economic aspects, and hydrogen economy targets. J Energy Storage 2024;97:112773. https://doi.org/10.1016/j.est.2024.112773.

[101] Tarkowski R. Underground hydrogen storage: characteristics and prospects. Renew Sustain Energy Rev 2019;105:86–94. https://doi.org/10.1016/j.rser.2019.01.051.

[102] Abdalla AM, Hossain S, Nisfindy OB, Azad AT, Dawood M, Azad AK. Hydrogen production, storage, transportation and key challenges with applications: a review. Energy Convers Manag 2018;165:602–27. https://doi.org/10.1016/j.enconman.2018.03.088.

[103] Niaz S, Manzoor T, Pandith AH. Hydrogen storage: materials, methods and perspectives. Renew Sustain Energy Rev 2015;50:457–69. https://doi.org/10.1016/j.rser.2015.05.011.

[104] Qiu Y, Yang H, Tong L, Wang L. Research progress of cryogenic materials for storage and transportation of liquid hydrogen. Metals 2021;11. https://doi.org/10.3390/met11071101.

[105] Usman MR. Hydrogen storage methods: review and current status. Renew Sustain Energy Rev 2022;167:112743. https://doi.org/10.1016/j.rser.2022.112743.

[106] U S Department of Energy. DOE technical targets for onboard hydrogen storage for light-duty vehicles. https://www.energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles. [Accessed 8 March 2025]. n.d.

[107] Bakuru VR, Dmello ME, Kalidindi SB. Metal-organic frameworks for hydrogen energy applications: advances and challenges. ChemPhysChem 2019;20:1177–215. https://doi.org/10.1002/cphc.201801147.

[108] Niu L, Zhao X, Wu F, Tang Z, Lv H, Wang J, et al. Hotpots and trends of covalent organic frameworks (COFs) in the environmental and energy field: bibliometric analysis. Sci Total Environ 2021;783:146838. https://doi.org/10.1016/j.scitotenv.2021.146838.

[109] Eberle U, Felderhoff M, Schüth F. Chemical and physical solutions for hydrogen storage. Angew Chem Int Ed 2009;48:6608–30. https://doi.org/10.1002/anie.200806293.

[110] Man Mohan, Kumar Sharma Vinod, E, Anil Kumar VG. Hydrogen storage in carbon materials. Energy Storage 2019:1–26. https://doi.org/10.1002/est2.35.

[111] Singh R, Altaee A, Gautam S. Nanomaterials in the advancement of hydrogen energy storage. Heliyon 2020;6:e04487. https://doi.org/10.1016/j.heliyon.2020.e04487.

[112] Gend C, Chaudhari A. Multiple Ti and Li doped carbon nanoring for hydrogen storage. Int J Hydrogen Energy 2023;48:10636–43. https://doi.org/10.1016/j.ijhydene.2022.11.321.

[113] Zacharia R, Rather SU. Review of solid state hydrogen storage methods adopting different kinds of novel materials. J Nanomater 2015;2015. https://doi.org/10.1155/2015/914845.

[114] Rusman NAA, Dahari M. A review on the current progress of metal hydrides material for solid-state hydrogen storage applications. Int J Hydrogen Energy 2016;41:12108–26. https://doi.org/10.1016/j.ijhydene.2016.05.244.

[115] Yartys VA, Lototskyy MV, Akiba E, Albert R, Antonov VE, Ares JR, et al. Magnesium based materials for hydrogen based energy storage: past, present and future. Int J Hydrogen Energy 2019;44:7809–59. https://doi.org/10.1016/j.ijhydene.2018.12.212.

[116] Abe JO, Popoola API, Ajenifuja E, Popoola OM. Hydrogen energy, economy and storage: review and recommendation. Int J Hydrogen Energy 2019;44:15072–86. https://doi.org/10.1016/j.ijhydene.2019.04.068.

