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Green hydrogen pathways for a net-zero future: technologies, circular economy integration, life-cycle performance and safety dimensions

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This review critically evaluates the technological, environmental, and policy dimensions of green hydrogen using an integrated framework grounded in green chemistry, the circular economy, and the sustainable development goals. Rather than treating green hydrogen as a universal energy solution, the review synthesises advances in production, storage, transport, safety, and policy instruments to assess where and under what conditions hydrogen deployment is sustainable. Conventional, biological, electrolytic, photocatalytic, and waste-derived pathways are compared in terms of efficiency, lifecycle emissions, resource intensity, material criticality, and toxicity. Storage and distribution options including compressed and liquefied hydrogen, chemical carriers, and porous materials are assessed for energy density, safety, recyclability, and infrastructure readiness. Life-cycle assessment data are integrated to identify key hotspots in global warming potential, water use, cumulative energy demand, and human toxicity. Policy frameworks, including India's National Green Hydrogen Mission, are examined with emphasis on implementation mechanisms, certification, and industrial integration. The analysis demonstrates that no single pathway satisfies all sustainability criteria, highlighting the need for targeted deployment, system integration, and regional optimisation. Embedding green chemistry principles alongside coordinated policy and infrastructure planning is essential for a resilient and equitable hydrogen economy.

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1. Introduction

1.1 Current global energy scenario and fossil fuel dependency

The global energy landscape remains heavily reliant on fossil fuels despite growing interest in clean and renewable energy sources. As of 2022, fossil fuels, namely coal, oil, and natural gas, continued to dominate the primary energy consumption mix, accounting for approximately 82% of the global supply.[1] The distribution of energy sources in the global energy mix for 2022 is illustrated in Fig. 1. Renewable energy sources, although expanding rapidly, contributed only about 12.6% of the total global energy consumption, while nuclear energy comprised around 5.4%.[2]

Global energy demand has been steadily increasing, driven by population growth, industrialisation, and rising living standards, particularly in developing regions.[4] Between 2010 and 2020, global primary energy demand grew by approximately 1.3% per year, a trend expected to continue, albeit at a slower rate in the coming decades.[3] The International Renewable Energy Agency (IRENA) projects that under current policy trajectories, energy-related CO_2 emissions may plateau but not decline sufficiently to meet climate goals, reflecting the entrenched role of fossil fuels in economic systems.[5]

Despite notable progress in renewable energy deployment and increasing global efforts toward decarbonisation, fossil fuels remain the backbone of the World's energy systems. This persistence is sustained by existing infrastructure, the high energy density of fossil fuels, and their historical reliability for baseload energy supply. Projections consistently indicate that

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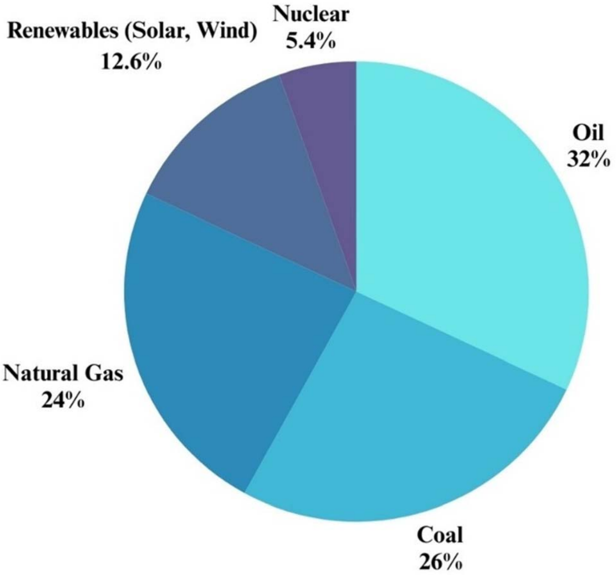

Fig. 1 Global primary energy consumption by source, highlighting the continued dominance of fossil fuels compared to renewable and nuclear energy sources.[1,3]

without a substantial shift in policy direction, accelerated technological advancement, and stronger global cooperation, fossil fuels will retain a significant share in the global energy mix by mid-century. Addressing this deep-rooted dependency will require overcoming a complex array of political, technical, and economic hurdles that continue to challenge the pace of the global energy transition.

1.2 Emergence of hydrogen as an alternative energy source

Escalating climate concerns and fossil fuel depletion have positioned hydrogen as a pivotal energy carrier for low-carbon transitions. Its primary advantages include high energy density and zero-emission end-use, as its utilization particularly in fuel cells yields only water vapor.[6,7] While historical adoption was limited by technical and economic hurdles, recent breakthroughs in electrolysis and renewable integration have catalyzed interest in green hydrogen. Unlike grey or blue hydrogen derived from fossil fuels, green hydrogen is produced by splitting water using renewable electricity (solar, wind, and hydropower), resulting in a carbon-neutral footprint.[5,8,9] Currently, however, 96% of global production remains fossil-fuel dependent primary through steam methane reforming (SMR) and coal gasification underscoring the urgent need for cleaner production pathways.[6]

Green hydrogen is uniquely suited to decarbonize hard to abate sectors (*e.g.*, heavy industry, chemical manufacturing, and long-haul transport) where direct electrification is not feasible.[9] Furthermore, it serves as a flexible storage solution for surplus renewable energy, mitigating the intermittency of wind and solar power. Because it can be produced from diverse feedstocks (biomass, water, or hydrocarbons), hydrogen acts as a strategic bridge to sustainable energy systems.[7] Leading economies, including Germany, Japan, South Korea, and Australia, have already integrated hydrogen into their national energy frameworks.[6,8] Nevertheless, achieving a hydrogen based economy requires overcoming significant techno-economic, regulatory, and infrastructural barriers through global innovation and supportive market policies.[6]

1.3 Global transformation goals and decarbonisation

The shift from fossil fuel dependence is essential to meet the Paris Agreement (2015) targets of limiting global temperature rise to 1.5–2 °C.[10] Decarbonisation is the foundation of this shift; IRENA predicts that renewable technologies and green hydrogen will provide roughly 41% of the CO_2 reductions required by 2050.[5] Green hydrogen is particularly vital for hard to electrify sectors including heavy industry, aviation, and long-distance shipping.[11]

World Energy Council scenarios highlight green hydrogen's dual role as a clean energy carrier and large-scale storage medium. By providing system flexibility and grid stability, it facilitates a higher penetration of variable solar and wind energy.[5,10,11] Despite these benefits, the current transition is too slow. In 2023, fossil fuels still met 70% of global energy demand, resulting in 36.8 billion metric tons of CO_2 emissions.[12] Accelerating the transition requires a combination of technological innovation, international cooperation, and massive infrastructure investment.[6]

Ultimately, green hydrogen serves as a bridge between energy supply and demand, advancing SDG7 (affordable and clean energy) and SDG13 (climate action) toward a zero-carbon economy by 2050.[10] This review moves beyond simple technological comparisons by introducing a system-oriented analytical framework. This approach integrates resource availability, infrastructure coupling, and sustainability, positioning hydrogen within interconnected industrial, energy, and waste valorization networks.

1.4. Research gaps and scope of this review

While the hydrogen economy has attracted substantial research attention, significant gaps remain in the comparative analysis of green hydrogen production technologies, lifecycle assessments, infrastructure scalability, and integration into diverse regional energy systems. Additionally, the interplay between policy frameworks, market dynamics, and technological innovation in accelerating hydrogen adoption is not comprehensively addressed in existing literature. This review seeks to address these gaps by providing a comprehensive and integrative analysis of green hydrogen, encompassing production, storage, transport, policy drivers, and sustainable development implications. Special emphasis is placed on critically evaluating the challenges, emerging solutions, and commercial readiness levels of green hydrogen technologies, thereby offering valuable insights for researchers, industry stakeholders, and policymakers engaged in the global energy transition.

2. Hydrogen economy

2.1 Concept and significance

The hydrogen economy envisions a future energy system in which hydrogen replaces conventional fossil fuels as a major energy carrier across multiple sectors. In this model, hydrogen serves as a versatile, clean, and sustainable vector capable of enabling deep decarbonisation in transportation, industry, and energy storage.[13] Its high energy density (120 MJ kg^{-1}) and ability to be produced from a wide range of primary sources, including renewable electricity *via* electrolysis, position hydrogen as a key enabler of the transition to net-zero emissions.[13,14]

The significance of hydrogen extends beyond environmental benefits. It offers critical flexibility for balancing renewable electricity systems, providing long-duration energy storage, and powering sectors that are difficult to electrify, such as steel manufacturing, shipping, and aviation.[15] Moreover, hydrogen presents an opportunity to enhance energy security by diversifying energy supply sources and reducing reliance on imported fossil fuels.[11] As nations work to meet the Paris Agreement targets and their net-zero commitments, hydrogen is increasingly recognised as a cornerstone technology for decarbonising economies while fostering economic growth and innovation.[16] A conceptual overview of the hydrogen economy ecosystem, covering production, distribution, and utilisation pathways, is illustrated in Fig. 2.

Hydrogen systems also contribute to green chemistry objectives by enabling non-toxic, circular, and resource-efficient energy pathways, especially when powered by renewables and integrated with low-impact materials and catalysts.

2.2 Global market trends and economic potential

The global hydrogen market is experiencing rapid evolution, fueled by government initiatives, industrial investments, and declining costs of renewable energy.[17] According to McKinsey's Global Energy Perspective, hydrogen demand could reach 500–660 million tonnes per year by 2050, representing up to 22% of final global energy demand. The market for hydrogen and hydrogen-based fuels could generate over United States Dollar (USD) 2.5 trillion in annual revenues by mid-century.[17]

Markets and Markets (2024)[18] projects that the global hydrogen market, valued at USD 242 billion in 2023, will grow to over USD 410 billion by 2030, fueled by expanding applications in mobility, power generation, industrial feedstocks, and residential energy use. Significant regional developments are evident, with Europe, East Asia, and North America leading investments in green hydrogen projects, electrolyser manufacturing, and hydrogen refuelling infrastructure.[14]

Despite these promising trends, global studies indicate persistent challenges in aligning hydrogen supply with regional demands. Approximately 60% of optimal hydrogen production potentials are located in water-scarce regions, creating bottlenecks for scaling production sustainably.[14] Nevertheless, initiatives such as India's National Green Hydrogen Mission aim to position nations as global hubs for green hydrogen, with projected multi-billion-dollar investments and creation of millions of new green jobs.[19]

2.3 Policy drivers and industry outlook

Policy frameworks are pivotal in shaping the future of the hydrogen economy. Governments worldwide have introduced national hydrogen strategies, financial incentives, and regulatory measures to support the production, distribution, and utilisation of low-carbon hydrogen.[4,11] The EU's Hydrogen Strategy under the European Green Deal targets 40 Gigawatt (GW) of electrolyser capacity by 2030, while countries like Japan, Australia, and India are developing policy frameworks to boost hydrogen adoption across domestic and export markets.[19]

The industry outlook for hydrogen remains optimistic yet cautious. Cost reduction remains a key priority, with targets to bring the production cost of green hydrogen below USD 2 per kg by 2030.[13] Technological advances in electrolysers, fuel cells, hydrogen storage, and transport infrastructure are steadily improving hydrogen's competitiveness relative to fossil fuels.[13,15]

However, realising the hydrogen economy will require overcoming persistent barriers, such as high capital costs, limited infrastructure, and the environmental impacts of large-scale hydrogen production.[14] Strategic international collaboration, public-private partnerships, and robust carbon pricing mechanisms are recognised as essential for creating demand signals, de-risking investments, and accelerating the scaling of hydrogen technologies.[11,17] With increasing commitment from governments, industries, and investors, hydrogen is poised to become an indispensable pillar of the global clean energy transition, underpinning economic decarbonisation, energy security, and climate resilience by mid-century.

While national hydrogen strategies are often presented as strong transition enablers, historical evidence shows that policy announcements alone do not ensure timely or large-scale deployment. The credibility of such instruments depends on regulatory bindingness, secured financing, institutional capacity, and alignment with infrastructure readiness, as recent analyses highlight that many hydrogen roadmaps remain aspirational without robust demand mandates or carbon pricing mechanisms.[13,14] Deployment trajectories are highly sensitive to market design, grid expansion, and capital mobilization, meaning production targets may outpace infrastructure and demand absorption if not carefully phased.

Although green hydrogen is positioned as an important pillar of net-zero transitions, this review explicitly treats it as a selective decarbonization vector rather than a universal solution. Recent systems-level analyses demonstrate that hydrogen deployment is environmentally and economically justified primarily in hard-to-abate sectors such as steel, chemicals, long-haul transport, and seasonal energy storage, while its use in low-temperature heating or passenger mobility is often less efficient than direct electrification pathways.[13–15] In particular, lifecycle and supply demand assessments highlight that large-scale hydrogen expansion can introduce environmental trade-offs related to land use, water scarcity, and renewable electricity diversion, potentially undermining broader decarbonization objectives if applied indiscriminately.[14] These constraints are reflected in national strategies, including India's Green Hydrogen Mission, which prioritizes industrial applications over diffuse end-use of deployment, acknowledging both infrastructure limitations and resource competition.[20] Global readiness evaluations further emphasize that hydrogen should be strategically allocated where electrification is technically infeasible or economically prohibitive, rather than framed as a blanket substitute for fossil fuels.[21] Accordingly,

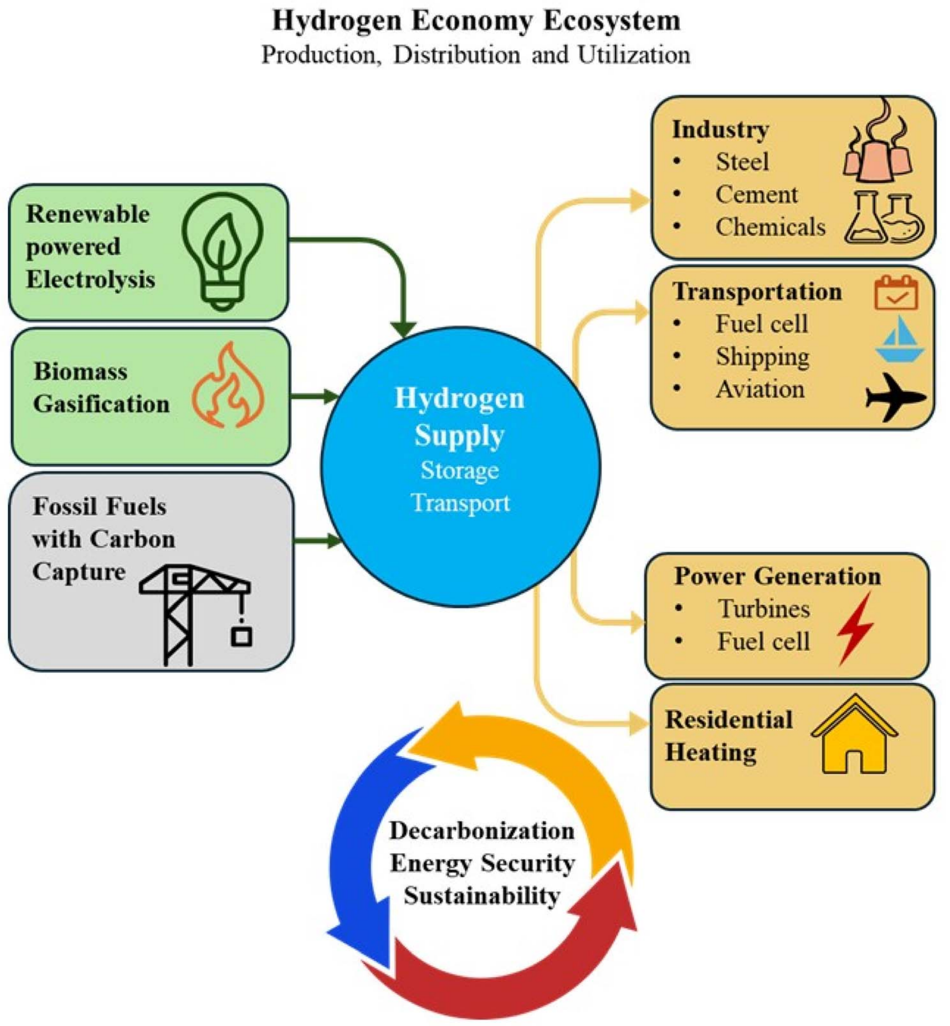

Fig. 2 Representation of the hydrogen economy ecosystem, highlighting production pathways, distribution networks, and diverse utilisation sectors that collectively enable decarbonisation and sustainable energy.[11,13,17]

this review consistently situates green hydrogen within a systems-integration framework, emphasizing targeted deployment aligned with sectoral suitability, resource availability, and life-cycle performance to avoid inefficient or counterproductive applications.

3. Strategic policy frameworks and global cooperation for hydrogen transition

3.1 India's green hydrogen mission

Launched in January 2023, India's National Green Hydrogen Mission (NGHM) is a landmark step toward energy self-reliance and climate neutrality by 2070. Spearheaded by the Ministry of New and Renewable Energy, it targets an annual production of 5 million metric tonnes (MMT) based on international demand. The mission focused on decarbonizing energy-intensive sectors like steel, fertilizer, petrochemicals, and heavy-duty transport while developing export markets.[20] The NGHM is built upon two strategic pillars funded by a ₹19 744 crore (∼USD 2.4 billion) allocation. The primary pillar, strategic Interventions for Green Hydrogen Transition, receives ₹17 490 crore to provide capital support for domestic electrolyser manufacturing and production incentives. The second pillar receives ₹1466 crore for pilot projects and ecosystem development, targeting and hydrogen hubs, R&D, supply chain expansion, and safety/purity standardization, with remaining funds earmarked for capacity-building. Operationally, India plans to develop regional hydrogen hubs near ports and resource-rich areas, utilizing public-private partnerships and Production-Linked Incentives (PLI) to encourage private participation. This strategy includes decentralized production *via* rooftop solar-electrolyser models and global hydrogen diplomacy through bilateral trade agreements with Europe, Japan, and the Middle East. Furthermore, India actively participates in the Green Hydrogen Catapult and the International Partnership for Hydrogen and Fuel cells in the Economy.[22,23] Despite this framework, the mission face critical hurdles in scaling electrolyser manufacturing, improving water use efficiency, establishing certification systems, and integrating hydrogen into existing power grids.

In India, although the NGHM provides structured incentives through the Strategic Interventions for Green Hydrogen Transitions programme (SIGHT) and production-linked mechanisms, the absence of binding domestic purchase obligation and firm offtake guarantees may slow industrial uptake in cost-sensitive sectors.[20] Policy credibility is strengthened when supply-side incentive is complemented by enforceable demand instruments, carbon pricing, and long-term contracting frameworks.[21] Without such alignment, capacity targets risk creating supply-side momentum without commensurate demand, potentially leading to underutilized assets.

3.2 International efforts

Green hydrogen has emerged as a central pillar of national energy transition strategies among advanced economies aiming for net-zero emissions by mid-century. The global policy ecosystem supporting green hydrogen scale-up (Fig. 3) outlines key policy levers across the value chain. The European Union (EU) demonstrated leadership through its EU Hydrogen strategy (2020), part of the European Green Deal, setting targets of 40 GW of renewable hydrogen electrolyser capacity within the EU and 40 GW in neighboring regions like North Africa by 2030.[24] The REPower EU plan intensified this focus to diversify energy mixes following the Russia-Ukraine conflict, supported by the innovation fund, Horizon Europe, and the connecting Europe facility. Additionally, the CertifHy system ensures transparency and enables cross-border trade.