[117] Kumar A, Muthukumar P, Sharma P, Kumar EA. Absorption based solid state hydrogen storage system: a review. Sustain Energy Technol Assessments 2022;52:102204. https://doi.org/10.1016/j.seta.2022.102204.

[118] Tarhan C, Çil MA. A study on hydrogen, the clean energy of the future: hydrogen storage methods. J Energy Storage 2021;40:102676. https://doi.org/10.1016/j.est.2021.102676.

[119] Manna J, Vashistha M, Sharma P. Lithium borohydride as a hydrogen storage material: a review. Int J Energy a Clean Environ (IJECE) 2010;11:65–97. https://doi.org/10.1615/InterJEnerCleanEnv.2011002432.

[120] Muthu RN, Rajashabala S, Kannan R. Hydrogen storage performance of lithium borohydride decorated activated hexagonal boron nitride nanocomposite for fuel cell applications. Int J Hydrogen Energy 2017;42:15586–96. https://doi.org/10.1016/j.ijhydene.2017.04.240.

[121] Manna J, Roy B, Sharma P. Efficient hydrogen generation from sodium borohydride hydrolysis using silica sulfuric acid catalyst. J Power Sources 2015;275:727–33. https://doi.org/10.1016/j.jpowsour.2014.11.040.

[122] Otto M, Chagoya KL, Blair RG, Hick SM, Kapat JS. Optimal hydrogen carrier: holistic evaluation of hydrogen storage and transportation concepts for power generation, aviation, and transportation. J Energy Storage 2022;55:105714. https://doi.org/10.1016/j.est.2022.105714.

[123] Wijayanta AT, Oda T, Purnomo CW, Kashiwagi T, Aziz M. Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: comparison review. Int J Hydrogen Energy 2019;44:15026–44. https://doi.org/10.1016/j.ijhydene.2019.04.112.

[124] Klerke A, Christensen CH, Nørskov JK, Vegge T. Ammonia for hydrogen storage: challenges and opportunities. J Mater Chem 2008;18:2304–10. https://doi.org/10.1039/b720020j.

[125] Wulf C, Zapp P. Assessment of system variations for hydrogen transport by liquid organic hydrogen carriers. Int J Hydrogen Energy 2018;43:11884–95. https://doi.org/10.1016/j.ijhydene.2018.01.198.

[126] Crandall BS, Brix T, Weber RS, Jiao F. Techno-Economic assessment of green H2 carrier supply chains. Energy Fuels 2023;37:1441–50. https://doi.org/10.1021/acs.energyfuels.2c03616.

[127] Chung CH, Ihm J, Lee H. Recent progress on Kubas-type hydrogen-storage nanomaterials: from theories to experiments. J Kor Phys Soc 2015;66:1649–55. https://doi.org/10.3938/jkps.66.1649.

[128] Hoang TKA, Webb MI, Mai HV, Hamaed A, Walsby CJ, Trudeau M, et al. Design and synthesis of vanadium hydrazide gels for kubas-type hydrogen adsorption: a new class of hydrogen storage materials. J Am Chem Soc 2010;132:11792–8. https://doi.org/10.1021/ja104926h.

[129] Hoang TKA, Antonelli DM. Exploiting the kubas interaction in the design of hydrogen storage materials. Adv Mater 2009;4:1787–800. https://doi.org/10.1002/adma.200802832.

[130] Qureshi F, Yusuf M, Kamyab H, Zaidi S, Junaid Khalil M, Arham Khan M, et al. Current trends in hydrogen production, storage and applications in India: a review. Sustain Energy Technol Assessments 2022;53:102677. https://doi.org/10.1016/j.seta.2022.102677.

[131] Department of science and technology. Government of India. India country status report on hydrogen and fuel cells. https://dst.gov.in/sites/default/files/Country%20status%20report%20final%20Hydrogen.pdf. [Accessed 8 October 2023]. n.d.

[132] Rivard E, Trudeau M, Zaghib K. Hydrogen storage for mobility: a review. Materials 2019;12. https://doi.org/10.3390/ma12121973.

[133] Song P, Sui Y, Shan T, Hou J, Wang X. Assessment of hydrogen supply solutions for hydrogen fueling station: a shanghai case study. Int J Hydrogen Energy 2020;45:32884–98. https://doi.org/10.1016/j.ijhydene.2020.09.117.

[134] Rong Y, Chen S, Li C, Chen X, Xie L, Chen J, et al. Techno-economic analysis of hydrogen storage and transportation from hydrogen plant to terminal refueling station. Int J Hydrogen Energy 2024;52:547–58. https://doi.org/10.1016/j.ijhydene.2023.01.187.

[135] Hren R, Vujanović A, Van Fan Y, Klemeš JJ, Krajnc D, Čuček L. Hydrogen production, storage and transport for renewable energy and chemicals: an environmental footprint assessment. Renew Sustain Energy Rev 2023;173. https://doi.org/10.1016/j.rser.2022.113113.

[136] Liu H, Ma J, Member S. A review of models and methods for hydrogen supply chain system planning. CSEE J Power Energy Syst; 2020. https://doi.org/10.17775/cseejpes.2020.02280.

[137] Yang C, Ogden J. Determining the lowest-cost hydrogen delivery mode. Int J Hydrogen Energy 2007;32:268–86. https://doi.org/10.1016/j.ijhydene.2006.05.009.

[138] Öney F, Vezirolu TN, Dülger Z. Evaluation of pipeline transportation of hydrogen and natural gas mixtures. Int J Hydrogen Energy 1994;19:813–22. https://doi.org/10.1016/0360-3199(94)90198-8.