In the United States, the Inflation Reduction Act of 2022 offers up to USD 3 per kg of clean hydrogen through the 45 V production tax credit. This is complemented by the Bipartisan Infrastructure Law's USD 8 billion allocation for Regional Clean Hydrogen Hubs. The Department of Energy's Hydrogen Shot initiative further targets reducing green hydrogen costs to USD 1 per kg within a decade through public-private partnerships and coordinated regional value chains.[25]

Japan, a pioneer in the hydrogen economy, announced its Basic Hydrogen Strategy in 2017. Unlike the EU and USA, Japan focuses on import-based supply chains from resource-rich countries while promoting domestic applications in fuel cell vehicles, stationary fuel cells, and thermal power co-firing. Japan targets a cost of USD 3 per kg by 2030.[26] Similarly, South Korea targets the deployment of 6.2 million hydrogen-powered vehicles and 1200 refueling stations by 2040, supported by strong public private partnerships.[27]

Other regions are aggressively pursuing development:

Australia: Envision becoming a leading export *via* mega-projects like the 26 GW Asian Renewable Energy Hub.[28]

Germany: Fosters domestic production and international cooperation, particularly with African nations, under its €9 billion strategy.

Middle East: Saudi Arabia's NEOM project serves as a flagship initiative for green hydrogen export.

China: Prioritizes industrial decarbonization and fuel cell vehicles within its 14th Five-Year-Plan (2021–2025).[28]

China currently holds a prominent position in global hydrogen production, with an annual capacity of approximately 41 million tons and an actual output of 33.42 million tons. However, the production structure is heavily reliant on fossil fuels, with coal gasification accounting for 63.54% of output, followed by industrial by-products (21.18%) and natural gas (13.76%), while water electrolysis constitutes only 1.52%. To align this industry with national objectives of peaking carbon emissions by 2030 and reaching neutrality by 2060, the China Hydrogen Alliance (CHA) implemented the standard and evaluation of low-carbon hydrogen, clean hydrogen and renewable hydrogen in December 2020. This framework utilizes a life cycle Assessment (LCA) methodology to quantify emissions and categorize hydrogen into three tiers: Low-carbon hydrogen, which requires a 50% reduction from the coal to hydrogen baseline (threshold of 14.51 kg CO_2 e per kg H_2), and clean or renewable hydrogen, which must meet a stricter threshold of 4.90 kg CO_2 e per kg H_2. By transitioning from qualitative color-based descriptions to these verifiable, data-driven benchmarks, China is establishing a technical foundation to shift its massive industrial energy demand toward sustainable, renewable-powered production pathways.[29]

Internationally, policy ambition frequently exceeds current deployment trajectories, with permitting delays, grid bottlenecks, and infrastructure financing gaps introducing multi-year lags between strategy formulation and implementation.[13,24] Moreover, large-scale hydrogen expansion interacts with land use, water availability, and renewable electricity allocation, potentially constraining deployment beyond projected timelines.[14] While China's lifecycle based hydrogen standards enhance enforceability and verification, effective implementation across jurisdictions ultimately depends on legally binding targets, secured funding, harmonized certification, and coordinated infrastructure planning.[21,24]

3.3 Policy incentives, roadmaps, and collaborations

Policy incentives and strategic roadmaps form the backbone of national efforts to develop viable green hydrogen economies, utilizing financial and regulatory support to address high costs and market immaturity. Capital subsidies for electrolyser manufacturing are prominent in the EU, US, and India to achieve economies of scale, while the U.S. Inflation Reduction Act provides transformative production tax credits to improve project financial viability.[11,24] Regulatory tools like hydrogen blending mandates in France and the UK stimulate early demand, while Carbon Contracts for Difference in Germany and the Netherlands de-risk investments by compensating for the gap between market prices and production costs. Facilitating cross-border trade, certification schemes like CertifHy in Europe and carbon intensity benchmarks in Japan and Australia define green hydrogen *via* lifecycle GHG emissions, with India developing a similar mechanism through the Bureau of Energy Efficiency.[24] Global development is further driven by multilateral initiatives like the Green Hydrogen Catapult,

Fig. 3 Global green hydrogen policy ecosystem, illustrating key policy levers required for scaling up green hydrogen production, distribution, and utilisation.[22,24,25]

Mission Innovation, and IRENA, alongside bilateral partnerships such as the Australia-Japan corridor, Germany-Morocco Power-to-X, and India's cooperation with the EU and UAE. However, notable policy gaps remain, including fragmented regulations, infrastructure lags in pipelines and storage, and high risks for first-of-a-kind projects. Achieving a mature, integrated economy will require continued regulatory innovation, harmonized certification, and the integration of green chemistry metrics such as process safety, life-cycle toxicity, and material circularity into future funding and standards. Table 1 compares major national green hydrogen strategies, highlighting targets, incentives, and flagship initiatives across countries.

4. Hydrogen colour codes: classification based on production source and carbon intensity

As hydrogen gains prominence in global decarbonization, a widely used classification system known as hydrogen colour codes has emerged to distinguish types based on feedstock, production method, and GHG emissions. This informal taxonomy is vital for policy, finance, and industrial decision-making, enabling stakeholders to evaluate the environmental impact of various pathways.[37] The most common categories are grey, blue, and green hydrogen; grey hydrogen, produced *via* SMR or coal gasification without carbon capture, dominates global production despite high emissions of 9–12 kg CO_2 per kg H_2.[37,38] In contrast, blue hydrogen utilizes fossil feedstock but integrates carbon capture, utilization, and storage (CCUS) technologies, which can theoretically reduce emissions by upto 90%, though upstream methane leakage and CCUS limitations may diminish its net climate benefits.[39]

In August 2023, India's Ministry of New and Renewable Energy (MNRE) formalized its National Green Hydrogen Mission by defining Green Hydrogen as having a well-to-gate emission threshold of no more than 2 kg CO_2 e per kg H_2 over a 12 month average. These standard covers both electrolysis and biomass-based production, accounting for the entire lifecycle from water treatment to final compression. By

Table 1 Comparative overview of major national green hydrogen strategies, highlighting targets, incentives, and flagship initiatives based on country-specific energy transition plans[22–25,30–36]

Country/region	Launch year	Main target (2030)	Key incentives	Notable initiatives	Policy credibility (funding + targets)	Enforceability (binding mandates, standards)	Temporal alignment with infrastructure	Current green hydrogen capacity (approx.)
India	2023	5 MMT green hydrogen production	Capital subsidies, manufacturing PLI	National green hydrogen mission	Moderate-high (NGHM funding committed)	Low-moderate (limited domestic offtake mandates)	Moderate	862 000 tonnes per annum (allocated under SIGHT programme, 2025)
EU	2020	40 GW electrolyser capacity	Innovation fund, REPowerEU funding	Hydrogen valleys, H2Med pipeline	High (innovation fund, REPowerEU)	Moderate (certification progressing, limited binding demand)	Moderate	2.84 GW under construction (2025)
USA	2022	$1 per kg green hydrogen cost target	Production tax credits	Regional clean hydrogen hubs	High (IRA tax credits, hydrogen hubs)	Moderate (market-driven uptake)	Moderate	1.74 GW operational and under construction electrolyser capacity (2024)
Japan	2017	Cost reduction to $3 per kg	R&D funding, infrastructure support	International hydrogen supply chains	Moderate-high (long-term strategy, sustained METI support)	Moderate (clear roadmap but limited binding domestic mandates)	Moderate (import-focused infrastructure developing gradually)	15 GW by 2030 (global deployment *via* Japanese-related companies)
Australia	2019	Green hydrogen export leadership	Grants, funding for mega-projects	Asian renewable energy hub	Moderate (export-oriented grants)	Low	Low-moderate	1 GW announced/under development (2024)
China	2022	100 000–200 000 ton per year by 2025	Manufacturing scale support, industrial integration	Hydrogen industry development report	High (large industrial base)	High (large industrial base)	Moderate	125 000 tonnes per year (completed green hydrogen projects by end 2024)

establishing this measurable benchmark and designating the Bureau of Energy Efficiency (BEE) as the certification authority, India has become a global leader in providing regulatory clarity for the clean energy sector.[40]

Green hydrogen is produced *via* electrolysis powered by renewable sources such as wind, solar, or hydropower and is regarded as the cleanest pathway, with lifecycle emissions typically below 1 kg CO_2 per kg H_2.[41] Variants like pink/purple hydrogen utilize nuclear-powered electrolysis for low emissions, while turquoise hydrogen employs methane pyrolysis to yield solid carbon instead of CO_2, though it remains at a low technology readiness level. Yellow hydrogen uses grid electricity *via* electrolysis, reflecting the existing energy mix, whereas the newly proposed cyan hydrogen integrates low-carbon ethanol and water through advanced thermal processes to valorize carbon into solid products.[42] Additionally, white hydrogen refers to naturally occurring geological deposits that remain largely untapped due to extraction and distribution challenges.[42] Despite its utility, this color-based taxonomy is increasingly criticized for lacking precision, promoting a shift toward carbon intensity-based labeling using quantified lifecycle emission thresholds to improve transparency and global alignment.[43] A comparative summary of hydrogen colours, production sources, and lifecycle emissions is provided in Table 2. A visual representation of the hydrogen colour spectrum is illustrated in Fig. 4.

Hydrogen colour codes offer a simplified framework for interpreting environmental performance and carbon impact based on production source. The detailed technological, economic, and environmental features of hydrogen production routes, including bio-based, electrolytic, and solar-assisted processes, are addressed in Section 5. From a green chemistry perspective, grey and blue hydrogen pathways conflict with the principle of avoiding hazardous substances and emissions. In contrast, green hydrogen adheres to these principles by eliminating toxic intermediates and prioritising environmental compatibility.

Current PEM electrolyzers rely on iridium-based oxygen evolution catalyst, with present day loadings corresponding to approximately 0.3–0.6 kg Ir per MW of installed capacity. Given global primary iridium production of only ∼7–8 ton per year, this implies that existing supply could support merely

Table 2 Classification of hydrogen based on energy source, production method, and carbon intensity, illustrating the diversity and maturity of each colour-coded[38,40,42,43]

Hydrogen type	Feedstock/energy source[a]	Production process	Carbon intensity	Technology status
Green	Solar, wind, hydropower	Electrolysis	<2 kg CO_2 per kg H_2	Growing/commercial
Yellow	Grid electricity (mixed source)	Electrolysis	Varies by grid mix	Commercial
Pink/purple	Nuclear electricity	Electrolysis	Very low (nuclear-dependent)	Niche/emerging
Blue	Natural gas with CCS	SMR + carbon capture	~1.5–4.5 kg CO_2 per kg H_2	Emerging/commercial
Grey	Natural gas or coal	SMR	~9–12 kg CO_2/kg H_2	Commercial
Turquoise	Methane	Methane pyrolysis	Solid C byproduct, low CO_2	R&D stage
Cyan	Ethanol + water	Hybrid pyrolysis + reforming	Low CO_2 + carbon valorisation	Lab-scale/emerging
Brown	Lignite coal	Coal gasification	Very high	No CO_2 capture
Black	Bituminous coal	Coal gasification	Very high	No CO_2 capture

[a] CCS – carbon capture and storage

~10–20 GW per yearr of new PEM electrolyzer deployment, even assuming complete diversion of iridium from competing industries. This contrasts sharply with hydrogen roadmaps targeting hundreds of GW to MTW capacities by mid-century. Recent system-level assessments therefore identify iridium availability as a binding constraint on large-scale PEM expansion unless catalyst loadings are reduced by an order of magnitude, recycling rates exceed ~90%, or alternative earth-abundant catalyst are commercialized. Although alkaline and Solid Oxide Electrolyser cell (SOEC) technologies reduce dependence on precious metals, they increase demand for nickel, zirconia, and rare-earth-containing ceramics, which face their own supply risks and competition from batteries and electronics. Consequently, long-term green hydrogen scalability must be evaluated through integrated energy-materials frameworks, elevating catalyst availability and circularity to first order constraints alongside electricity and water availability.[44,45]

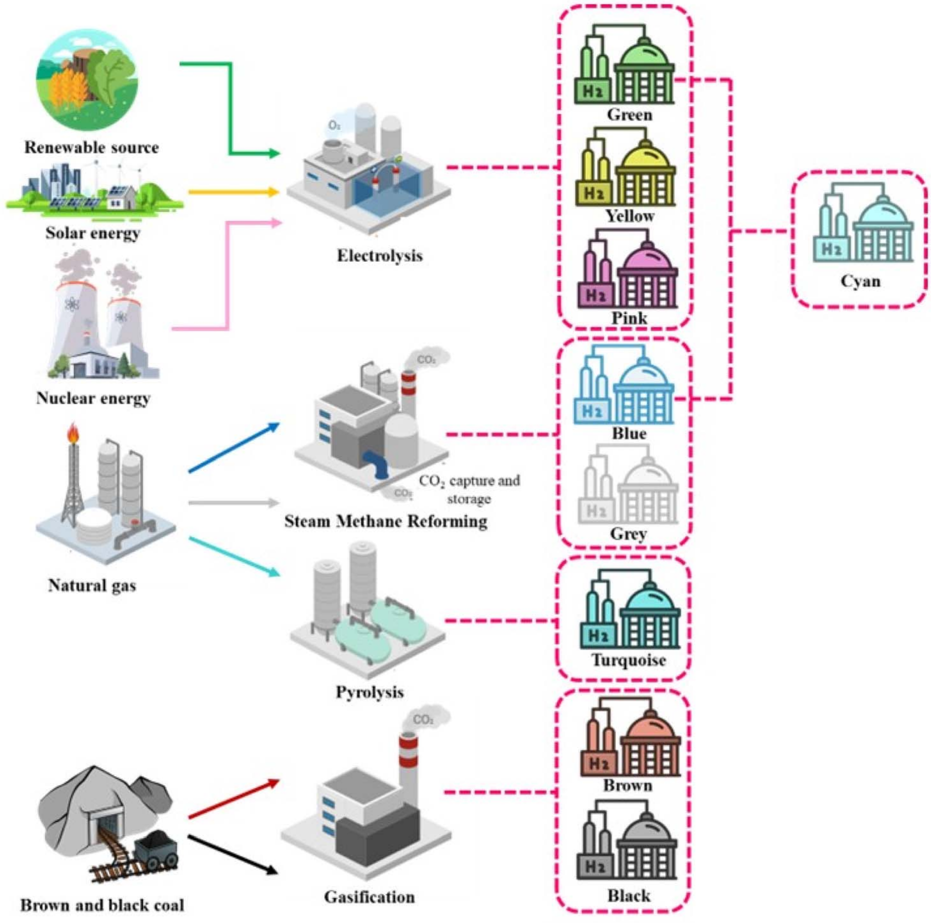

Fig. 4 Visual spectrum of hydrogen colour codes arranged by production source.[38,42]

The hydrogen production pathways discussed in this work span a wide range of Technology Readiness levels (TRLs), from commercially mature systems such as SMR and alkaline/PEM electrolysis (TRL 8–9) to laboratory and pilot-scale concepts including advanced Biophotolysis and emerging hydrogen variants (typically TRL ≤4–5). In accordance with the standardized TRL frameworks adopted by the International Energy Agency and Organization for Economic co-operation and Development, the inclusion of low-TRL concepts is intended solely for forward-looking systems assessments and should not be interpreted as implying near-term industrial relevance. Deployment feasibility in the coming decades is dominated by demonstrated scale, supply-chain maturity, bankability, and regulatory acceptance rather than theoretical performance metrics. Accordingly, comparisons involving low-TRL technologies are presented to illustrate potential long-term sustainability trajectories under future innovation scenarios, not as candidates for immediate commercialization.[46,47]

5. Hydrogen production routes

5.1. Conventional methods (from fossil fuels)

Hydrogen production is currently dominated by fossil-fuel-based technologies, which together account for approximately 95% of the global hydrogen supply. The key processes include SMR, partial oxidation (POX), autothermal reforming (ATR), coal gasification, and hydrocarbon pyrolysis (Fig. 5a–e). While these methods are economically mature and scalable, they are carbon-intensive and pose substantial environmental concerns unless integrated with CCS technologies.[9,48] Although conventional hydrogen production remains prevalent due to economic feasibility, these methods often contravene key green chemistry principles, particularly those aimed at minimising toxicity and waste. Consequently, transition strategies must prioritise greener and cleaner alternatives.

SMR is the most widely used hydrogen production method, contributing to over 45% of global supply.[48] It involves the endothermic reaction of methane with steam at 700–1000 °C in the presence of a nickel-based catalyst to produce syngas, followed by a water-gas shift reaction to maximise hydrogen output:

$$\cdot CH_4 + H_2O \rightarrow CO + 3H_2$$

$$\cdot CO + H_2O \rightarrow CO_2 + H_2$$

Despite its high hydrogen yield and technical maturity, SMR emits approximately 9–12 kg of CO_2 per kg of hydrogen produced, making it a key target for carbon mitigation strategies.[9] Recent innovations, such as membrane reactors and low-temperature reforming, aim to enhance energy efficiency and reduce emissions.[48]

POX involves the exothermic reaction of methane or heavier hydrocarbons with sub-stoichiometric oxygen to produce syngas. Although it requires pure oxygen thereby increasing costs), POX can process a broader range of feedstocks and offers greater sulfur tolerance than SMR.[9]

ATR combines the POX and SMR reactions in a single reactor, using the heat from oxidation to drive the endothermic reforming. This approach enables a more compact reactor design and achieves thermodynamic equilibrium without the need for external heating.[9]

Coal gasification converts coal into hydrogen and carbon monoxide at temperatures of 700–1200 °C using steam and oxygen. This process is widely used in coal-rich countries like China and India.[48] However, it results in high CO_2 emissions, making CCS integration essential. From an economic perspective, coal gasification benefits from lower feedstock costs but suffers from higher capital costs.[9]

Methane pyrolysis thermally decomposes natural gas into hydrogen and solid carbon without emitting CO_2. The reaction ($CH_4 \rightarrow C + 2H_2$) occurs at 500–800 °C and is increasingly considered a low-emission alternative to SMR and gasification. While still emerging, the process can yield valuable byproducts like solid carbon and avoids the need for CCS.[9,49]

Although fossil-based hydrogen technologies are commercially mature, their long-term sustainability is fundamentally constrained by high lifecycle greenhouse gas emissions and dependence on CCS effectiveness. Reported efficiencies often overlook upstream methane leakage and carbon pricing sensitivity, which significantly affect true climate impact. A rigorous lifecycle and techno-economic benchmarking approach is therefore essential to determine whether these routes represent transitional solutions or structural impediments to deep decarbonisation.

A comprehensive overview of key conventional hydrogen production technologies is presented in Table 3. Emerging methods include thermal cracking of hydrocarbons and the steam-iron process, which avoid direct CO_2 emissions by relying on intermediate redox reactions or high-temperature cracking.[50] These methods remain in the early stages of commercialisation.

5.2. Biohydrogen production routes

Biohydrogen production is a promising and sustainable pathway for green hydrogen generation, leveraging the metabolic versatility of microorganisms to convert renewable organic substrates such as biomass, wastewater, and industrial residues into hydrogen gas. Unlike conventional hydrogen production methods like SMR, biohydrogen systems can operate under milder environmental conditions and offer dual benefits of waste valorisation and carbon-neutral energy production.