[139] Witkowski A, Rusin A, Majkut M, Stolecka K. Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. Energy 2017;141:2508–18. https://doi.org/10.1016/j.energy.2017.05.141.
[140] Dodds PE, Demoullin S. Conversion of the UK gas system to transport hydrogen. Int J Hydrogen Energy 2013;38:7189–200. https://doi.org/10.1016/j.ijhydene.2013.03.070.
[141] Abbas AJ, Hassani H, Burby M, John IJ. An investigation into the volumetric flow rate requirement of hydrogen transportation in existing natural gas pipelines and its safety implications. Gases 2021;1:156–79. https://doi.org/10.3390/gases1040013.
[142] Ogden J, Jaffe AM, Scheitrum D, McDonald Z, Miller M. Natural gas as a bridge to hydrogen transportation fuel: insights from the literature. Energy Policy 2018;115:317–29. https://doi.org/10.1016/j.enpol.2017.12.049.
[143] Petroleum and Natural Gas Regulatory Board. PNGRB annual report 2019-2020. https://www.pngrb.gov.in/pdf/annualreports/eng2019-2020.pdf. [Accessed 12 February 2025]. n.d.
[144] Jena H, Das T, Kumar A. Study of transportation prospects and safety regulations of hydrogen in Indian context: a green fuel for greener future. Mater Today Proc 2022;65:3382–7. https://doi.org/10.1016/j.matpr.2022.05.481.
[145] Castello P, Tzimas E, Moretto P, Peteves SD. Techno-economic assessment of hydrogen transmission & distribution systems in Europe in the medium and long term. European Commission; 2005.
[146] Melaina MW, Antonia Mp O. Blending hydrogen into natural gas pipelines networks: a review of key issues. Tec Rep NREL/TP-500-51995 2013.
[147] Gondal IA, Sahir MH. Prospects of natural gas pipeline infrastructure in hydrogen transportation. Int J Energy Res 2011. https://doi.org/10.1002/er.
[148] Gondal IA. Hydrogen transportation by pipelines. Elsevier Ltd.; 2015. https://doi.org/10.1016/B978-1-78242-362-1.00012-2.
[149] Riedl SM. Development of a hydrogen refueling station design tool. Int J Hydrogen Energy 2020;45:1–9. https://doi.org/10.1016/j.ijhydene.2019.09.234.
[150] Alazemi J, Andrews J. Automotive hydrogen fuelling stations: an international review. Renew Sustain Energy Rev 2015;48:483–99. https://doi.org/10.1016/j.rser.2015.03.085.
[151] Chen F, Zhang Y, Jin Z. Co-design and aerodynamic study on a two-step high pressure reducing system for hydrogen decompression: from hydrogen refueling station to hydrogen fuel cell vehicle. Int J Hydrogen Energy 2023;48:10968–81. https://doi.org/10.1016/j.ijhydene.2022.12.158.
[152] Hurskainen M, Ihonen J. Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers. Int J Hydrogen Energy 2020;45:32098–112. https://doi.org/10.1016/j.ijhydene.2020.08.186.
[153] Wulf C, Reuß M, Grube T, Zapp P, Robinius M, Hake JF, et al. Life cycle assessment of hydrogen transport and distribution options. J Clean Prod 2018;199:431–43. https://doi.org/10.1016/j.jclepro.2018.07.180.
[154] Anastasopoulou A, Furukawa H, Barnett BR, Jiang HZH, Long JR, Breunig HM. Technoeconomic analysis of metal-organic frameworks for bulk hydrogen transportation. Energy Environ Sci 2021;14:1083–94. https://doi.org/10.1039/d0ee02448a.
[155] Amos WA. Costs of storing and transporting hydrogen. National Renewable Energy Laboratory; 1998.
[156] Ishimoto Y, Voldsund M, Nekså P, Roussanaly S, Berstad D, Gardarsdottir SO. Large-scale production and transport of hydrogen from Norway to Europe and Japan: value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. Int J Hydrogen Energy 2020;45:32865–83. https://doi.org/10.1016/j.ijhydene.2020.09.017.
[157] Demir ME, Dincer I. Cost assessment and evaluation of various hydrogen delivery scenarios. Int J Hydrogen Energy 2018;43:10420–30. https://doi.org/10.1016/j.ijhydene.2017.08.002.