Several biological pathways have been explored, with dark fermentation (DF) emerging as the most mature and widely implemented. In this anaerobic process, hydrogen-producing bacteria such as *Clostridium* spp., *Enterobacter* spp., and *Bacillus* spp. convert carbohydrates and organic wastes into molecular hydrogen and volatile fatty acids (VFAs). Reported yields typically range from 1.5 to 3.2 mol H_2 per mol of glucose, depending on factors such as microbial strain, substrate type, and operating conditions. Integrated into wastewater treatment

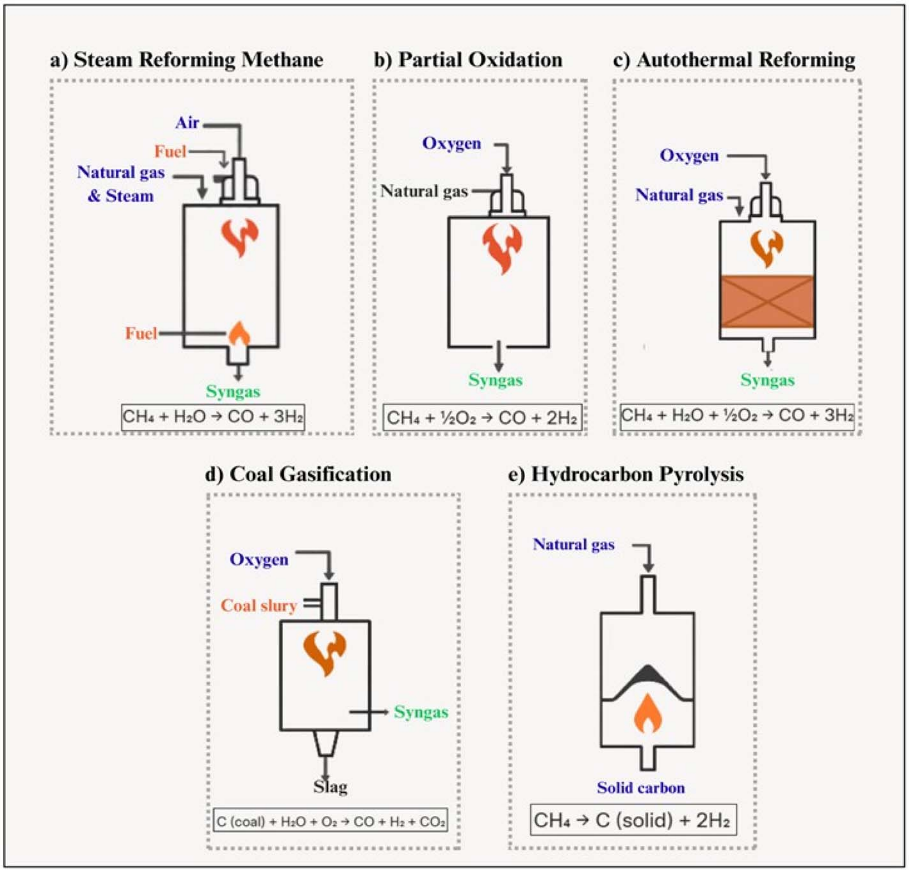

Fig. 5 (a) Steam methane reforming, (b) partial oxidation, (c) autothermal reforming, (d) coal gasification, and (e) hydrocarbon pyrolysis.

plants, DF can enhance energy recovery while achieving significant pollutant removal. For example, the fermentation of 1 kg Chemical Oxygen Demand (COD) can yield up to 0.42 m^3 H_2, with over 60% COD removal.[51]

Photofermentation (PF), by contrast, is a light-driven biological process that utilises purple non-sulfur bacteria like *Rhodobacter sphaeroides* and *Rhodopseudomonas palustris* to convert VFAs (produced during DF) into hydrogen. The theoretical hydrogen yield reaches up to 9 mol H_2 per mol of acetate under ideal conditions. However, practical applications are constrained by high light energy demand, slow bacterial growth, and the oxygen sensitivity of nitrogenase enzymes. Coupling DF and PF (DF + PF) in hybrid reactors has been shown to improve substrate utilisation and cumulative hydrogen yields, with total yields reaching 5–6.5 mol H_2 per mol substrate.[52]

Biophotolysis employs cyanobacteria and green microalgae to produce hydrogen *via* water splitting using sunlight. In direct biophotolysis, enzymes such as hydrogenase and photosystem II catalyse the reaction, while in indirect biophotolysis, photosynthesis produces organic compounds that are later fermented into hydrogen. Despite its conceptual elegance and low substrate requirement, hydrogen yields from biophotolysis remain modest up to 2 mol H_2 per mole of water, with practical

Table 3 Comprehensive overview of conventional hydrogen production technologies.[5,9,48]

Technology	Feedstock	Temp (°C)	Main products	Maturity	CO_2 emissions	Analysis
SMR	Natural gas (CH_4)	700–1000	$H_2 + CO + CO_2$	Commercial	High (8–12 kg per kg H_2)	Requires carbon capture, utilisation, and storage for decarbonisation
POX	Heavy oils, CH_4	>1000	$H_2 + CO$	Commercial	High	Needs pure O_2
ATR	$CH_4 + O_2$ + steam	>1000	$H_2 + CO + CO_2$	Early-commercial	Moderate	Combines SMR and POX
Coal gasification	Coal	700–1200	$H_2 + CO$	Commercial	Very high	Suitable for low-grade coal
Methane pyrolysis	CH_4	500–800	H_2 + solid C	Emerging	Low	Produces solid carbon, avoids CO_2

yields much lower due to enzyme inhibition by oxygen and low photon utilisation efficiency.[53,54]

Microbial Electrolysis Cells (MECs) represent a hybrid bioelectrochemical route in which electroactive microbes oxidise organic matter and transfer electrons to an anode. With an external voltage of 0.2–1.0 V, protons are reduced to hydrogen at the cathode. MECs treating wastewater or acetate-rich streams have achieved hydrogen production rates between 3.6 and 7.9 L H_2 per L per day, while simultaneously removing up to 80% of COD.[55] Although promising, MECs face scale-up challenges including electrode cost, system fouling, and energy input requirements.

Recent advances in synthetic biology have opened new avenues to engineer microbial strains for enhanced hydrogen metabolism. Genetically modified *E. coli*, cyanobacteria, and other hosts have been designed to reroute electron flows toward hydrogen production, bypassing native metabolic limitations. While these engineered systems exhibit high specificity and yield potential, challenges such as strain stability, cost, and regulatory acceptance remain under investigation.[54,56] A comparative summary of major biohydrogen production routes is in Table 4, and Fig. 6 provides a conceptual diagram of microbial hydrogen production pathways.

Biological hydrogen production technologies offer flexible, environmentally sound alternatives for sustainable hydrogen generation. While DF and PF are closest to field-scale application, MECs and engineered microbial systems are rapidly evolving. Continued progress in metabolic engineering, integrated bioreactor design, and renewable feedstock optimisation will be vital to improving process efficiency and supporting commercial viability. These biological routes align with green chemistry by valorising waste and operating under mild, non-toxic conditions.

Although biologically mediated hydrogen production aligns strongly with circular economy principles, most systems remain limited by low yields, scale-up complexity, and process instability. A rigorous comparison of energy balance, hydrogen productivity per reactor volume, and cost per kg hydrogen is necessary to evaluate realistic commercial potential. Without such benchmarking, claims of sustainability risk remaining conceptual rather than practical.

5.3. Electrolytic hydrogen

Electrolysis of water represents one of the cleanest and most sustainable pathways for hydrogen generation, especially when powered by renewable electricity sources like solar or wind. In this process, water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) using electrical energy, offering a zero-carbon route to produce high-purity hydrogen when integrated with green energy systems.

Several electrolysis technologies are commercially available or under active development, each differing in operating temperature, electrolyte type, cell architecture, efficiency, and technological maturity. The three primary electrolyser types are Proton Exchange Membrane (PEM) Electrolysers, Alkaline Electrolysers (AEL), Solid Oxide Electrolyser Cells (SOECs) (Fig. 7).

Electrolysers can produce hydrogen with purities exceeding 99.99% and are modular, allowing scalability for both industrial and distributed energy applications. However, each technology faces specific challenges, including cost, degradation rate, catalyst requirements, and complexity integration with variable renewable energy sources.[60,61] This section presents a comparative discussion of the three main water electrolysis technologies, PEM, AEL, and SOEC, in terms of their operating

Table 4 Summary of biohydrogen production routes from biomass and wastewater[a]

Route	Mechanism	Substrates	Key microorganisms	H_2 yield (mol mol^{-1} substrate)	Advantages	Limitations	References
DF	Anaerobic fermentation to H_2 and VFAs	Glucose, starch, wastewater	*Clostridium* spp., *Enterobacter* spp.	1.5–3.2	Simple, scalable, no light required	Inhibitory metabolites, modest yields	51 and 52
PF	Light-driven VFA conversion *via* nitrogenase	Acetate, lactate, butyrate	*Rhodobacter sphaeroides*, *R. palustris*	5–9	High theoretical yield, uses DF byproducts	Light-dependent, oxygen-sensitive enzymes	52 and 56
Biophotolysis	Water splitting using photosynthesis and hydrogenase	Water, CO_2	*Chlamydomonas reinhardtii*, *Anabaena* spp.	Up to 2 (theoretical)	Minimal feedstock, direct solar-to-H_2 pathway	Very low efficiency, oxygen inhibition	53 and 54
Microbial electrolysis	Electron-assisted H_2 generation with low voltage input	Acetate, glucose, was LCA to water	*Geobacter* spp., *Shewanella* spp.	3.6–7.9 L H_2 per L per day (volumetric)	High COD removal, suitable for wastewater	Needs electricity, scale-up constraints	52 and 55
Combined DF + PF	Two-stage system: DF generates VFAs, PF converts to H_2	Food/agro-waste, wastewater	Mixed microbial consortia	5.0–6.5	Maximised yield, improved waste valorisation	Complex operation, increased HRT	52 and 57
Engineered microorganisms	Genetic modifications to optimise hydrogen metabolism	Glucose, CO_2	GM *E. coli*, cyanobacteria	Variable (up to 4–5+)	High specificity, metabolic control	Strain stability, biosafety regulation	54 and 56

[a] HRT – hydraulic retention time.

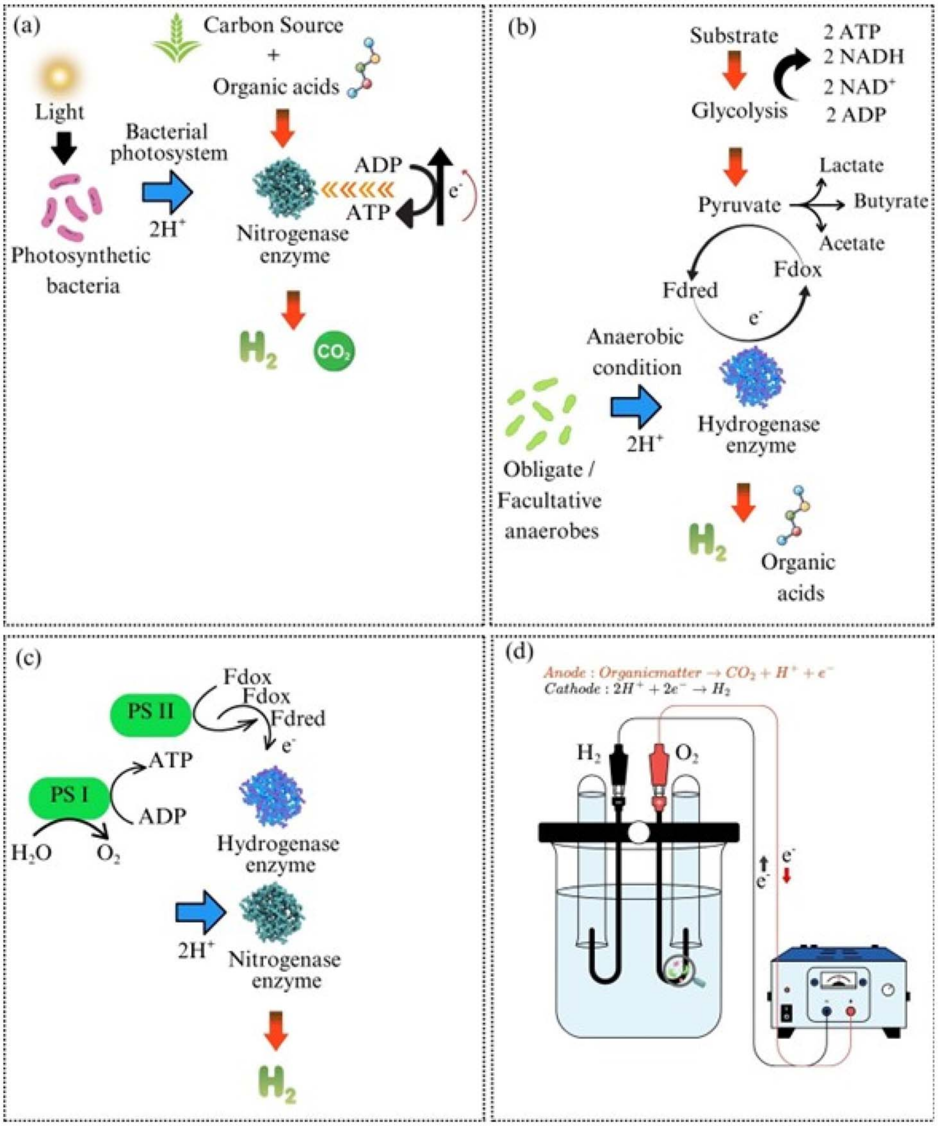

Fig. 6 Biological and bioelectrochemical hydrogen production pathways: (a) photobiological H_2 production by photosynthetic bacteria *via* nitrogenase using light and organic acids; (b) DF by anaerobes using hydrogenase to convert pyruvate to H_2 and organic acids; (c) biophotolysis in cyanobacteria/algae using photosystems and hydrogenase/nitrogenase for H_2 evolution; (d) microbial electrolysis cell generating H_2 *via* electrode-driven proton reduction using microbial metabolism.[58,59]

principles, performance, system integration potential, and techno-economic feasibility.

Electrolysis is central to long-term decarbonisation strategies; however, its sustainability depends heavily on electricity carbon intensity and grid stability. Cost reductions hinge more on renewable energy pricing than purely electrolyser efficiency gains. A comparative Levelised cost of Hydrogen (LCOH) sensitivity analysis across electricity price scenarios would significantly enhance critical depth.

5.3.1. PEM electrolysis. PEM electrolysis is a leading electrochemical pathway for green hydrogen production, offering several advantages over alkaline and solid oxide electrolysis, particularly in terms of high-purity hydrogen output, system compactness, and operational flexibility. In PEM systems, water is fed to the anode, where it splits into protons, electrons, and oxygen. Protons migrate through a solid polymer electrolyte to the cathode, where they recombine with electrons to form hydrogen gas.[62]

PEM electrolysers typically operate at temperatures between 20–80 °C and support current densities from 1 to 6 A cm^{-2}, with advanced systems achieving electrochemical (cell) efficiencies of up to 94% at a current density of $\sim$1 A cm^{-2}, corresponding to cell voltages as low as 1.567 V under optimized laboratory-scale conditions.[62,63] This value represents cell-level performance and does not account for balance-of-plant or auxiliary losses, which reduce overall system efficiency. The hydrogen produced can reach purity levels above 99.999%, making it suitable for fuel cells and other applications requiring ultrapure hydrogen.[63]

The core components of a PEM electrolyser include the membrane electrode assembly, bipolar plates, gas diffusion

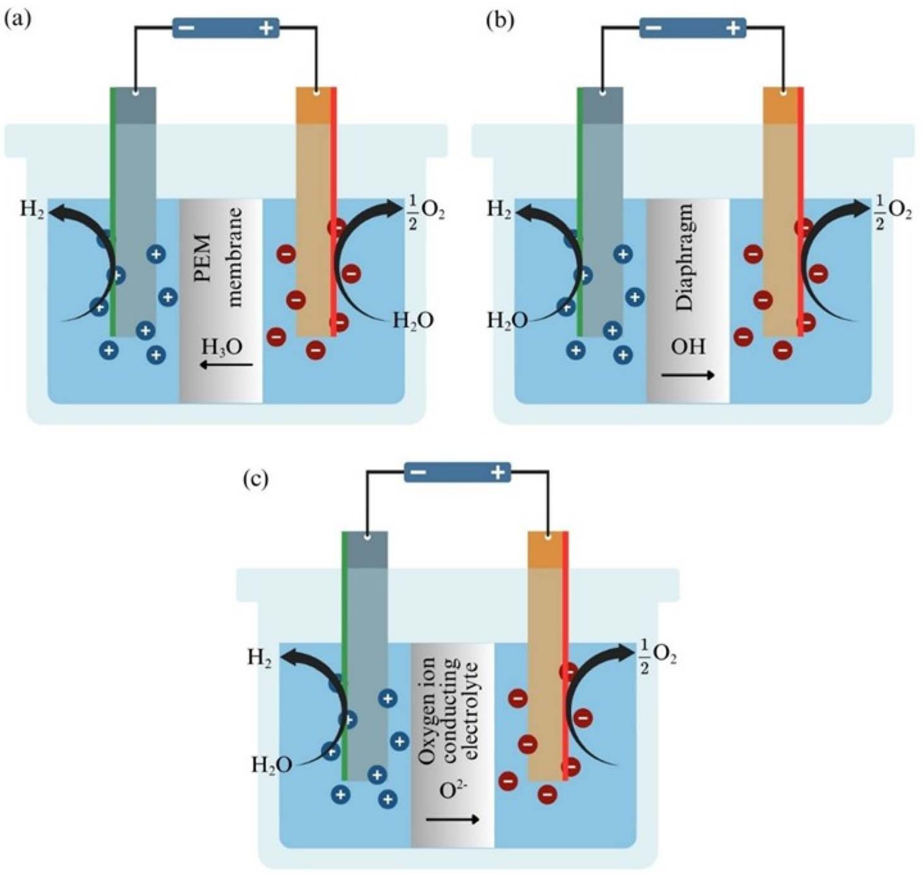

Fig. 7 Schematic of three primary electrolyser types: (a) PEM uses proton-conducting membrane, (b) alkaline electrolyser uses hydroxide ion conduction, and (c) solid oxide electrolyser cell uses oxygen ion-conducting electrolyte.

layers, and electrocatalysts. The membrane electrode assembly typically uses Nafion™ membranes for high proton conductivity and mechanical stability. Catalysts for the hydrogen evolution reaction (HER) are often platinum-based, while oxygen evolution reaction (OER) catalysts include iridium or ruthenium oxides. However, the high cost and limited supply of these noble metals present significant challenges for large-scale adoption.[64]

Economic assessments suggest the LCOH from PEM electrolysis is around USD 4.5–6.0 per kg under current grid-connected conditions but could fall to USD 1.4–2.5 per kg by 2035 with improvements in materials and renewable electricity integration.[65] Furthermore, PEM systems are well-suited for dynamic operation, enabling effective coupling with variable renewable energy sources such as wind and solar.[67] The main technical and economic parameters of PEM electrolysis systems, including temperature range, pressure capability, hydrogen purity, and LOCH, are summarised in Table 5. The emphasis on efficiency and clean inputs aligns with green chemistry principles, particularly the goal of developing safer and sustainable energy processes.

PEM systems offer dynamic operation advantages, yet dependence on scarce noble metals (Ir, Pt) presents supply chain risks. Catalyst loading reductions and recycling strategies are critical for scalability. Long-term degradation under intermittent operation remains a key research gap.

5.3.2. Alkaline electrolysis. Alkaline electrolysis, also known as Alkaline Water Electrolysis (AWE), is one of the most established and commercially available technologies for hydrogen production. It operates using an aqueous alkaline electrolyte, typically 20–30% KOH or NaOH and employs nickel-based or transition metal-based electrodes to drive the OER and HER.[66]

This technology has matured over more than a century. It is noted for its long system lifetime (up to 90 000 hours), use of non-noble metal catalysts, and ability to operate continuously at low cost. Industrial AWE systems typically operate in the 50–80 ° C range and at pressures up to 30 bar, with current densities ranging between 0.2 to 0.7 A cm^{-2} depending on the configuration and diaphragm type.[66] The electrochemical reactions occur at porous electrodes immersed in the electrolyte and separated by a diaphragm (*e.g.*, Zirfon Perl), which prevents product gas crossover while allowing OH^- ions to migrate between the anode and cathode.

Despite its advantages, AEL is limited by relatively lower efficiency at partial loads and slower system response, making it less suitable for highly fluctuating renewable energy sources. At low-load operation, AWE efficiency can drop below 30%, and

Table 5 Technical and economic features of PEM electrolysis systems

Parameter	Value/range	Remarks	References
Operating temperature	20–80 °C	Enables fast startup/shutdown	63
Operating pressure	Up to 200 bar	Eliminates need for post-compression	63
Current density	1–6 A cm^{-2}	Higher densities enable compact systems	62
Electrolyte	Solid polymer (*e.g.*, Nafion™)	High proton conductivity	64
Catalysts	Pt (HER), Ir/Ru (OER)	Noble metal cost is a key constraint	62
Hydrogen purity	>99.999%	Suitable for fuel cells and industrial use	63
LCOH (current estimate)	$4.5–6.0 per kg	Varies with electricity price and CAPEX	65
LCOH (2035 scenario)	$1.4–2.5 per kg	Based on reduced catalyst use and cheap renewable energy	65
Efficiency at 1 A cm^{-2}	Up to 94%	Cell (electrochemical) efficiency measured at lab scale; excludes balance of plant losses	62
System lifespan	40 000–80 000 hours	Dependent on catalyst stability and membrane durability	64

gas crossover can lead to dangerous hydrogen–oxygen mixtures.[67] Advanced control strategies such as multi-mode self-optimisation electrolysis have been proposed to address these issues by adapting power supply modes and improving consistency across cells, achieving efficiency above 53% at 15% rated load in laboratory trials.[67]

Catalyst development remains central to improving AEL improvement. Ni-based alloys, Raney nickel, and Ni–Mo and Ni–Fe composites are widely used. The OER, being kinetically sluggish, remains the principal bottleneck and has been the focus of research into Co-, Fe-, and Mn-based catalysts. Recent studies show that Fe-doped $Ni(OH)_2$ or Co-based Heusler compounds can substantially enhance activity and reduce overpotential, with theoretical OER activity following a volcano relationship with *e.g.* orbital occupancy.[66]

A detailed overview of AEL operating parameters, component materials, and economic performance is provided in Table 6. AEL remains a reliable and scalable technology for green hydrogen generation, particularly for baseload operations with renewable energy. Continued improvement in electrode materials, gas separation membranes, and flexible power operation strategies will be essential to overcome current limitations and enhance compatibility with variable energy sources. Its cost-effectiveness and system longevity make AEL an attractive technology for large-scale deployment in the near term.

AEL benefits from lower capital cost but lacks operational flexibility compared to PEM. Gas crossover at partial loads limits renewable coupling. Performance under fluctuating power inputs requires more extensive field validation to justify large-scale hybrid deployment.

5.3.3 Anion exchange membrane (AEM) electrolysis.

AEM water electrolysis utilizes a solid polymer membrane in a zero-gap configuration, enabling hydroxide (OH^-) transport between the electrodes.[68] This configuration has been demonstrated in small-area cells operating with alkaline electrolytes such as 1 M KOH, where stable performance was achieved under constant current operation over extended testing periods.[68]

Advanced AEM systems have demonstrated high current density operation. A laboratory scale system operating at elevated temperature achieved low cell voltage at high current density. In a renewable-integrated configuration, the electrolyzer model reported hydrogen production at the megawatt scale, demonstrating suitability for distributed energy applications.[69] Membrane selection plays a critical role in performance. An ultrathin A-901 membrane showed improved electrochemical performance compared to thicker commercial membranes when operated in dilute alkaline electrolyte. Long-term testing indicated low voltage degradation over continuous operation, and membrane thickness was shown to influence internal resistance and overall cell performance.[70]

AEM systems in the referred studies operated with dilute alkaline electrolytes including K_2CO_3 and KOH solutions.[69,71] Membrane properties such as ion-exchange capacity, ionic

Table 6 Key technical features of alkaline electrolysis systems[66,67]

Parameter	Typical value/range	Remarks
Operating temperature	50–80 °C	Moderate; promotes stable ion transport
Operating pressure	Up to 30 bar	Suitable for pipeline injection and storage
Current density	0.2–0.7 A cm^{-2}	Limited by gas crossover risk and membrane stability
Electrolyte	20–30 wt% KOH or NaOH	High ionic conductivity
Electrode materials	Raney Ni, Ni–Mo, Ni–Fe, stainless steel	Abundant and low-cost; good long-term stability
Separator	Zirfon Perl (porous diaphragm)	Prevents gas crossover, allows OH^- transport
Hydrogen purity	99.7–99.9%	Post-processing may be needed for fuel cells
LCOH (current estimate)	$4–5 per kg	Lower than PEM due to cheaper materials
LCOH (projected with RES coupling)	<$2.5 per kg	Possible with scale-up and hybrid RES use
System lifespan	60 000–90 000 hours	Long durability under steady operation

conductivity, area resistance, and specific resistance were evaluated to assess internal losses and hydrogen production performance. Functionalized membranes containing quaternary ammonium and 1,4-diazabicyclo[2.2.2] octane groups were investigated for their electrochemical behavior and hydrogen generation capability.[71]

AEM electrolysis promises reduced noble metal reliance; however, membrane chemical stability in alkaline environments remains a critical bottleneck. Long-term degradation mechanisms and carbonate formation under CO_2 exposure require systematic investigation before commercial competitiveness can be claimed.

5.3.4. Solid oxide electrolysis cell. SOECs are high-temperature electrochemical devices that convert steam into hydrogen and oxygen using electrical energy, often supplemented by thermal energy. Operating typically between 600–850 °C, SOECs are regarded as among the most energy-efficient water-splitting technologies due to the reduced electrical energy demand at elevated temperatures and enhanced electrode kinetics.[72,73]

Unlike alkaline or PEM electrolysers, SOECs employ a solid oxide ceramic, typically yttria-stabilised zirconia, which conducts oxygen ions (O^{2-}) from the cathode to the anode. At the cathode, steam is reduced to hydrogen and oxygen ions; the oxygen ions migrate through the electrolyte and are oxidised at the anode, releasing electrons to the external circuit.[74]

SOECs can theoretically achieve efficiencies above 90% when integrated with renewable or waste heat sources. For example, integration with solar thermal systems has demonstrated that the thermal energy input can significantly reduce the required electrical input.[72] Furthermore, hybrid SOECs using mixed ion conductors (proton and oxygen ion conduction) offer operation flexibility and higher current densities.[75]

A key limitation to widespread adoption is the material degradation under harsh redox conditions and thermal cycling. Prolonged operation can lead to delamination, increased ohmic resistance, and interfacial degradation between the electrode and electrolyte layers. Modelling studies indicate degradation rates of 0.3–0.5% per 1000 h, with economic feasibility heavily dependent on achieving extended durability.[75]

Recent research has focused on advanced perovskite-based cathode materials like $La_{0.7}Sr_{0.2}FeO_3$ and Ni-doped variants, which exhibit improved electrochemical stability and mixed ionic-electronic conductivity. These materials allow 100% faradaic efficiency at current densities above 10 mA cm^{-2}. Both U.S. DOE and EU programs are actively funding pilot-scale SOEC systems, aiming to achieve hydrogen production costs below USD 2 per kg by 2030.[74] The integration of thermal energy with efficient catalysis reflects green chemistry principles of energy and material conservation. A summary of the key technical parameters and performance indicators for SOEC systems, including efficiency, degradation rates, and life-cycle emissions under practical operating conditions, is presented in Table 7.

SOECs offer superior thermodynamic efficiency when integrated with waste heat, yet thermal cycling degradation limits operational lifetime. Economic viability is tightly linked to high-capacity utilization and stable heat sources. Durability improvements are essential to reduce lifecycle cost.

5.4. PC (photocatalytic)/solar hydrogen production

PC hydrogen production harnesses solar energy to split water into hydrogen and oxygen using semiconductor-based materials. This clean and sustainable approach mimics natural photosynthesis and has attracted considerable attention as a promising route for decentralised green hydrogen generation.[76,77] Photocatalysis offers a decentralised and low-toxicity pathway aligned with green chemistry principles, eliminating the need for external electricity input to drive the primary water-splitting reaction, avoiding expensive electrochemical hardware. Instead, it relies on the solar excitation of electrons within the photocatalyst. However, it is important to note that in practical, large-scale reactor configurations, auxiliary electrical energy remains necessary to power peripheral components such as circulation pumps, stirrers, and control systems[78] to maintain optimal reaction conditions.

The process is generally categorised into three pathways: PC, photoelectrochemical (PEC), and photovoltaic-electrochemical (PV-EC) systems. PC systems are the simplest, using powdered or immobilised semiconductor photocatalysts suspended in water. In contrast, PEC uses a light-absorbing photoelectrode and PV-EC couples a photovoltaic panel to a conventional electrolyser. Among these, PC systems are notable for their structural simplicity and potential for low-cost scale-up, although they typically exhibit low solar-to-hydrogen (STH) conversion efficiency, often below 2%.[76,79]

Recent advances in photocatalysis hydrogen production have focused on bandgap engineering, heterojunction formation, cocatalyst decoration, and improvements in reactor design. For example, Domen's group has reported apparent quantum efficiencies of up to 30% for $SrTiO_3$-based photocatalysts under UV irradiation, although performance remains limited under full-spectrum sunlight.[77] Novel *Z*-scheme designs, which spatially separate HER and OER into different compartments using redox mediators like I^-/I_3^-, have achieved up to 2.47% STH in laboratory conditions and 1.21% under natural sunlight in scaled-up systems over 692.5 cm^2.[82]

Photoreforming, which utilises organic wastes such as alcohols or biomass derivatives in place of pure water, offers another promising approach. In these stems, organic compounds act as sacrificial electron donors, lowering the required Gibbs free energy requirement for the oxidation half-reaction and improving hydrogen yields.[76] An emerging subfield focuses on seawater photocatalysis, which tackles freshwater scarcity by directly using saline water. While promising in theory, challenges such as chloride-induced photocorrosion, selectivity issues, and photoanode stability still hinder practical deployment.[81]

Despite promising pilot-scale demonstrations, practical deployment of solar hydrogen technologies remains constrained by the low STH efficiency (target >10% for commercial viability), photocatalyst stability, and economic viability. For example, current large-scale Photocatalytic systems reach only 0.76% STH on 100 m^2 panel reactors, as demonstrated by Nishiyama *et al.* (2021), indicating that substantial progress is still needed. A comparison of major PC hydrogen production

Table 7 Technical comparison of solid oxide electrolysis cell performance metrics

Parameter	Value/range	References
Operating temperature	600–850 °C	72
Electrical efficiency	75–85% (up to 90% with heat)	73
H_2 production rate	70 L min^{-1} at 1.8 V (pilot stack)	72
Degradation rate	0.3–0.5% per 1000 h	75
Faradaic efficiency (Ni-doped)	∼100%	74
LCOH	\$2.78–11.67 per kg H_2	75
CO_2 emissions (life-cycle)	1.6–3.6 kg CO_2 per kg H_2 (low grid)	75

strategies, their efficiencies, and technical features is summarised in Table 8. The basic principles and configurations of PC, PEC, and PV-EC systems are illustrated in Fig. 8.

Photocatalytic systems remain constrained by low STH efficiency and photocatalyst instability under real sunlight conditions. Reported laboratory efficiencies often rely on UV-rich illumination, limiting real-world translation. A standardized reporting framework comparing AM 1.5 G conditions and durability metrics would improve critical robustness.

5.5. Glycerol reforming and other novel pathways

The valorisation of glycerol, a by-product of biodiesel production, into hydrogen presents a compelling alternative for sustainable fuel generation. Glycerol accounts for roughly 10% of biodiesel output and, due to oversupply and declining prices, has become an economical feedstock for hydrogen production.[83] Such valorisation of industrial by-products directly supports the green chemistry principle of waste minimisation and feedstock circularity.

Among the most prominent methods is steam reforming of glycerol. This process typically operates at 600–850 °C over Ni-based catalysts and involves glycerol reacting with water vapor to yield hydrogen, CO, and CO_2. For example, González *et al.* (2023)[84] reported that in a pilot-scale reactor, hydrogen yields were maximised at 850 °C using La_2O_3 and NiO catalysts, achieving H_2/CO ratios suitable for downstream applications. However, catalyst deactivation and coke formation remain significant challenges.[84]

Another innovative route is chemical looping steam reforming (CLSR), in which oxygen carriers like NiO–Fe_2O_3/Al_2O_3 enable cyclic oxidation and reduction reactions, allowing autothermal operation without external oxygen input. Li *et al.* (2022)[85] demonstrated that CLSR achieved hydrogen selectivity of above 85% and H_2 content above 78% under optimised conditions (600 °C, S/C = 1.0). This system offers reduced energy consumption and enhanced carbon management through internal redox cycling.

Aqueous phase reforming is also gaining traction for the valorisation of glycerol-rich wastewater. Operating under milder temperatures (200–300 °C), this process enables hydrogen generation in liquid-phase reactors. Di Nardo *et al.* (2024)[83] highlighted that sodium metaborate used as a reaction partner achieved over 55% hydrogen selectivity from crude glycerol, while simultaneously yielding value-added liquid products like 1,2-propanediol and acetic acid. This aligns with circular economy objectives by recovering chemicals and energy from waste.

Dry reforming of glycerol and supercritical water reforming are additional pathways under investigation for their high H_2/CO ratios and favorable thermodynamic efficiency, albeit under more extreme conditions (T > 700 °C, high pressure). These methods still face hurdles in scalability and corrosion control.[86]

Electrocatalytic glycerol reforming has gained attention as an alternative hydrogen production strategy in which glycerol oxidation replaces the oxygen evolution reaction at the anode, thereby lowering the overall energy requirements for electrolysis. In alkaline electrolyzers, glycerol oxidation proceeds at significantly lower potentials than water oxidation, enabling hydrogen evolution at the cathode with reduced cell voltage while simultaneously converting glycerol into value-added oxygenated products such as glyceric and glycolic acids. This approach leverages the high availability of glycerol as

Table 8 Key performance metrics of different PC hydrogen production systems, including lab-scale STH efficiencies, catalyst types, and application-specific challenges

PC strategy	STH efficiency (lab scale)	Key materials/features	Challenges	Source
Overall water splitting photocatalysis	0.5–2.0%	$SrTiO_3$, TiO_2, $BiVO_4$, g-C_3N_4	Bandgap mismatch, recombination, slow OER	76 and 77
Z-scheme PC (dual cells)	Up to 2.5%	$MoSe_2$/perovskite (H_2), $BiVO_4$/LDH (O_2)	Complexity, redox mediator loss	80
Organic photoreforming	3–9.2% (peak)	Alcohols, biomass; Pt/TiO_2, CdS-based catalysts	Product separation, CO_2 byproducts	76
Seawater splitting	<1%	Modified TiO_2, carbon-based composites	Photocorrosion, low selectivity, scaling	81
Panel reactor (100 m^2)	0.76% (real sun)	$SrTiO_3$: Al sheets, polyimide separation membrane	Low efficiency, gas recovery limitations	82

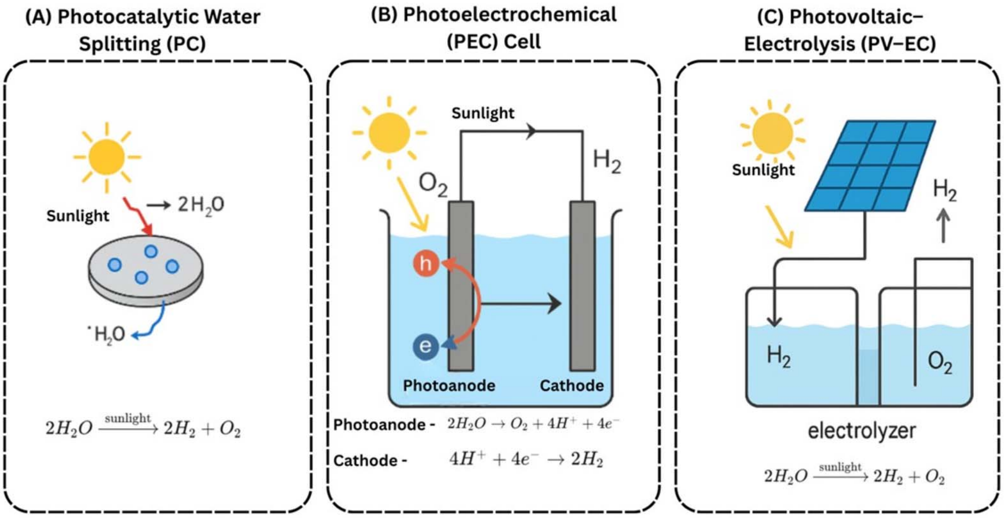

Fig. 8 Overview of three major solar hydrogen production methods: (A) PC water splitting, (B) PEC cell, and (C) Photovoltaic-powered electrolysis (PV-EC).

a biodiesel by-product and avoids CO_2 formation during oxidation, positioning the process as a potentially carbon-negative route for green hydrogen production. The electrochemical and glycerol conversion experiments were conducted at room temperature (approx. 25 °C). The system utilizes an alkaline medium, specifically a 1.0 M KOH electrolyte solution, to facilitate the reaction.[87] By using palladium nanotube catalysts in 1 M KOH, this process reduces the voltage needed for hydrogen production from 1.5 V to just 0.40 V. This efficiency lowers energy consumption to 3.7 kWh m^{-3} of H_2 significantly less than standard water electrolysis. The system simultaneously converts 85% of waste glycerol into valuable chemicals like glyceric and glycolic acids while maintaining stable, carbon-negative operation for over 120 hours.[87]

Glycerol reforming presents strong circular economy potential, yet hydrogen economics depend on biodiesel market dynamics and catalyst longevity. Coke formation, corrosion, and separation costs remain key barriers. A comparative life-cycle carbon and cost analysis *versus* conventional reforming is necessary to determine its strategic importance rather than niche applicability.

The glycerol reforming landscape is rapidly evolving, driven by advances in catalysis, reactor engineering, and system integration aimed at overcoming economic and technical bottlenecks. A detailed comparison of major glycerol reforming technologies is presented in Table 9.

5.6. Summary of advancements and challenges

The hydrogen production landscape is undergoing a transformative shift from conventional fossil-fuel-based processes toward renewable and sustainable technologies. While conventional methods such as SMR, POX, and coal gasification dominate global production due to their economic viability and scalability, they are inherently carbon-intensive. SMR alone accounts for over 45% of global hydrogen supply and emits 9–12 kg of CO_2 per kilogram of hydrogen produced, making it a key target for decarbonisation through CCS.[9,48]

Alternative thermochemical methods like methane pyrolysis offer low-emission routes without direct CO_2 release, producing solid carbon as a byproduct. However, this route remains at a relatively early stage of commercial development and requires high-temperature reactors and robust carbon separation systems.[9,49]

Biological hydrogen production pathways such as DF, PF, MECs, and biophotolysis leverage organic waste and microbial metabolism for hydrogen generation. DF stands out as the most mature, achieving yields of 1.5–3.2 mol H_2 per mol glucose and COD removal efficiencies exceeding 60% during wastewater treatment.[51] PF using purple non-sulfur bacteria can improve overall yield potential, but is limited by oxygen sensitivity and dependence on light.[52] Biophotolysis, despite minimal feedstock requirements, suffers from low practical hydrogen output due to the oxygen inhibition of hydrogenase enzymes.[53,54] MECs, which integrate microbial processes with electrochemical hydrogen recovery, have achieved production rates up to 7.9 L H_2 per L per day while removing significant organic load from wastewater, though scale-up challenges remain.[55]

Electrolytic water splitting technologies such as PEM electrolysis, AEL, and SOECs provide clean, electricity-driven production routes. PEM electrolysers offer compact, modular systems capable of operating at high current densities and producing ultra-pure hydrogen (>99.999%), though reliance on expensive catalysts such as platinum and iridium is a major limitation.[62–64] AEL offers a more cost-effective alternative using non-noble metal catalysts and robust systems, although it struggles with dynamic load operation and gas crossover risks.[66,67] SOECs, operating at 600–850 °C, achieve exceptional electrical efficiency by utilising thermal energy to reduce power input, yet are constrained by material degradation and high costs associated with high temperature operation.[72,74,75]

Table 9 Comparison of glycerol reforming technologies for hydrogen production, highlighting key operational conditions, catalysts, hydrogen yields, advantages, and challenges

Reforming method	Temp (°C)	Catalyst/material	H_2 yield/selectivity	Key advantages	Limitations	Reference
Steam reforming	700–850	Ni/La_2O_3, Ni/Y_2O_3–ZrO_2	75–90% conversion, high H_2	High H_2 yield, proven at pilot scale	Coke formation, catalyst sintering	84
Chemical looping (CLSR)	~600	NiO–Fe_2O_3/Al_2O_3 OCs	78.4% H_2 content, 85% select	Auto thermal, no direct oxygen required	Complex carrier regeneration	85
Aqueous phase reforming	200–300	$NaBO_2$ with crude glycerol	55% H_2 selectivity	Mild conditions, produces value-added co-products	Reactor corrosion, lower yields	83
Supercritical water reform	>374	Ni-based	High, variable	High efficiency, full conversion	Harsh conditions, high pressure	88

PC and solar hydrogen production technologies, particularly PC, PEC, and PV-EC systems, offer promising long-term decentralised solutions by directly harnessing solar energy. Despite their potential, current PC systems typically exhibit STH efficiencies below 2%, with pilot-scale demonstrations achieving only 0.76% on a 100 m^2 reactor under real sunlight.[76,77,82] Advanced designs such as *Z*-schemes and photoreforming using organic substrates have achieved over 2.5% STH under laboratory conditions.[80] Still, challenges such as catalyst stability, oxygen evolution efficiency, and seawater compatibility persist.[81]

A comparative summary of the major hydrogen production technologies, their key advancements, and associated challenges is presented in Table 10. Collectively, these emerging hydrogen technologies demonstrate a clear transition toward the foundational principles of green chemistry.