[158] Okunlola A, Giwa T, Di Lullo G, Davis M, Gemechu E, Kumar A. Techno-economic assessment of low-carbon hydrogen export from Western Canada to eastern Canada, the USA, the asia-pacific, and Europe. Int J Hydrogen Energy 2022;47:6453–77. https://doi.org/10.1016/j.ijhydene.2021.12.025.
[159] Cui J, Aziz M. Techno-economic analysis of hydrogen transportation infrastructure using ammonia and methanol. Int J Hydrogen Energy 2023;48:15737–47. https://doi.org/10.1016/j.ijhydene.2023.01.096.
[160] Niermann M, Timmerberg S, Drünert S, Kaltschmitt M. Liquid organic hydrogen carriers and alternatives for international transport of renewable hydrogen. Renew Sustain Energy Rev 2021;135:110171. https://doi.org/10.1016/j.rser.2020.110171.
[161] Raab M, Maier S, Dietrich RU. Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media. Int J Hydrogen Energy 2021;46:11956–68. https://doi.org/10.1016/j.ijhydene.2020.12.213.
[162] Aakko-Saksa PT, Cook C, Kiviaho J, Repo T. Liquid organic hydrogen carriers for transportation and storing of renewable energy – review and discussion. J Power Sources 2018;396:803–23. https://doi.org/10.1016/j.jpowsour.2018.04.011.
[163] Teichmann D, Arlt W, Wasserscheid P. Liquid organic hydrogen carriers as an efficient vector for the transport and storage of renewable energy. Int J Hydrogen Energy 2012;37:18118–32. https://doi.org/10.1016/j.ijhydene.2012.08.066.
[164] Lahnaoui A, Wulf C, Heinrichs H, Dalmazzone D. Optimizing hydrogen transportation system for mobility via compressed hydrogen trucks. Int J Hydrogen Energy 2019;44:19302–12. https://doi.org/10.1016/j.ijhydene.2018.10.234.
[165] Di Lullo G, Giwa T, Okunlola A, Davis M, Mehedi T, Oni AO, et al. Large-scale long-distance land-based hydrogen transportation systems: a comparative techno-economic and greenhouse gas emission assessment. Int J Hydrogen Energy 2022;47:35293–319. https://doi.org/10.1016/j.ijhydene.2022.08.131.
[166] Singh S, Jain S, Ps V, Tiwari AK, Nouni MR, Pandey JK, et al. Hydrogen: a sustainable fuel for future of the transport sector. Renew Sustain Energy Rev 2015;51:623–33. https://doi.org/10.1016/j.rser.2015.06.040.
[167] Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Prog Energy Combust Sci 2009;35:490–527. https://doi.org/10.1016/j.pecs.2009.08.001.
[168] Huang Y, Surawski NC, Zhuang Y, Zhou JL, Hong G. Dual injection: an effective and efficient technology to use renewable fuels in spark ignition engines. Renew Sustain Energy Rev 2021;143:110921. https://doi.org/10.1016/j.rser.2021.110921.
[169] Szwaja S, Grab-Rogalinski K. Hydrogen combustion in a compression ignition diesel engine. Int J Hydrogen Energy 2009;34:4413–21. https://doi.org/10.1016/j.ijhydene.2009.03.020.
[170] Neacsa A, Eparu CN, Stoica DB. Hydrogen–natural gas blending in distribution systems—an energy, economic, and environmental assessment. Energies 2022;15:6143.
[171] Singh P, Balasubramanian D, Venugopal IP, Tyagi VV, Goel V, Varuvel EG. A comprehensive review on the applicability of hydrogen and natural gas as gaseous fuel for dual fuel engine operation. Energy Sources, Part A Recover Util Environ Eff 2024;46:1559–87. https://doi.org/10.1080/15567036.2023.2298004.
[172] Morrison GM, Kumar R, Chugh S, Puri SK, Tuli DK, Malhotra RK. Hydrogen transportation in Delhi? Investigating the hydrogen-compressed natural gas (H-CNG) option. Int J Hydrogen Energy 2012;37:644–54. https://doi.org/10.1016/j.ijhydene.2011.09.090.
[173] Dominković DF, Bačeković I, Pedersen AS, Krajačić G. The future of transportation in sustainable energy systems: opportunities and barriers in a clean energy transition. Renew Sustain Energy Rev 2018;82:1823–38. https://doi.org/10.1016/j.rser.2017.06.117.
[174] Hossain MS, Fang YR, Ma T, Huang C, Peng W, Urpelainen J, et al. Narrowing fossil fuel consumption in the Indian road transport sector towards reaching carbon neutrality. Energy Policy 2023;172:113330. https://doi.org/10.1016/j.enpol.2022.113330.