When scaled beyond pilot installations, water availability emerges as a first-order constraint for green hydrogen deployment, rather than a secondary operational challenge. Life-cycle inventory data show that production of 1 kg H_2 requires approximately 18 kg of deionized water for PEM electrolysis, ~9 kg per kg H_2 for SOEC, ~305 per kg H_2 for biomass gasification, and ~104 kg per kg H_2 for dark fermentation microbial electrolysis pathways, while even conventional SMR consumes ~22 kg water per kg H_2. Although the stoichiometric requirement of electrolysis is only ~9 kg water per kg H_2, upstream purification, cooling, and electricity generation substantially increase life-cycle water consumption. At industrial scale, a 1Mt H_2 per year green hydrogen facility would therefore require approximately 9–18 million m^3 of high-quality water embedded in electricity supply chains. This corresponds to 25 000–50 000 m^3 day^{-1}, comparable to the municipal water demand of a medium-sized city.

Consequently, in arid and semi-arid regions, large-scale green hydrogen production competes directly with drinking water, agriculture, and industrial users, elevating freshwater availability to a primary siting and scalability criterion alongside renewable electricity access. These findings imply that meaningful deployment in water-scarce regions is only realistic with parallel integration of non-freshwater sources (*e.g.*, desalination or treated wastewater), high-efficiency electrolyzers such as SOEC, and coordinated water energy planning frameworks; otherwise, water scarcity is likely to become a limiting factor of comparable importance to power availability.[89]

Reported cost targets for green hydrogen are highly contingent on a narrow set of favorable techno-economic assumptions and therefore exhibit strong sensitivity to real-word market conditions. System-level assessments show that levelized hydrogen cost is dominated by electrolyzer utilization rate, electricity price, and weighted average cost of capital (WACC), with electricity alone typically contributing 50–70% of total production cost. Scenario analysis by the IEA demonstrates that achieving sub-USD 2 $kg^{-1}H_2$ generally requires renewable electricity below ~20–25 USD MWh^{-1}, electrolyzer capacity factors exceeding 50–60% and low-risk financing environments (WACC ≤6–8%). Conversely, modest deviations from these conditions such as intermittent renewable supply without grid balancing, capacity factors below ~30%, or capital costs exceeding ~10% rapidly increase production costs above USD 4–6 per kg, rendering green hydrogen uncompetitive relative reforming or alternative electrification pathways. Similar conclusions are reported in techno-economic sensitivity studies, which show that a 10% reduction in capacity factor or a 5% increase in WACC can raise hydrogen costs by 20–40%, even before accounting for transmission, storage, or policy uncertainty. These findings indicate that widely cited cost targets are achievable only under optimized deployment scenarious combining high utilization, low-cost electricity, and concessional financing, and should therefore be interpreted as conditional outcomes rather than universally attainable benchmarks.[90–92]

6. Hydrogen storage technologies

The successful deployment of hydrogen as a clean energy vector critically depends on the development of safe, efficient, and cost-effective storage technologies. Due to hydrogen's low volumetric energy density under standard conditions, diverse storage methods have been developed to meet the requirements of various applications, ranging from vehicular fuel systems to stationery and grid-level energy storage. Broadly, these technologies are categorised into physical storage (gaseous, liquid, and cryo-compressed forms), chemical storage (metal hydrides, chemical hydrides, complex hydrides,

Table 10 Comparative summary of hydrogen production technologies

Technology	Maturity level	Key advancements	Major challenges	H_2 yield/efficiency	Thermodynamic considerations	Sources
SMR	Commercial	Low-temp reforming, CCS integration	High CO_2 emissions	~70–85% efficiency; ~9–12 kg CO_2 per kg H_2	Endothermic requires high heat input (800–1000 °C)	9 and 48
Methane pyrolysis	Emerging	Solid carbon byproduct	High temps, scalability	~75–85% efficiency	Strongly endothermic >1000 °C needed	9 and 49
DF	Pilot-scale	Wastewater integration, co-culturing	Low yields, VFA inhibition	1.5–3.2 mol H_2/mol glucose	Exergonic under anaerobic conditions; limited by thermodynamic shift due to H_2 partial pressure	51
PF	Lab-scale	DF + PF hybrid systems	Light dependency, oxygen sensitivity	Up to 9 mol H_2/mol acetate (theoretical)	Driven by light energy; near thermodynamic maximum under ideal photon flux	52
Biophotolysis	Lab-scale	Cyanobacterial water splitting	Oxygen inhibition of hydrogenase	Up to 2 mol H_2/mol H_2O	Overall endergonic; requires photon energy	53 and 54
MEC	Pilot-scale	Bioelectrochemical hybridisation	Energy input, system fouling	3.6–7.9 L H_2 per L per day; ~80% COD removal	Requires external voltage to overcome thermodynamic barrier	55
AEM electrolysis	Pilot-scale	Utilization of non-precious metal catalysts (Ni, Fe) and inexpensive hydrocarbon membranes	Chemical degradation of membranes/inomers; lower current densities compared to PEM	~73% overall efficiency; performance varies significantly with electrolyte concentration	Lower overpotential in alkaline medium	68 and 70
PEM electrolysis	Scaling-commercial	High purity H_2, fast response	Catalyst cost, membrane durability	>99.999% purity; 4.5–6.0 $ per kg H_2 (current)	Theoretical efficiency 80%; practical losses from overpotentials and ohmic resistance	62 and 63
AEL	Commercial	Long lifespan, low-cost materials	Gas crossover, slow response	63–70% efficiency; up to 90 000 h lifespan	Similar thermodynamics to PEM; higher ohmic losses due to liquid electrolyte	66 and 67
SOEC	Demonstration	High efficiency with heat integration	Thermal cycling, electrode degradation	life>90% (theoretical); degradation ~0.3%/1000 h	Operates at 700–850 °C; part of supplied heat, reducing electrical demand	72, 74, and 75
Photocatalysis	Lab/pilot	Bandgap tuning, *Z*-schemes, photoreforming	Low STH, catalyst instability	0.5–2.5% STH; 0.76% at 100 m^2 scale	Solar-driven process; limited by thermodynamic and recombination losses	76, 77, 80, and 82

liquid organic hydrogen carriers (LOHCs), and ammonia), and physical adsorption-based storage using porous materials such as metal–organic frameworks (MOFs), covalent organic frameworks (COFs), and carbon-based frameworks. Each technology presents unique trade-offs between energy density, operating conditions, cost, and safety, as illustrated in Fig. 9. Designing safe, recyclable, and low-toxicity storage materials aligns with green chemistry's objective of creating inherently safer chemical systems.

6.1. Gaseous and liquid storage

Hydrogen's low volumetric energy density under ambient conditions presents significant storage challenges, which are critical to the widespread adoption of hydrogen energy systems. Among the physical storage technologies, compressed gaseous hydrogen (CGH_2) and liquefied hydrogen (LH_2) are the most mature and widely adopted.

Compressed hydrogen gas is typically stored at pressures of 350–700 bar using specialised pressure vessels. These are classified into four types according to their construction materials. Type I vessels are all-metal and relatively heavy, making them more suitable for stationary applications. In contrast, Type IV vessels, constructed entirely of composite materials with a polymer liner, are lightweight and well-suited for vehicular storage. Although hydrogen's gravimetric energy density is high (about 120 MJ kg^{-1}), its volumetric energy density remains low (~5.6 MJ L^{-1} at 700 bar), necessitating high compression to achieve practical storage capacities.[93,94]

LH_2 is stored at cryogenic temperatures of around −253 °C, offering a higher volumetric energy density (~8.5 MJ L^{-1}) compared with compressed gas. However, the liquefaction process is energy-intensive, consuming about 10–15 kWh per kg per LH_2, and it is subject to boil-off losses during storage and transport.[95] To address these challenges, innovations such as

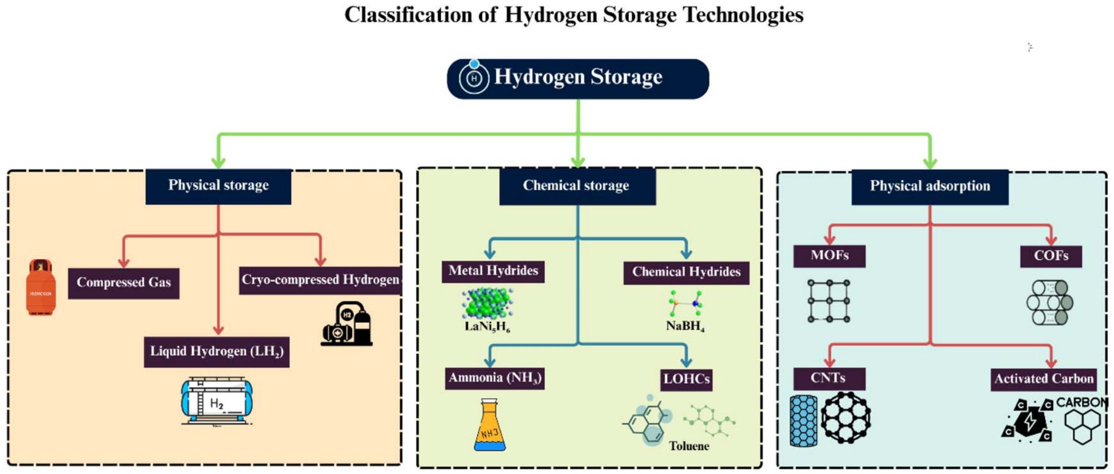

Fig. 9 Overview of hydrogen storage technologies classified by storage principle (physical storage, chemical storage, physical adsorption).

mixed refrigerant cycles, cascade liquefaction, and cold energy recovery from liquefied natural gas are being explored to reduce energy consumption and improve overall efficiency. The economic viability of LH_2 improves at large production scales (>100 TPD), with costs projected to drop below USD 2 per kg in optimised systems.[93] Cryo-compressed hydrogen, a hybrid approach combining compression and cryogenic storage, offers benefits such as reduced boil-off and higher density, but remains in the developmental stage.[93]

From a safety perspective, high-pressure gas storage remains the widely adopted method globally, particularly in fuel cell vehicles, while LH_2 is favoured in aerospace applications where energy density is paramount.[94] Novel methods such as gravel-pipe storage in lakes are also being investigated as region-specific, cost-competitive alternatives, with projected levelised costs of USD 0.17 per kg at 200 m depth.[95] Table 11 presents a comparative analysis of key parameters associated with gaseous and liquid hydrogen storage systems.

6.2. Chemical storage

Chemical hydrogen storage systems store hydrogen in the form of chemical compounds, releasing it through thermal or catalytic decomposition. Unlike physical storage (compressed or LH_2), chemical methods offer the potential for high hydrogen densities, safer handling, and compatibility with decentralised energy systems. However, they face challenges related to reversibility, regeneration, and energy efficiency.

Metal hydrides are among the most extensively studied reversible chemical hydrogen storage materials. For example, MgH_2 has a theoretical hydrogen capacity of 7.6 wt%, while other systems such as $NaAlH_4$ and Mg_2FeH_6 provide gravimetric densities in the range of 5–6 wt% with superior volumetric energy densities up to 130 g H_2 per L. These hydrides operate at elevated temperatures (200–400 °C) and typically require activation with transition metal catalysts (*e.g.*, Ti, Nb) to improve desorption kinetics.[94,96]

Complex hydrides, such as borohydrides and alanates, offer even higher hydrogen capacities. $LiBH_4$, for instance, can store up to 18 wt% hydrogen, while $Mg(BH_4)_2$ stores around 14 wt%. However, these materials generally require temperatures above 300 °C for hydrogen release and are mostly irreversible in practice without significant energy input for regeneration.[7,96]

Chemical hydrides, such as $NaBH_4$ and NH_3BH_3, undergo hydrolysis or thermal decomposition to release hydrogen. $NaBH_4$ has a theoretical hydrogen yield of 10.8 wt%, can release hydrogen in aqueous solution with the aid of a catalyst. Still, the hydrolysis process is irreversible, and regeneration of the spent material remains energy-intensive. NH_3BH_3 possesses one of the highest hydrogen contents (19.6 wt%) and decomposes between 60–120 °C but generates undesirable byproducts such as borazine.[93]

LOHCs are a class of hydrogen storage media that reversibly absorb and release hydrogen *via* catalytic hydrogenation and dehydrogenation reactions. Representative LOHC systems such as *N*-ethylcarbazole, toluene, and dibenzyl toluene store hydrogen in liquid form at ambient pressure, offering gravimetric hydrogen capacities of 5–7 wt%. The dehydrogenation process typically requires temperatures of 180–300 °C and is catalysed by noble metals like Pd or Pt. LOHC systems are particularly advantageous for long-distance hydrogen transport and stationary storage due to their inherent safety and compatibility with existing fuel infrastructure.[94,96]

Ammonia (NH_3) also serves as a promising hydrogen carrier with a high hydrogen content (17.6 wt%) and established production, storage, and transport infrastructure. Hydrogen can be released from NH_3 by catalytic decomposition at temperatures between 350–500 °C. However, the toxicity of NH_3 and the requirement for downstream hydrogen purification remain barriers to its direct application in fuel cells.[94]

A comparison of major chemical hydrogen storage systems is summarised in Table 12, highlighting their hydrogen content, operating conditions, and associated technical challenges.

6.3. Physical storage

Physical hydrogen storage involves retaining molecular hydrogen through weak interactions, typically van der Waals

Table 11 Comparative overview of gaseous and liquid hydrogen storage technologies[93–96]

Parameter	Compressed gas (700 bar)	Liquid hydrogen	Cryo-compressed hydrogen
Volumetric energy density (MJ L^{-1})	∼5.6	∼8.5	∼7.0
Gravimetric energy density (MJ kg^{-1})	120	120	120
Storage temperature (°C)	Ambient	−253	−150 to −253
Pressure requirement	350–700 bar	∼1 bar	200–300 bar
Boil-off loss	None	High	Low
Energy consumption (kWh kg^{-1})	2–4	10–15	6–10
Storage cost ($ per kg)	1.5–2.5	2.0–4.0	∼2.5–3.5
Suitability	Vehicles, portable storage	Aerospace, bulk storage	Advanced vehicles, grid

forces, without chemical transformation. This includes adsorption onto porous materials and cryogenic storage within solid frameworks. Key materials used include carbon nanotubes, MOFs, COFs, and activated carbon, owing to their high surface areas and tunable pore structures.

Carbon nanotubes offer a gravimetric hydrogen storage capacity of up to 6 wt% under cryogenic conditions and high pressures, with physical adsorption enhanced by the curvature and porosity of the tube walls. However, practical applications are limited by their cost and reduced capacity at ambient temperature.[96] Similarly, MOFs such as MOF-210 exhibit storage capacities of up to 7.9 wt% at −196 °C and 8 MPa, making them suitable for low-temperature applications, though storage performance drops below 1 wt% under ambient conditions.[97] COFs, as a newer class of materials, have shown promise due to their crystallinity, large pore volumes, and thermal stability, although their hydrogen uptake at ambient conditions remains below 2 wt%.[96]

Despite their potential, physisorption-based systems typically require cryogenic temperatures or elevated pressures to achieve adequate uptake, which presents challenges for onboard or distributed hydrogen use. Future efforts in material functionalisation and composite hybrid structures are expected to improve storage densities and operational flexibility.[96] Table 13 presents a comparison of major physisorption materials.

7. Hydrogen re-electrification

Hydrogen re-electrification serves as a cornerstone of long-term energy storage and grid flexibility within the Power-to-Hydrogen-to-Power (P2H2P) framework. This closed-loop energy system is especially relevant for decarbonising sectors reliant on intermittent renewable energy by enabling surplus renewable electricity to be stored as hydrogen and later reconverted to electricity during demand peaks or renewable deficits. As shown in Fig. 10, a P2H2P system comprises renewable energy input, electrolysis for hydrogen production, hydrogen storage, and re-electrification using fuel cells or gas turbines. This integrated approach not only enhances energy reliability and decarbonisation but also facilitates sector coupling across mobility, industry, and the building environment, positioning hydrogen as a flexible vector in future sustainable energy networks.

7.1 Principles and technologies of hydrogen re-electrification

Hydrogen re-electrification is a critical link in the hydrogen energy cycle, converting stored hydrogen back into electricity. Central to the P2H2P systems, it enables long-duration energy storage and supports balancing of intermittent renewable energy sources such as solar and wind.[98] In essence, surplus electricity is used to produce hydrogen *via* electrolysis, which is then stored and subsequently re-electrified using fuel cells or gas turbines during periods of high electricity demand or low renewable generation.

Two primary technologies dominate this domain: fuel cells and hydrogen combustion turbines. Fuel cells are electrochemical devices that convert the chemical energy of hydrogen into electricity with high efficiency (60–80%) and water as the only by-product.[99] Common types include Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), and Alkaline Fuel Cells, each suited to different operating conditions and applications.[98,99]

PEMFCs operate at low temperatures (∼80 °C), allowing for rapid startup and high-power density, making them ideal for vehicles and distributed power systems. SOFCs, by contrast,

Table 12 Comparative overview of chemical hydrogen storage.[9,93,94,96,97]

Storage type	Representative materials	H_2 capacity (wt%)	Operating temp (°C)	Reversibility	Key challenges
Metal hydrides	MgH_2, $NaAlH_4$, Mg_2FeH_6	5–7.6	200–400	Yes	High desorption temp, sluggish kinetics
Complex hydrides	$LiBH_4$, $Mg(BH_4)_2$	14–18	>300	Limited	Irreversibility, regeneration energy
Chemical hydrides	$NaBH_4$, NH_3BH_3	10–19.6	60–120	No	Slurry formation, boron byproducts
LOHCs	*N*-Ethylcarbazole, toluene	5–7	180–300	Yes	Catalyst cost, thermal energy input
Ammonia	NH_3	17.6	350–500	Yes	Toxicity, purification after decomposition

Table 13 Summary of physical hydrogen storage materials and performance

Material	Surface area (m^2 g^{-1})	Max storage capacity (wt%)	Optimal conditions	Key features	References
Carbon nanotubes	2000–3000	~6.0	−196 °C, >30 bar	Lightweight, high gravimetric capacity	96
MOF-210	~6240	7.9	−196 °C, 8 MPa	Ultra-high porosity, tunable frameworks	97
COFs	1000–4000	3.0–5.0	−196 °C	Crystalline, low-cost synthesis	96
Activated carbon	800–3000	4.5–5.0	−196 °C, 5–6 MPa	Scalable, low-cost	96
Zeolites	~1000	~2.0	−196 °C, high pressure	Stable, limited by rigid pore structure	97

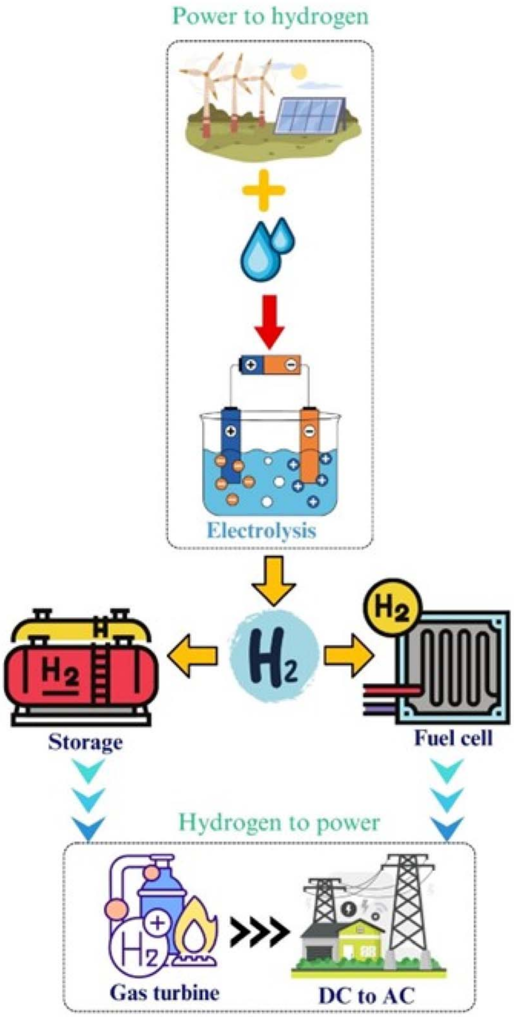

Fig. 10 Schematic of P2H2P system.

operate at high temperatures (~800–1000 °C) and are preferred for stationary applications due to their ability to use multiple fuels and achieve high efficiency.[98] Fuel cells are particularly promising for grid integration and backup systems owing to their flexibility and fast response to power demands.

Hydrogen-fueled gas turbines provide dispatchable power solutions by combusting hydrogen to generate electricity. These turbines, often adapted from natural gas infrastructure, provide robust power output and are valuable for balancing grid fluctuations. Modern gas turbines, such as the Siemens SGT-800, have been adapted to operate with up to 100% hydrogen, enabling CO_2-free electricity generation.[98]

Re-electrification systems also enable sector coupling, the integration of power, heat, mobility, and industrial applications by exploring hydrogen's versatility across various end uses.[100] In addition to balancing energy supply and demand, hydrogen re-electrification enhances energy security, strengthens grid resilience, and reduces reliance on fossil-based Peaker plants.

Despite these advantages, challenges remain, including high capital costs, efficiency losses during multiple energy conversions, and the need for supporting infrastructure. Furthermore, dynamic energy system modelling is required to optimise performance and cost-effectiveness.[98]

7.2 Applications of hydrogen fuel cells

Hydrogen fuel cells have emerged as pivotal components in the transition toward a sustainable, low-carbon energy future. Their versatility, high efficiency, and zero-emission operation make them well-suited for deployment across multiple sectors, including transportation, stationary power generation, and grid support systems. A sector-wise summary of hydrogen fuel cell applications, associated technologies and benefits is presented in Table 14.

7.2.1 Transportation sector. Fuel cell electric vehicles (FCEVs) are gaining momentum in the transportation sector due to their rapid refueling times and extended driving ranges compared to battery electric vehicles. FCEVs powered by PEMFCs have been deployed in buses, trucks, trains, and even maritime transport.[100] For example, hydrogen fuel cell trains have been introduced in Germany, replacing diesel-powered locomotives on non-electrified routes. In aviation, small drones and auxiliary power units for commercial aircraft are being equipped with fuel cells to extend endurance and reduce emissions.[101]

7.2.2. Stationary and backup power. Fuel cells are also extensively used for decentralised and backup power generation. Phosphoric Acid Fuel Cells (PAFCs), SOFCs, and PEMFCs are commonly deployed in residential, commercial, and industrial settings. Notably, Japan's ENE-FARM project has installed over 400 000 residential PEMFC units for combined heat and power (CHP), demonstrating the technology's viability in domestic applications.[6] These systems achieve high overall efficiency by utilising both electricity and the heat generated during operation, reaching total energy utilisation rates up to 85%.

Table 14 Sector-wise applications of hydrogen fuel cells[6,98,100,101]

Sector	Fuel cell type	Application examples	Advantages
Transportation	PEMFC	Buses, trucks, trains, UAVs	Fast refueling, long range, zero emissions
Residential/CHP	PEMFC, PAFC	ENE-FARM systems in Japan	High efficiency, heat and power cogeneration
Industrial	SOFC, MCFC	Power for data centers, factories	High fuel flexibility, scalability
Maritime	PEMFC, SOFC	Ferries, port vessels	Low noise, reduced NO_x and SO_2 emissions
Grid integration	PEMFC, SOFC	Wind-hydrogen hybrid storage systems	Grid balancing, renewable energy storage

7.2.3. Grid integration and re-electrification. In the context of renewable energy integration, fuel cells play a critical role in P2H2P systems. During periods of excess renewable generation, electricity can be used to produce hydrogen *via* electrolysis, which is then stored and later converted back into electricity using fuel cells. This process enhances grid flexibility and enables long-duration energy.[98] For example, fuel cells have been integrated with wind farms to ensure a stable electricity supply during low-wind periods, particularly in off-grid and remote areas.

7.2.4. Industrial and emerging applications. Industrial facilities are increasingly adopting SOFCs and Molten Carbonate Fuel Cells (MCFCs) for power generation owing to their high efficiency and capability to operate on multiple fuels, including biogas and syngas.[100] Forklift trucks powered by PEMFCs are widely used in logistics centers in the United States and Europe, offering fast refueling and extended operational times. Additionally, fuel cells are being explored for marine propulsion and portable electronics where energy density and clean operation are critical.[101]

7.3. Hydrogen-powered turbines and grid integration

Hydrogen-powered turbines are gaining traction as flexible, low-carbon energy conversion technologies capable of enhancing the stability and decarbonisation of modern power grids. They are particularly well suited for peak-load applications and backup power in renewable-dominated systems due to their rapid ramp-up time, modularity, and potential for CO_2-free operation.[99,101]

Modern hydrogen turbines are either retrofitted versions of conventional natural gas turbines or specifically engineered to accommodate hydrogen's unique combustion characteristics. Turbines such as Siemens' SGT-800 and Mitsubishi's H-25 have demonstrated successful operation with hydrogen–natural gas blends and are being upgraded for 100% hydrogen combustion.[100] These systems provide a practical pathway for repurposing existing gas infrastructure during the energy transition.

Hydrogen's high flame speed and low ignition energy introduce operational challenges, including combustion instabilities, flashback risks, and increased NO_x formation. Consequently, advanced dry low-NO_x burners, staged combustion designs, and real-time flame monitoring systems are required to ensure safe and efficient hydrogen combustion (Bhuiyan and Siddique, 2025).[6] Despite these challenges, the thermal efficiency of hydrogen turbines typically ranges from 35–40%, comparable to natural gas-fired units, with the added benefit of near-zero CO_2 emissions when operating on green hydrogen.[101]

Grid integration is among the most compelling applications for hydrogen turbines. In power-to-gas-to-power schemes, excess renewable electricity is converted into hydrogen *via* electrolysis, stored, and later reconverted into electricity using hydrogen turbines during periods of high demand or low renewable output.[98] This approach enables long-duration energy storage, grid balancing, frequency regulation, and black-start capabilities.

Hydrogen turbines are compatible with co-firing strategies, blending hydrogen with natural gas to progressively reduce the carbon footprint of power generation. Studies indicate that blending hydrogen at concentrations above 30% by volume can achieve up to a 50% reduction in CO_2 emission while utilising existing gas turbines with minimal modifications.[99]

Although hydrogen turbines remain largely in the demonstration or pilot deployment phase, their strategic role in hybrid renewable systems and the decarbonisation of dispatchable power positions them as a key component of future smart grids. Table 15 provides a comparative overview of hydrogen-powered turbines and conventional natural gas turbines, outlining key technical parameters such as fuel type, emissions, flame speed, retrofit feasibility, efficiency, and commercial readiness. It highlights the environmental advantages of hydrogen turbines while emphasising current technological challenges and their developmental status.

7.4. Efficiency and infrastructure requirements

Hydrogen energy systems, while offering sustainable decarbonisation potential, are constrained by inherent efficiency losses and significant infrastructure requirements across the entire hydrogen value chain. From electrolysis to storage and final re-electrification, round-trip efficiency is a critical parameter influencing both economic and environmental viability.

7.4.1. Efficiency challenges. Electrolysis remains the most energy-intensive stage of hydrogen production. Despite technological advances, water electrolysis systems (PEM, AEL, SOEC) still consume significant electrical energy, with system efficiencies ranging from 62–86% depending on the technology and operational conditions.[100] When ancillary losses, power electronics, and auxiliary systems are factored in, overall efficiency can drop significantly. For example, in practical setups, PEM electrolysers efficiency decreases with increasing current density, due to higher stack losses and heat buildup.[100]

Table 15 Comparison of hydrogen-powered and conventional gas turbines[99–101]

Feature	Hydrogen turbines	Natural gas turbines
Primary fuel	H_2 or H_2/CH_4 blends	CH_4 (natural gas)
CO_2 emissions	Zero (green H_2)	High
Flame speed	High ($\sim$270 cm s^{-1})	Moderate ($\sim$38 cm s^{-1})
NO_x emissions	High (requires DLN burners)	Moderate
Energy density (volumetric)	Lower	Higher
Retrofit feasibility	Moderate (design changes needed)	High (existing infrastructure)
Grid roles	Peak-shaving, black-start, storage	Base load and intermediate loads
Efficiency (%)	35–40%	35–45%
Commercial readiness	Demonstration/pilot	Mature and widely deployed

Additional energy penalties occur during compression and liquefaction. Compressing hydrogen to 875 bar can result in up to 7% energy loss per kilogram, while liquefaction can consume as much as 30% of the hydrogen's energy content.[102] Consequently, energy-efficient storage strategies are essential for improving system performance. Technologies such as advanced insulation, cryo-compression, and solid-state storage using metal hydrides are being explored to reduce these losses.[6]

Hydrogen re-electrification *via* fuel cells can achieve relatively high efficiency (60–80%) in stationary applications. However, this decreases substantially in vehicular and off-grid uses due to parasitic losses.[100] When upstream compression, storage, and distribution losses are included, the net round-trip efficiency from renewable electricity to re-electrified hydrogen electricity falls to approximately 30–45%.[6,100]

7.4.2. **Infrastructure requirements.** A robust hydrogen infrastructure is pivotal for scaling up green hydrogen production and use. This encompasses production hubs, pipelines, storage facilities, and distribution networks. However, building and maintaining these assets demand substantial capital investments and substantial policy commitments. Key infrastructure challenges include limited pipeline availability, constraints in pressure containment technology, and an insufficient number of refuelling stations, particularly for mobility applications.[102]

Material degradation under high-pressure hydrogen exposure is another major concern. Hydrogen embrittlement, leakage, and diffusion into container materials necessitate the use of expensive composite or alloy-based materials to ensure safe containment.[6] Regulatory inconsistencies across regions further hinder infrastructure standardisation and interoperability.[102]

Solid oxide electrolysis and thermally integrated systems offer potential for improved efficiency and cost-effectiveness, particularly when coupled with waste heat from industrial processes or solar thermal sources. However, their deployment is limited by scale, cost, and material durability at high operating temperatures.[63] Table 16 summarises the efficiency ranges and key loss mechanisms across various stages of the hydrogen energy chain, from production to final power output. It offers a quantitative overview of where energy losses occur, informing optimisation strategies for future hydrogen systems.

8. Hydrogen transport and distribution

The distribution of hydrogen from production sites to end users is a crucial component of the hydrogen value chain. Due to hydrogen's low volumetric energy density under ambient conditions (0.0899 kg m^{-3} at 1 atm and 0 °C), efficient transport requires physical or chemical modification, such as compression, liquefaction, or conversion to carriers like NH_3 or LOHCs. This section outlines and compares the main hydrogen transport technologies in terms of cost, capacity, efficiency, and applicability.

Table 17 provides a comparative overview of the major hydrogen transport methods, highlighting critical performance metrics such as transport capacity, operational range, energy loss, capital expenditure (CAPEX), and suitability for specific transport scenarios. CGH_2 trucks are typically used for short-range, local delivery due to their limited capacity and moderate energy losses. LH_2 trucks offer higher transport capacity and are more suited for medium-distance routes, but incur substantial energy losses during liquefaction.

Fig. 11 illustrates the comparative performance of various hydrogen transport and distribution methods.[103] For large-scale or long-distance transport, pipelines offer low energy losses and continuous delivery, although their high initial CAPEX limits rapid deployment. On an intercontinental scale, chemical carriers such as NH_3 and LOHCs provide high transport capacities and utilise existing maritime infrastructure, albeit with higher energy penalties due to hydrogen conversion and dehydrogenation steps. The selection of transport modalities must therefore be based on a strategic assessment of logistical, economic, and technical factors to support the scale-up of hydrogen economy.

8.1. Compressed gaseous hydrogen

CGH_2 is one of the most established and readily deployable methods for transporting hydrogen over short to medium distances. Hydrogen gas is compressed to high pressures, typically between 200 and 700 bar and stored in high-strength cylinders or composite tanks for transport *via* trucks, trailers, or pipelines. While CGH_2 transport systems are relatively simple in design and compatible with existing road infrastructure, they are constrained by limited payloads and energy inefficiencies

Table 16 Efficiency losses across the hydrogen energy chain

Stage	Efficiency range (%)	Major energy loss factors	References
Electrolysis (PEM/AEL/SOEC)	62–86	Stack voltage drop, auxiliary systems	100 and 102
Compression (to 875 bar)	~93 (7% loss)	Mechanical inefficiencies, heat loss	102
Liquefaction	60–70 (30–40% loss)	Cryogenic cooling, boil-off losses	6
Storage (composite tanks/cryogenic)	90–95	Embrittlement, permeability, insulation loss	102
Fuel cell re-electrification	60–80	Parasitic loads, stack ageing	100
Round-trip efficiency	30–45	Combined losses from all stages	6

arising from compression requirements and unfavorable mass-to-volume ratios.

8.1.1. Transport by tube trailers. CGH_2 is primarily distributed in high-pressure tube trailers using steel or composite cylinders. Traditional steel trailers typically operate at 200–250 bar and transport around 180–300 kg of hydrogen per trip, whereas newer composite-based trailers operating at 500–700 bar can carry 500–720 kg of hydrogen depending on configuration.[6,93] The volumetric energy density of CGH_2 at 700 bar is approximately 5.6 MJ L^{-1}, which is significantly lower than liquid fuels, resulting in substantial space requirements. In practice, CGH_2 delivery is economically viable only for distances under 200–300 km, beyond which compression energy losses and logistical costs outweigh the benefits.[106]

8.1.2. Compression energy and efficiency. Hydrogen compression is an energy-intensive step, For a final pressure of 800 bar the compression energy requirements would amount to about 13% of the energy content of hydrogen, depending on the compression method and cooling systems.[104] Multi-stage compression with intercooling is typically employed to improve efficiency and reduce mechanical wear. The energy loss from compression adds to the already moderate round-trip efficiency of hydrogen systems. For example, if hydrogen is produced *via* PEM electrolysis at 70% efficiency and then compressed for transport with a 12% energy penalty, the effective delivered energy is reduced to around 61% before end-use conversion.[93]

8.1.3. Storage vessels and safety considerations. Pressurised hydrogen is stored in cylinders constructed from high-strength materials such as steel (Type I), carbon fiber composites with polymer linings (Type III/IV), or hybrid constructions. Composite cylinders offer reduced weight and improved safety, enabling higher payloads. However, high pressures storage presents safety risks including embrittlement, leakage, and catastrophic rupture in the event of accidents.[106] The International Organisation for Standardisation (ISO) and United Nations Economic Commission for Europe (UNECE) have established regulatory standards such as ISO 11119 and UN ECE R134 governing the design, testing, and operation of these tanks, including burst resistance and leak-before-break safety requirements.[6]

The capital cost of a high-pressure trailer ranges from €660 000 to €860 000, depending on the number of storage tubes, pressure rating, and materials used.[105] Operating costs increase with transport distance, and road-based CGH_2 delivery is generally viable only when infrastructure such as refueling stations or industrial users is nearby. For small-scale and decentralised hydrogen supply chains such as fueling stations, research facilities, or backup power systems, CGH_2 transport remains a practical and flexible option.

8.2. Liquid hydrogen

LH_2 offers a significantly higher volumetric energy density than CGH_2, making it an attractive option for medium to long distance bulk transport. To achieve the liquid state, hydrogen must be cooled to cryogenic temperatures near −253 °C, requiring complex liquefaction systems, highly insulated storage vessels, and specialised transportation infrastructure. Despite its volumetric advantages, LH_2 faces technical and economic challenges due to energy-intensive processing and boil-off losses.

At atmospheric pressure and cryogenic temperatures, LH_2 attains a volumetric energy density of 8.5 MJ L^{-1}, compared with CGH_2 at 700 bar (~5.6 MJ L^{-1}).[93] This enables cryogenic tankers to transport larger hydrogen masses per trip, typically up to 4000–4500 kg of LH_2 in a single trailer (Bhuiyan and Siddique, 2025).[6] As a result, LH_2 becomes economically favorable for distances exceeding 500 km, particularly for supplying industrial clusters, ports, or fueling stations in remote locations.[104]

Table 17 Comparative overview of hydrogen transport methods.[6,93,104,105]

Method	Capacity (kg)	Distance range	Energy loss (%)	CAPEX (€ per unit)	Suitable for
CGH_2 trucks	180–720	≤300 km	~10	€660 000–860 000	Local delivery
LH_2 trucks	~4000	>500 km	30–40	€900 000+	Mid-range shipping
Pipelines	10 000+/h	≤1000 km	~5–10	€179M (160 000 m^3)	Large-scale supply
NH_3 ships	~19,200 000	>1000 km	15–20	€134M to 180M	Intercontinental
LOHC ships	~8 265 600	>1000 km	25–30	€99M+	Intercontinental

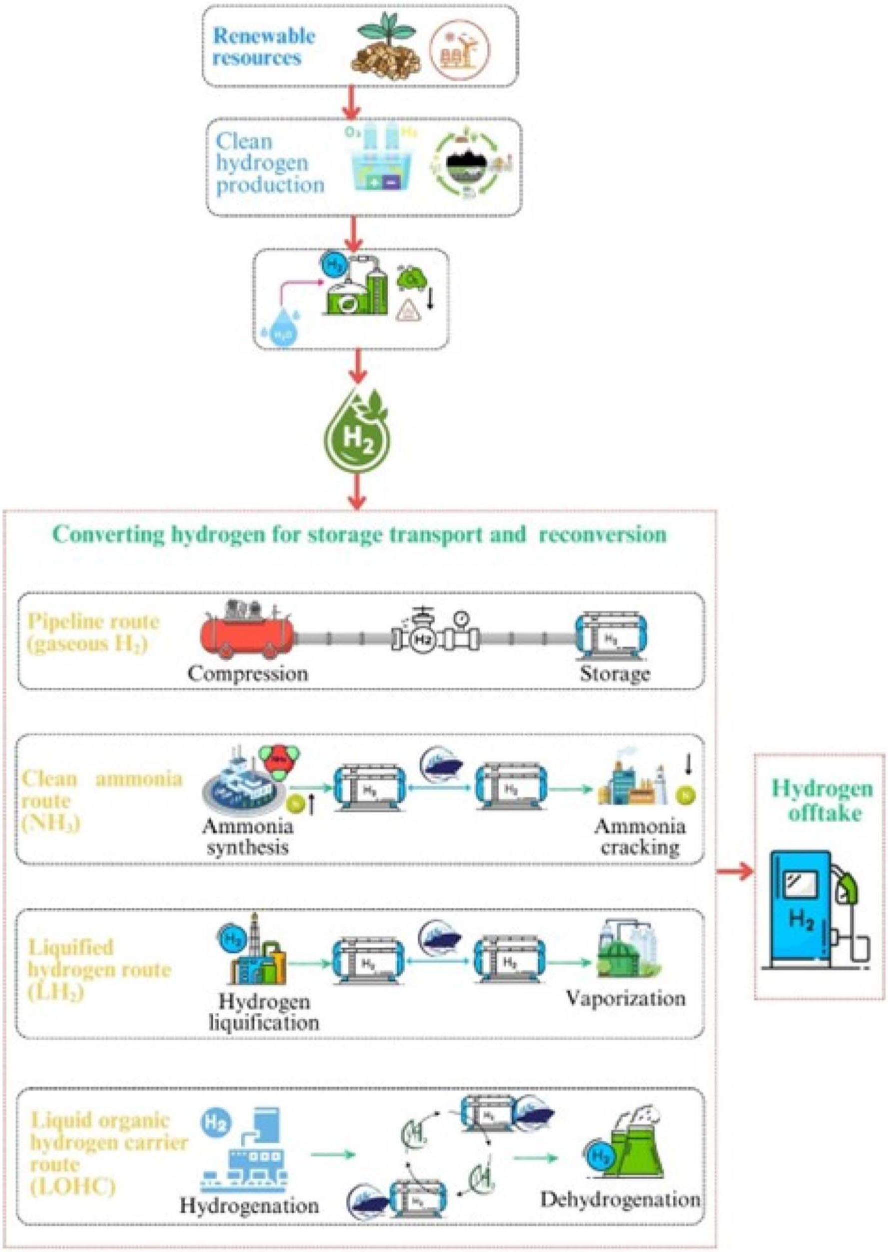

Fig. 11 Hydrogen transportation and distribution.[103]

Hydrogen liquefaction is highly energy-intensive, consuming approximately 10–13 kWh kg^{-1} of hydrogen, equivalent to 30–40% of its lower heating value.[93,106] This energy penalty significantly impacts overall well-to-tank efficiency and must be offset by the advantages in storage and transportation capacity. Proposed methods to improve liquefaction efficiency include Brayton and Claude cycle-based refrigeration systems, magnetic refrigeration, and hybrid liquefaction using industrial waste heat.[104] However, these remain limited in deployment due to high capital cost and operational complexity.