[175] Rosen MA, Koohi-Fayegh S. The prospects for hydrogen as an energy carrier: an overview of hydrogen energy and hydrogen energy systems. Energy, Ecol Environ 2016;1:10–29. https://doi.org/10.1007/s40974-016-0005-z.
[176] Schoettle B, Sivak M. The relative merits of battery-electric vehicles and fuel-cell vehicles. The University of Michigan; 2016. Available at: https://public.websites.umich.edu/~umtriswt/PDF/UMTRI-2016-5.pdf. [Accessed 3 March 2024]. n.d..
[177] Ahluwalia RK, Wang X, Rousseau A, Kumar R. Fuel economy of hydrogen fuel cell vehicles. J Power Sources 2004;130:192–201. https://doi.org/10.1016/j.jpowsour.2003.12.061.
[178] Hassan Q, Algburi S, Sameen AZ, Jaszczur M, Salman HM. Hydrogen as an energy carrier: properties, storage methods, challenges, and future implications. Environ Syst Decis 2024;44:327–50. https://doi.org/10.1007/s10669-023-09932-z.
[179] Kar SK, Bansal R, Harichandan S. An empirical study on intention to use hydrogen fuel cell vehicles in India. Int J Hydrogen Energy 2022;47:19999–20015. https://doi.org/10.1016/j.ijhydene.2022.04.137.
[180] Rath R, Kumar P, Mohanty S, Nayak SK. Recent advances, unsolved deficiencies, and future perspectives of hydrogen fuel cells in transportation and portable sectors. Int J Energy Res 2019;43:8931–55. https://doi.org/10.1002/er.4795.
[181] Hwang HT, Varma A. Hydrogen storage for fuel cell vehicles. Curr Opin Chem Eng 2014;5:42–8. https://doi.org/10.1016/j.coche.2014.04.004.
[182] Patil V, Shastry V, Himabindu M, Ravikrishna RV. Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: part 2 - well-to-wheels analysis. Energy 2016;96:699–712. https://doi.org/10.1016/j.energy.2015.11.076.
[183] Farrell AE, Keith DW, Corbett J. A strategy for introducing hydrogen into transportation. Energy Policy 2003;31:1357–67. https://doi.org/10.1016/S0301-4215(02)00195-7.
[184] Veziroğlu A, MacÁrio R. A system dynamics model for the reduction of health expenditures through transition to hydrogen vehicles (Srth): case studies in the USA, China, and India. Int J Green Energy 2014;11:695–726. https://doi.org/10.1080/15435075.2013.809723.
[185] Boretti A. How close is a hydrogen hypersonic commercial aircraft? Int J Hydrogen Energy 2023;48:10684–91. https://doi.org/10.1016/j.ijhydene.2022.11.303.
[186] Robinius M, Otto A, Heuser P, Welder L, Syranidis K, Ryberg DS, et al. Linking the power and transport sectors - part 1: the principle of sector coupling. Energies 2017;10. https://doi.org/10.3390/en10070956.
[187] Varela C, Mostafa M, Zondervan E. Modeling alkaline water electrolysis for power-to-x applications: a scheduling approach. Int J Hydrogen Energy 2021;46:9303–13. https://doi.org/10.1016/j.ijhydene.2020.12.111.
[188] Guerra OJ, Zhang J, Eichman J, Denholm P, Kurtz J, Hodge BM. The value of seasonal energy storage technologies for the integration of wind and solar power. Energy Environ Sci 2020;13:1909–22. https://doi.org/10.1039/d0ee00771d.
[189] Kong L, Li L, Cai G, Liu C, Ma P, Bian Y, et al. Techno-economic analysis of hydrogen energy for renewable energy power smoothing. Int J Hydrogen Energy 2021;46:2847–61. https://doi.org/10.1016/j.ijhydene.2020.07.231.
[190] Gracia L, Casero P, Bourasseau C, Chabert A. Use of hydrogen in off-grid locations, a techno-economic assessment. Energies 2018;11. https://doi.org/10.3390/en11113141.
[191] Abbas M, Boumeddane B, Said N, Chikouche A. Dish Stirling technology: a 100 MW solar power plant using hydrogen for Algeria. Int J Hydrogen Energy 2011;36:4305–14. https://doi.org/10.1016/j.ijhydene.2010.12.114.
[192] Ditaranto M, Li H, Løvås T. Concept of hydrogen fired gas turbine cycle with exhaust gas recirculation: assessment of combustion and emissions performance.