LH_2 is stored in vacuum-insulated double-walled cryogenic tanks, typically made of stainless steel or composite materials. Boil-off losses caused by unavoidable heat ingress generally range from 0.3% to 1.5% per day, depending on tank size, insulation quality, and ambient conditions.[6] To mitigate these losses, research is advancing in areas such as multi-layer insulation and aerogels, along with active re-liquefaction and vent gas recovery systems. Carbon fiber-reinforced polymer tanks are also under development to reduce weight and improve portability for mobile storage applications.[93]

Handling LH_2 presents distinct risks due to its extreme cold and flammability. Contact with materials not rated for cryogenic service can cause embrittlement and structural failure. Moreover, boil-off gas accumulation in confined spaces can lead to pressure build-up and explosive mixtures. Stringent safety regulations such as ISO 13985 and ASME Boiler and Pressure

Vessel Codes govern cryogenic system integrity.[104] Modern LH_2 trailers are equipped with venting, relief, and monitoring systems to prevent overpressure and leakage. Operational protocols also require grounding procedures to eliminate static charge accumulation, which could otherwise ignite released hydrogen vapour.

LH_2 transport is employed in applications where high energy density and long-range delivery are essential. It is notably used to supply high-throughput refueling stations serving hydrogen-powered buses or freight trucks and to connect production hubs with ports for export, facilitating international hydrogen trade. LH_2 is also utilised for interim storage in large-scale energy storage systems and backup power plants, providing a reliable supply during peak demand or grid outages. From an economic perspective, the viability of LH_2 transport improves when the substantial capital and operational cost of liquefaction are distributed over long distances and bulk quantities. The construction cost of an LH_2 tanker ranges from €900 000 to 1 100 000 per unit, making them capital-intensive assets. Operational costs are further increased by the need for continuous refueling, pressure regulation, cryogenic insulation, and monitoring systems to liquid state hydrogen throughout transport.[105] Therefore, optimising logistics and scale is critical for cost-effective LH_2 distribution.

8.2.1. Pipeline transmission. Pipeline transmission represents the most cost-effective and scalable method for transporting large volumes of hydrogen over medium to long distances. Similar to natural gas pipelines, hydrogen pipelines can operate continuously with minimal labour, enabling high-capacity delivery to industrial hubs, storage terminals, or refueling networks. However, transporting hydrogen *via* pipelines presents unique engineering and material challenges due to its low molecular weight, high diffusivity, and potential to degrade pipeline materials over time.

Hydrogen is typically transported through pipelines in a gaseous state at pressures between 2 and 10 MPa (20–100 bar). Lower pressures are used in local or industrial distribution networks, while higher pressures are preferred for long-distance transmission to reduce volumetric flow rates.[93] For comparison, hydrogen's volumetric energy density at 70 bar is approximately 2.7 MJ L^{-1}, considerably lower than that of methane (~35.8 MJ L^{-1}), necessitating higher flow rates or larger pipeline diameters to achieve equivalent energy throughput.[6]

Pipeline material must withstand hydrogen embrittling, which occurs when hydrogen diffuse into metals, particularly high-strength steels, causing cracks and fractures under cyclic loading. Common materials for hydrogen pipelines include carbon steel (X52, X60, X70) and austenitic stainless steels. However, polymer-lined or fibre-reinforced composite pipelines are being explored for enhanced safety and cost efficiency.[104]

Hydrogen embrittlement is a critical risk in pipeline transmission especially in high-pressure, high-strength steel systems where hydrogen atoms infiltrate the crystal lattice and cause microstructural damage.[93] Studies show that X70 steel, widely used in natural gas pipelines, suffers from fatigue crack growth when exposed to hydrogen at pressures exceeding 100 bar. Mitigation measures include limiting pressure fluctuations, using lower strength steel, applying internal coatings or polymer liners, and conducting routine inspection with in-line tools (smart pigs).[6]

One promising strategy for accelerating hydrogen pipeline deployment is repurposing existing natural gas infrastructure. Estimates suggest that up to 70% of Europe's gas pipelines could be adapted for hydrogen transport with minimal modifications.[93] However, retrofitting requires detailed assessment of pipeline condition, pressure regulation systems, and compatibility of valves and compressors. Hydrogen purity is another consideration: blending hydrogen with natural gas (>10–20%) necessitates separation and purification at the end-use site, typically *via* pressure swing adsorption or membrane separation. The European Hydrogen Backbone initiative envisions 50 000 km of hydrogen pipeline infrastructure across 28 countries by 2040, largely through a combination of repurposed assets and dedicated hydrogen lines to support a pan-European hydrogen economy.[105]

Pipelines can transport between of 10 000 and 20 000 kg of hydrogen per hour, depending on diameter and pressure. For long distances (*e.g.*, 1000 km), the transport cost *via* pipeline ranges from €0.11–0.20 per kg H_2, making it the cheapest large-scale option when high throughput is maintained.[104,106] CAPEX for new hydrogen pipelines ranges from €1 million to €2.5 million per km, depending on size, material, terrain, and installation method.[6]

8.3. Maritime transport and intermodal shipping

As hydrogen emerges as a globally traded commodity, maritime transport and intermodal logistics are becoming central to connecting large-scale production hubs such as those in Australia, the Middle East, and South America with demand centers in Asia, Europe, and North America. Due to hydrogen's physical properties, it cannot be transported in its raw gaseous form across oceans at scale. Instead, it must be converted into energy-dense forms such as LH_2, NH_3, or LOHCs before being loaded onto ships. These energy carriers can then be reconverted into hydrogen or used directly in industrial or power generation applications.

8.3.1. Liquid hydrogen shipping. LH_2 shipping is technically mature but remains highly energy-intensive. To achieve liquefaction, hydrogen must be cooled to −253 °C, reducing its volume by a factor of approximately 850. A typical cryogenic hydrogen tanker is equipped with vacuum-insulated double-wall tanks, capable of transporting approximately 75 000 to 160 000 m^3 of LH_2, equating to 11 000–13 000 tonnes of hydrogen per trip.[93,106]

Despite its volumetric advantage, LH_2 shipping incurs significant energy penalties. Liquefaction consumes 10–13 kWh per kg H_2, equating to approximately 30–40% of its lowering heating value.[6] Boil-off losses during maritime transport also present a challenge, although modern cryogenic tanks can limit these to 0.2–0.5% per day, depending on insulation and voyage duration.[104]

Projects such as Kawasaki's Suiso Frontier have demonstrated the feasibility of shipping LH_2 from Australia to Japan, marking a milestone for international hydrogen logistics. However, the high cost of liquefaction plants, cryogenic tankers

(~€150M to 200M per vessel), and terminal infrastructure remains a barrier to widespread adoption.[105]

8.3.2 Ammonia shipping. NH_3 is a more energy-efficient hydrogen carrier that can be shipped using existing liquefied petroleum gas carriers. It contains 17.6% hydrogen by weight and offers a volumetric hydrogen density of 108 kg H_2 per m^3, much higher than LH_2 (71 kg m^{-3}). Ammonia is liquefied below −33 °C under moderate pressure (~1 bar), making it easier to store and ship over long distances using established chemical tanker infrastructure.[6,106]

At the destination port, ammonia can be either used directly for example, in ammonia fuel cells or co-fired turbines or "cracked" back into hydrogen *via* catalytic decomposition. This process incurs an additional 5–10% energy loss and requires dedicated infrastructure for ammonia handling and purification.[93] The shipping cost of ammonia is estimated at €0.10–0.15 per kg of H_2 equivalent, significantly lower than that of LH_2 or LOHC under similar conditions.[105]

8.3.3. Liquid organic hydrogen carrier-based shipping. LOHCs are hydrogen-rich compounds such as dibenzyltoluene or methylcyclohexane that chemically bind hydrogen and allow for transport at ambient pressure and temperature. They are liquid at room temperature, non-toxic, and compatible with existing fuel infrastructure, making them attractive for intermodal transport across trucks, trains, and ships.[6]

Hydrogen is stored in LOHC *via* hydrogenation at 150–200 °C and released at the destination through dehydrogenation at 250–350 °C in the presence of a catalyst. Typically, LOHCs have storage capacity of 5–7 wt% hydrogen, and exhibit low vapor pressure, minimising boil-off losses during maritime transport. However, the round-trip energy efficiency of LOHCs is relatively low (~40–50%) due to thermal processing on both the hydrogenation a dehydrogenation stages.[104]

8.4. Advanced chemical carriers: ammonia and LOHCs

Advanced chemical carriers such as NH_3 and LOHCs have emerged as promising alternatives for hydrogen storage and long-distance transport. These carriers enable hydrogen to be moved in more energy-dense, manageable, and infrastructure-compatible forms, addressing the limitations posed by hydrogen's low volumetric density and stringent cryogenic requirements.

Ammonia is a well-established industrial chemical that contains 17.6% hydrogen by weight and offers a high volumetric hydrogen density of approximately 108 kg H_2 per m^3, significantly higher than that of LH_2. It can be liquefied at a relatively mild temperature of −33 °C and at atmospheric pressure, making its storage and transport far less energy-intensive compared to LH_2, which requires cooling to −253 °C.[93] This advantage allows ammonia to be transported using existing LPG infrastructure, including pressurised tanks, pipelines, and chemical tankers. As a result, ammonia is widely considered one of the most viable hydrogen carriers for global maritime and intercontinental trade. Upon delivery, ammonia can be "cracked" back into hydrogen through catalytic thermal decomposition, although this adds an energy loss of around 5–10% and necessitates separation and purification to meet end-use fuel cell or combustion requirements.[6,106] Moreover, ammonia's toxicity and the formation of NO_x during combustion require stringent handling protocols and emission controls to ensure safe and clean use.

LOHCs, such as dibenzyl toluene or methylcyclohexane, provide an alternative route for chemically binding and transporting hydrogen. These compounds can be hydrogenated to store hydrogen and then dehydrogenated at the point of use to release it. LOHC systems offer the advantage of operating under ambient pressure and temperature conditions, simplifying storage, handling, and transportation logistics. In addition, LOHCs are typically non-toxic, have low vapor pressure, and exhibit good thermal and chemical stability, making them suitable for both stationary and mobile energy applications.[104] The hydrogen content of LOHCs typically ranges from 5 to 7 wt%, and they can be transported in standard fuel tankers without significant infrastructure modifications. However, hydrogenation and dehydrogenation require substantial energy inputs temperatures of 150–200 °C and 250–350 °C, respectively and expensive catalysts. These factors reduce round-trip energy efficiency to approximately 40–50%.[6,93] Additionally, LOHCs often accumulate by-products and degradation compounds after repeated cycling, shortening their operational lifetime and increasing regeneration costs.

Both ammonia and LOHCs represent technically viable and scalable hydrogen carriers that facilitate regional and international transport, particularly where direct hydrogen handling is technically or economically challenging. While ammonia benefits from an established infrastructure and high energy density, its toxicity and cracking requirements remain obstacles. LOHCs, offer safe and flexible logistics but suffer from energy inefficiency and system complexity. Continued advances in catalysts development, integrated carrier cycles, and safety systems will be essential to accelerating their adoption in the hydrogen economy.

9. Toxicology, safety, and environmental metrics

9.1. Life-cycle assessment and environmental indicators

LCA standardised under ISO 14040 and 14044, is a systematic methodology for evaluating the environmental impacts associated with a product or process throughout its life cycle. In the context of hydrogen production, LCA serves as a critical tool for identifying the most sustainable pathways and informing green chemistry strategies. It enables the quantification of environmental burdens, hotspots, and trade-offs from feedstock extraction to hydrogen generation and delivery, often adopting a cradle-to-gate boundary to maintain comparability across technologies.

Significant discrepancies in environmental performance are observed across hydrogen production pathways, particularly regarding global warming potential, cumulative energy demand (CED), and water use intensity. Grey hydrogen, typically produced *via* SMR without carbon capture, remains the most carbon-intensive route, emitting an average of 8.5 to 12 kg CO_2-

equivalent per kg of H_2 produced, and is often used as the benchmark for LCA comparison.[107,108] Blue hydrogen, which integrates CCS with SMR, demonstrates improved performance with GHG emissions in the range of 1.5 to 4.4 kg CO_2-eq per kg H_2, depending on the capture efficiency and energy source used.[108,109] In contrast, green hydrogen generated *via* water electrolysis powered by renewable energy exhibits the lowest carbon footprint, typically 0.3 to 2.5 kg CO_2-eq per kg H_2,[110,111] though this can rise significantly when grid electricity with a high fossil fraction is used.

Environmental trade-offs extended beyond carbon emissions. The water use intensity of green hydrogen production *via* electrolysis is notably high, requiring approximately 9 to 15 liters of deionised water per kilogram of hydrogen. While modest, in absolute terms, this can be a critical sustainability factor in water-scarce regions, particularly for large-scale electrolysis deployed.[110] CED provides an aggregated measure of the total energy input. Grey hydrogen typically requires 120 to 140 MJ per kg H_2, reflecting the energy-intensive nature of fossil fuel extraction and processing, whereas green hydrogen demonstrates lower CED values, typically 50–70 MJ per kg H_2, depending on electrolyser efficiency and the renewable power mix.[108,112] A comparative summary of major life-cycle environmental indicators for grey, blue, and green hydrogen pathways is presented in Table 18.

It is important to note that LCA results reported across the literature are not strictly uniform, as they differ in system boundaries, allocation procedures, background databases, electricity mix assumptions, and treatment of infrastructure and end-of-life stages. To address this variability, the present review adopts a harmonized cradle-to-gate perspective with a functional unit of 1 kg H_2 and interprets reported values as representative ranges rather than directly comparable point values. Consequently, emphasis is placed on identifying consistent trends and relative performance differences that remain robust across methodological variations, rather than on absolute numerical rankings.

In addition to these high-level indicators, process-level metrics are vital for assessing the overall sustainability and resource efficiency of hydrogen production. *E*-factor, which quantifies the mass of waste generated per unit of product, is a key green chemistry metric. Electrolysis exhibits low *E*-factor, generally below 1, due to its cleaner input–output profile, whereas SMR-based systems produce substantial carbon emissions and waste heat, often pushing *E*-factor above 3.[109] PMI, denoting the total mass of input per mass of product, is also lower in electrolysis systems (10–20), compared with grey hydrogen production, where PMI can exceed 40 due to the extensive upstream infrastructure and ancillary inputs.[116] EROI, the ratio of usable energy output to the energy input highlights further difference: grey hydrogen achieve EROI values of 3–4, though its fossil-based nature undermines long-term sustainability, while green hydrogen typically ranges between 0.5 and 1.5, reflecting high energy input requirements offset by its renewable origin.[108]

Despite the environmental advantages of green hydrogen, LCA-based studies reveal important trade-offs. The use of rare and precious metals such as platinum and iridium in PEM electrolysers contributes to a high abiotic depletion potential (ADP), especially when end-of-life (EoL) recycling strategies are absent or underdeveloped.[107,110] Large-scale deployment of solar and wind farms, may also result in land use and biodiversity impacts, while hydrogen leakage during transport and storage, could have indirect climate effects. Furthermore, shifting environmental burdens from GHG emissions to categories such as acidification, human toxicity, or mineral depletion must be carefully monitored through harmonised multi-impact LCA approaches.[107,112]

LCA thus provides a robust framework for comparing hydrogen production routes and their environmental ramifications. While green hydrogen offers the best climate performance when powered by renewable electricity, its broader environmental and resource impacts require careful management through improved system design, material substitution, and circularity strategies. Future research should integrate dynamic LCA with region-specific data, account for infrastructure development, and incorporate EoL scenarios to provide a comprehensively assessment of the sustainability of a global hydrogen economy.

9.2. Toxicological implications of materials and byproducts

The transition to hydrogen-based energy systems involves a complex range of materials and intermediates, many of which present toxicological and environmental risks. These must be evaluated through a life cycle prespective to identify key hotspots of human toxicity, ecotoxicity, and environmental persistence.

PEM and anion exchange membrane (AEM) electrolysers rely heavily on noble metals such as platinum (Pt), iridium (Ir), and ruthenium (Ru), which contribute significantly to abiotic resource depletion and human toxicity. For example, the ADP of Ir and Ti in PEM systems is notably higher than in AEM due to their low abundance and energy-intensive mining. In AEM systems, material depletion is estimated at 2×10^{-4} kgSbeq per kgH_2, with bipolar plates and end plates contributing 26.8% and 25% of impacts respectively, despite their low mass fraction. The NiMo catalyst, although comprising less than 1% by mass, accounts for over 10% of the impact due to molybdenum content.[117] Recycling of Pt group metals remains technologically limited, with low readiness levels, high costs, and the use of hazardous chemicals during recovery.[117] EoL recycling is often excluded from LCA assessments due to lack of data gaps, despite growing interest in circular economy frameworks.

PFSA membranes such as Nafion™ widely used in PEM electrolysers are chemically stable fluoropolymers classified under per- and polyfluoroalkyl substances. These materials exhibit high environmental persistence and bioaccumulation potential, with known impacts including endocrine disruption and carcinogenicity. Incineration of PFSA membranes can release of toxic fluorinated byproducts, raising environmental concerns.[118] Despite their prevalence, few LCA studies quantitatively assess toxic emissions from these membranes, representing a notable knowledge gap in hydrogen toxicity assessments.