Int J Greenh Gas Control 2015;37:377–83. https://doi.org/10.1016/j.ijggc.2015.04.004.
[193] Guney MS, Tepe Y. Classification and assessment of energy storage systems. Renew Sustain Energy Rev 2017;75:1187–97. https://doi.org/10.1016/j.rser.2016.11.102.
[194] Kinnon M Mac, Razeghi G, Samuelsen S. The role of fuel cells in port microgrids to support sustainable goods movement. Renew Sustain Energy Rev 2021;147:111226. https://doi.org/10.1016/j.rser.2021.111226.
[195] Badrinarayanan DSR, Bokkassam SD, Krishnan JN. Investigation on implementing hydrogen technology in residential sector. Energy Rep 2024;12:920–41. https://doi.org/10.1016/j.egyr.2024.07.005.
[196] Patel M, Roy S, Roskilly AP, Smallbone A. The techno-economics potential of hydrogen interconnectors for electrical energy transmission and storage. J Clean Prod 2022;335:130045. https://doi.org/10.1016/j.jclepro.2021.130045.
[197] Pawar ND, Heinrichs HU, Winkler C, Heuser PM, Ryberg SD, Robinius M, et al. Potential of green ammonia production in India. Int J Hydrogen Energy 2021;46:27247–67. https://doi.org/10.1016/j.ijhydene.2021.05.203.
[198] Sazali N. Emerging technologies by hydrogen: a review. Int J Hydrogen Energy 2020;45:18753–71. https://doi.org/10.1016/j.ijhydene.2020.05.021.
[199] Kim J, Park JK, Yoon YS. Simplified sulfur-iodine cycle process to hydrogen blast furnace: techno-economic and CO2 mitigation analysis. J Clean Prod 2022;355:131855. https://doi.org/10.1016/j.jclepro.2022.131855.
[200] Choi W, Kang S. Greenhouse gas reduction and economic cost of technologies using green hydrogen in the steel industry. J Environ Manag 2023;335:117569. https://doi.org/10.1016/j.jenvman.2023.117569.
[201] Ellersdorfer P, Wang C, Saydam S, Canbulat I, MacGill I, Daiyan R. Unlocking new export opportunities: an open-source framework for assessing green iron and steel supply chains. Int J Hydrogen Energy 2024;92:1366–74. https://doi.org/10.1016/j.ijhydene.2024.10.163.
[202] Renewable energy policies in a time of transition: heating and cooling. IRENA, OECD/IEA and REN21. 2020.
[203] Sgarbossa F, Arena S, Tang O, Peron M. Renewable hydrogen supply chains: a planning matrix and an agenda for future research. Int J Prod Econ 2023;255:108674. https://doi.org/10.1016/j.ijpe.2022.108674.
[204] Komarova AV, Filimonova IV, Novikov AY. The impact of the resource and environmental factors on the economic development of Russian regions. Energy Rep 2021;7:422–7. https://doi.org/10.1016/j.egyr.2021.07.109.
[205] Sharma GD, Verma M, Taheri B, Chopra R, Parihar JS. Socio-economic aspects of hydrogen energy: an integrative review. Technol Forecast Soc Change 2023;192:122574. https://doi.org/10.1016/j.techfore.2023.122574.
[206] Luta DN, Raji AK. Renewable hydrogen-based energy system for supplying power to telecoms base station. Int J Eng Res Afr 2019;43:112–26. https://dx.doi.org/10.4028/www.scientific.net/JERA.43.112.
[207] Garcia-Navarro J, Isaacs MA, Favaro M, Ren D, Ong WJ, Grätzel M, et al. Updates on hydrogen value chain: a strategic roadmap. Glob Challenges 2024;8:1–17. https://doi.org/10.1002/gch2.202300073.
[208] Chen X, Zheng L, Cai G, Qi X, He J. Promoting innovation: policy impacts on global hydrogen value chain. Renew Sustain Energy Rev 2025;223:116014. https://doi.org/10.1016/j.rser.2025.116014.
[209] Kar SK, Harichandan S, Roy B. Bibliometric analysis of the research on hydrogen economy: an analysis of current findings and roadmap ahead. Int J Hydrogen Energy 2022;47:10803–24. https://doi.org/10.1016/j.ijhydene.2022.01.137.



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