Table 18 Comparative environmental indicators for hydrogen production pathways (cradle-to-gate, per kg H_2). Indicators reflects both energy quantity (CED) and energy quality (EROI)[113–115]

Indicator[a]	Grey H_2 (SMR)	Blue H_2 (SMR + CCS)	Green H_2 (electrolysis: PEM/AEC)
Global warming potential (GWP_{100}) (kg CO_2-eq)	11.888	6.59	≈0.9
Water footprint (L H_2O per kg H_2)	19.8	≈20 L	≈9
CED (MJ kg^{-1} H_2)	183.2	≈180–190	≈194
Energy return on investment	0.66	≈0.6–0.7	≈0.62
PMI (kg input per kg H_2)	23.6	23.6	≈9.05
E-factor (kg waste per kg H_2 product)	0.20	0.20	≈0.01
Land use (m^2 year per kg H_2)	0.9	≈0.9	≈0.8
Critical raw material demand ($\times 10^{-3}$ kg Sb-eq)	1.6	1.6	≈5
Typical electrolyser efficiency (kWh per kg H_2)	—	—	50–58

[a] *E*-factor – environmental factor; PMI – process mass intensity; EROI – energy return on investment.

CdS and Pb-halide perovskites are prominent candidates for PC water splitting. However, cadmium and lead are high-toxicity heavy metals with long-term environmental persistence. Leaching from degraded or improperly disposed catalysts can result in aquatic and soil contaminants. Cadmium has a high potential in bioaccumulation in aquatic organisms, while perovskite solar cells have been linked to risks of lead leaching during operational failure or landfill disposal.[104,119]

Glycerol, a biodiesel by-product, can undergoes steam reforming to yield syngas and hydrogen. The main reaction is:

$$C_3H_8O_3 \rightarrow 3CO + 4H_2$$

Incomplete conversion can produce acrolein, a volatile aldehyde with high inhalation toxicity. In glycerol steam reforming, methanol residues and electricity consumption have been identified as toxicity hotspots, with natural gas and methanol production being the dominant contributors.[104] Methanol distillation and the use of Ni or La-based catalysts further add to environmental burdens.

Leaching from landfilled catalyst materials and spent membranes, particularly those containing Ni, Cd, or Pb, can cause long-term contamination of groundwater and aquatic ecosystems. For PEM systems using EU grid power the human toxicity potential was measured at 1.3×10^{-7} CTUh per kgH_2, decreasing nearly tenfold when switching to wind energy.[117] In AEM systems, electricity accounts for over 95% of HTP, with stack materials especially bipolar (34.1%) and end plates (26.5%) making significant contributions.

Volatile emissions such as NO_x and SO_x from reformers and solvents used in plant maintenance can exacerbate ecosystem toxicity if inadequately controlled. Additionally, catalysts such as Ni and PSA adsorbents (*e.g.* molecular sieves, activated carbon) must be periodically replaced and disposed of through certified channels to prevent toxic emissions.[120]

A consolidated overview of the toxicity profiles, exposure limits, and lifecycle implications of key materials and byproducts is provided in Table 19.

9.2.1 Occupational exposure and worker safety risks.

While hydrogen technology research and deployment have largely focused on environmental emissions and life cycle sustainability, occupational safety remains a critical dimension of toxicological assessment. Workers involved in catalyst preparation, membrane fabrication, electrolysis operation, reforming, and post-processing may be routinely exposed to hazardous substances such as volatile organic compounds, heavy metal dusts, acidic vapors, and nanomaterials. These exposures pose both acute and chronic health risks, many of which are insufficiently unquantified in conventional LCA frameworks.

Acrolein ($CH_2 = CH–CHO$) is a volatile α,β-unsaturated aldehyde produced as a byproduct in glycerol reforming and incomplete combustion processes. Classified by the International Agency for Research on cancer (IAR)C as a Group 3 carcinogen, acrolein is a potent irritant to the respiratory tract, eyes, and skin. The American Conference of Governmental Industrial Hygienists (ACGIH) sets the threshold limit value (TLV) of 0.1 ppm (0.25 mg m^{-3}) as an 8 hour time-weighted average reflecting its high reactivity with biological nucleophiles such as thiol and amine groups.[104,108] Inhalation at concentrations above 1 ppm can induce bronchial constriction, while exposures of 5 ppm for 10 minutes have shown to cause pulmonary edema in experimental models. The Immediately Dangerous to Life or Health (IDLH) concentrtation is 2 ppm, with an LC_{50} (rat, inhalation, 4 h) of 18 ppm.[128] In hydrogen systems employing glycerol steam reforming, at 500–600 °C and atmospheric pressure, transient acrolein formation is possible, especially under POX or startup conditions. Without adequate ventilation and scrubbing systems, operator exposure remains a credible risk, especially in pilot-scale or decentralised systems.

Catalyst manufacturing and handling involving platinum (Pt), iridium (Ir), and ruthenium (Ru) introduce airborne particulate and soluble salt hazards. Soluble Pt compounds, such as chloroplatinic acid (H_2PtCl_6), are strong respiratory sensitisers. Chronic exposure to Pt salts at concentrations as low as 20 ng m^{-3} can lead to allergic rhinitis, asthma, and dermal reactions. The ACGIH has proposed a TLV of 1 μg m^{-3} (inhalable fraction) for soluble Pt compounds. Workers in catalyst impregnation or sintering stages may be exposed to

Table 19 Toxicity profiles of key materials and byproducts in hydrogen systems

Material/byproduct	Function in H_2 system	Toxicological concern	Exposure/emission limit	Environmental impact	Lifecycle relevance	References
Platinum (Pt)	Catalyst in PEM/AEM electrolysers	Respiratory sensitiser (Pt salts); allergic asthma	TLV: 1 μg m^{-3} (inhalable); sensitisation at ∼20 ng m^{-3}	High ADP; poorly biodegradable; low recyclability	Catalyst prep, handling, EoL	108 and 117
Iridium (Ir)	OER catalyst in PEM	No formal OEL; possible systemic effects	No TLV; monitored *via* PGM exposure protocols	Rare element; high impact mining	Electrolyser stack manufacture	117
Nickel (Ni)	Catalyst/electrode material in AEM & alkaline electrolysers	Skin sensitization; respiratory toxicity; carcinogenic (Ni compounds)	TLV: 0.1 mg m^{-3} (Ni compounds, inhalable)	Moderate ecotoxicity; accumulates in soil/water	Catalyst fabrication, electrode coating, recycling	121–123
Ruthenium (ru)	Catalyst or electrode alloy	Eye/skin irritant; ingestion toxicity	No TLV; limited occupational data	Persistent; moderate toxicity	Electrode coating; spent materials	108
PFSA (*e.g.*, Nafion)	PEM membrane	PFAS class; bioaccumulative, HF risk on decomposition	TLV (HF): 0.5 ppm; ceiling: 2 ppm; IDLH: 30 ppm	PFAS persistence; long half-life in soil/water	Membrane failure, incineration	108 and 118
CdS (cadmium sulfide)	Photocatalyst for H_2 splitting	Carcinogen; nephrotoxic; oxidative stress	TLV: 0.01 mg m^{-3} (Cd); LC_{50} (rat, 4 h): ∼25 mg m^{-3}	High aquatic toxicity; bioaccumulation	Photocatalyst fabrication, disposal	104 and 119
TiO_2	Photocatalyst for PC H_2 production	Low acute toxicity; possible inhalation risk (nano TiO_2)	TLV: 10 mg m^{-3}	Environmentally stable; low aquatic toxicity	Photocatalyst synthesis, deployment, disposal	124 and 125
$SrTiO_3$	Photocatalyst (doped systems for PC H_2)	Low toxicity; Sr compounds may affect aquatic systems at high doses	No specific TLV; governed by Sr exposure limits	Chemically stable; low persistence risk	Catalyst synthesis and EoL	126 and 127
Pb-based perovskites	Photoelectrode for PEC hydrogen	Neurotoxic, developmental toxin	TLV (Pb dust): 0.05 mg m^3; banned in some electronics	Water and soil leaching risk	Degradation, landfill, PV disposal	108 and 119
Acrolein	Glycerol reforming byproduct	Respiratory toxin; probable carcinogen	TLV: 0.1 ppm; IDLH: 2 ppm; LC_{50}: ∼18 ppm (rat)	VOC; acute air and aquatic toxicity	Startup, incomplete combustion	104 and 128
VFAs (*e.g.*, acetic acid)	Anaerobic digestion intermediate	Corrosive to mucosa; odor nuisance	No TLV; low acute toxicity	Soil acidification if unmanaged	Digestate use, fugitive emissions	117

nanoparticle-bound platinum group of metals (PGMs), with aerodynamic diameters below 100 nm enabling deep lung penetration and alveolar retention.[108,119] These metals can catalyse redox reactions in lung lining fluid, generating reactive oxygen species and pro-inflammatory cytokines. There is currently no established occupational exposure limit for iridium and ruthenium in most regulatory systems, underscoring the need for precautionary measures and systematic monitoring in hydrogen catalyst production.

Perfluorosulfonic acid (PFSA) membranes such as Nafion™, when subjected to mechanical degradation, thermal decomposition (>250 °C), or electrical failure (*e.g.*, localized hot spots in electrolysers), can release hydrogen fluoride (HF), a highly corrosive gas. HF is recognised by Occupational Safety and Health Administration and ACGIH as a Class 1 corrosive substance, with a TLV of 0.5 ppm (0.4 mg m^{-3}) and a ceiling value of 2 ppm. The IDLH is 30 ppm, and exposures above 10 ppm can rapidly cause mucosal burns, bone decalcification, and systemic hypocalcemia due to fluoride ion complexation with calcium ions in the blood.[118] Post-mortem findings in fatal exposures reveal hemorrhagic pulmonary edema and multi-organ fluoride accumulation. In PEM electrolysis membrane failure events, localised HF emissions can occur at the anode–membrane interface. Thermal breakdown of just 1 g of PFSA under inert condition can produce up to 0.5 g of HF, according to thermogravimetric analysis (TGA) and gas-phase FTIR studies.[108]

Industrial-scale hydrogen facilities typically employ local exhaust ventilation, gloveboxes for catalyst handling, acid scrubbing towers, and HF detectors in membrane manufacturing units. However, decentralised or pilot-scale hydrogen system—particularly those in emerging economies or rural deployments may lack such engineered controls. Quantitative risk assessment and occupational exposure modeling (*e.g.*, using AIHA's Exposure Assessment Strategies) should be mandatory in technology deployment, particularly for:

- Electrolyser stack maintenance involving PFSA.
- Thermochemical reformers operating with oxygenates.
- Catalyst regeneration or leaching processes.
- Laboratory-scale synthesis of photocatalysts with heavy metals.

Failure to address this occupational risk may not only breach health and safety regulations but also undermine the social license to operate for hydrogen technologies promoted as sustainable.

9.3 Hydrogen safety hazards and risk assessment

Hydrogen, while pivotal to the decarbonisation of the global energy infrastructure, presents multifaceted safety challenges due to its unique physico-chemical properties. One of the most critical intrinsic hazards is its extremely wide flammability range of 4–75 vol% in air, significantly broader than that of methane (5–15%) or propane (2.1–9.5%), which increases the probability of forming combustible mixtures under leak conditions.[129] Hydrogen's minimum ignition energy is only 0.02 mJ in air and can drop further to 0.0056 mJ in oxygen-rich environments, compared with 0.29 mJ for methane and 0.25 mJ for gasoline vapors, making it susceptible to ignition from electrostatic discharges or minor mechanical sparks.[130] Its autoignition temperature is approximately 500 °C under standard atmospheric conditions, a relatively moderate threshold, which, when combined with leak scenarios in high-pressure systems or confined environments, substantially increases fire and explosion risks.[131] Hydrogen's high diffusivity (0.61 $cm^2 s^{-1}$ in air) enables rapidly dispersion, however in enclosed or semi-enclosed spaces, this can result in large homogeneous flammable clouds which, if ignited, may result in deflagration or detonation depending on the concentration profile and turbulence intensity.[130]

Hydrogen storage, whether as compressed gas, cryogenic liquid, or chemically bound in hydrides and LOHCs, introduces specific safety concerns tied to each method's thermodynamic and mechanical constraints. High-pressure CGH_2 is typically stored at 350–700 bar, often in Type III or Type IV composite tanks. Type IV vessels which use polymer liners reinforced with carbon fiber composites are designed to mitigate hydrogen embrittlement and permeation but remain vulnerable to mechanical damage, thermal decomposition, and localised overheating.[129] A 700 bar tank failure can release hydrogen at a sonic leak velocity exceeding 1300 $m s^{-1}$, generating a flammable cloud within seconds and producing overpressures above 0.2 bar at distances of up to 30 meters in congested environments.[130] For cryogenic LH_2, stored below 20.3 K at near-atmospheric pressure, hazards include rapid boil-off gas generation, pressure buildup, and cold embrittlement of containment materials. If LH_2 leaks and contacts warmer surfaces, rapid phase transition and vapor cloud formation can occur. Computational fluid dynamics simulations by Chauhan *et al.* (2024)[132] demonstrated that a 0.06 $kg s^{-1}$ LH_2 leak under crosswind conditions can yield a flammable cloud volume of 3.8 m^3, with explosion overpressures reaching 1.5 bar in confined areas. In solid-state storage using metal hydrides like magnesium or sodium alanate, thermal management is critical: hydrogen release is endothermic and relatively slow, while rehydrating is exothermic and may become uncontrolled if cooling fails.[131] LOHCs such as dibenzyltoluene provide safer ambient-condition transport by chemically binding hydrogen; however thermal dehydrogenation at >250 °C requires strict temperature control, and carrier degradation can lead to pressure excursions and toxic by-products. The gravimetric hydrogen density of hydrides and LOHCs ranges from 5–8 wt%, lower than that of compressed or LH_2 but favorable in distributed and mobile applications if robust safety measures are enforced.[130]

Risk mitigation in hydrogen systems spans both engineering and procedural interventions, guided by internationally accepted regulations, codes, and standards. Structural mitigation include composite pressure vessels made from high-strength carbon fibers and resin matrices, which resist hydrogen-induced cracking and minimise permeation.[129] Multilayer liners metallic or polymeric liners further reduce diffusion, while advanced tank designs incorporate thermally activated pressure relief devices, burst disks, and vent stacks to manage overpressure events safely. Empirical studies show that hydrogen deflagration within confined areas can generate peak overpressures of 0.3–0.7 bar if ignition occurs before adequate ventilation or relief. Ventilation systems are therefore essential in indoor environments to maintain hydrogen concentrations below the lower flammable limit (LFL); air exchange rates of 1–2 ACH (air changes per hour) can dilute minor leaks within 60–120 seconds.[130] ISO/TS 19880–1:2020 specifies requirements for hydrogen refueling stations, including component design, venting, fire protection, and minimum setback distances ranging from 1.5 to 10 meters based on system scale and layout.[131] National Fire Protection Association (NFPA) 2 (2023 edition) covers gaseous and liquid hydrogen systems, dictating spacing, ventilation, and leak detection requirements for stationary storage and dispensing, while NFPA 55 mandates dual-containment systems, active boil-off control, and fire-rated barriers for. For LH_2 facilities.[132]

Detection technologies are critical for early leak identification and rapid emergency response. Metal oxide semiconductor sensors, catalytic pellistors, and thermal conductivity detectors are standard for fixed installations, offering detection limits down to 0.01 vol% hydrogen with response times under 5 seconds.[129] Acoustic sensors have shown promise for pipeline monitoring, detecting high-frequency ultrasonic signatures from small leaks up to 50 meters away with directional resolution within ±5°.[130] Infrared and thermal imaging enable visualisation of low-temperature LH_2 leaks or heat-induced anomalies from rapid decompression. Integrated detection systems often employ logic controllers to trigger safety protocols such as valve shutdown, venting, and ventilation activation. Detection reliability is improved through multi-sensor arrays deployed in layered configurations with placement informed by CFD dispersion modeling to optimise coverage, in complex geometries or variable wind conditions.[132]

Hydrogen safety risk assessment benefits from systematic methodologies such as Hazard and Operability Study (HAZOP), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Bow-Tie modeling. In AWE hydrogen production, HAZID and What-If analyses have identified key failure points including membrane rupture, gas cross-over, and electrolyte leakage, as a key failure points, with FTA indicating that seal degradation accounts for over 40% of leak initiations at operating pressure >30 bar.[133] CFD analysis of hypothetical indoor release suggest that low-flow leaks of 0.01 kg s^{-1} can elevate ambient concentrations to the LFL within 6–10 seconds in unventilated enclosures, emphasising the critical role of pre-ignition dilution strategies.[130] Probabilistic risk assessment frameworks such as Dynamic Bayesian Networks are increasingly adopted for modeling conditional dependencies in leak-ignition-damage sequences integrating factors such as human error probabilities, corrosion rates, weather conditions, and failure histories to dynamically assess real-time risk. As hydrogen integration advances in transport, power-to-gas, and industrial decarbonisation, ensuring safety through robust, data-driven assessment and mitigation is fundamental to public confidence, regulatory compliance, and long-term viability.

While the technical parameters of hydrogen flammability and storage are well documented, critical gap remains in the transition from deterministic safety standards to probabilistic real-world performance. Current regulations, such as ISO/TS 19880 and NFPA 2, rely heavily on fixed setback distances; however, these do not fully account for the confinement-induced turbulence found in modern urban architectures, where hydrogen's high diffusivity can ironically facilitate the rapid formation of homogenous flammable pockets in semi-enclosed spaces. Furthermore, the reliance on Type IV composite vessels introduces a monitoring paradox. While these materials resist classic hydrogen embrittlement, their viscoelastic nature complicates the detection of micro-fatigue using standard acoustic sensors, which are often calibrated for metallic failure signatures. Additionally, current risk assessment methodologies like HAZOP and FTA frequently treat human error and sensor reliability as static variables. In practice, as hydrogen moves from controlled industrial environments to public-access refueling stations, the Dynamic Bayesian Network approach becomes essential to model the non-linear escalation of risks such as how a minor seal degradation interacts with variable wind turbulence and delayed sensor response times to create a catastrophic deflagration event.[130,132] Hydrogen safety considerations become increasingly complex at large deployment scales and cannot be fully addressed through qualitative assessment alone. Scale-dependent risks include hydrogen embrittlement and accelerated material degradation in legacy pipelines, elevated failure consequences in high-pressure storage and transport systems, and the potential for systemic risk in geographically concentrated hydrogen hubs. These challenges necessitate infrastructure-specific material compatibility assessments, enhanced monitoring and leak detection systems, and coordinated safety management across interconnected production, storage, and distribution assets.[134] Consequently, large-scale hydrogen deployment requires a shift from component-level safety considerations toward integrated, system-level risk assessment and mitigation strategies.

10. Hydrogen production routes supporting the circular bioeconomy

The integration of hydrogen technologies within circular economy models strongly complements green chemistry objectives, particularly those focused on resource efficiency, design for degradation, and the minimisation of environmental toxicity. When embedded within circular economy frameworks, hydrogen production technologies offer significant potential for resource efficiency, waste minimisation, and climate mitigation. Fossil fuel-based methods such as SMR, ATR, and coal gasification currently dominate the global hydrogen supply but generate substantial CO_2 emissions. However, when combined with CCS, as in the case of blue hydrogen, these processes can reduce lifecycle emissions and facilitate reuse of carbon, aligning with circularity principles through valorisation of by-products and minimisation of environmental burden.[134] Methane pyrolysis provides an alternative pathway that avoids direct CO_2 emissions and produces solid carbon, which can be reutilised in material applications, further supporting a closed-loop system.[135]

In the biological domain, hydrogen production *via* DF, PF, and MECs enables the transformation of organic waste into renewable hydrogen. These pathways not only divert waste from landfills but also recover nutrients and enable decentralised energy generation, thus contributing directly to bio-circularity.[135] Gasification of biomass and municipal solid waste provides another thermochemical option for circular hydrogen production, converting diverse carbonaceous feedstocks into syngas for hydrogen extraction. Integrating such systems with CCS, as demonstrated in waste-to-blue hydrogen models, enhances carbon efficiency and environmental performance while optimising hydrogen yields through system-level trade-offs.[134]

Electrolysis-based green hydrogen production, when powered by renewable energy, represents a zero-emission solution with potential for integration into wastewater and seawater treatment systems. Electrolysers such as PEM, AEL, and SOEC can utilise treated effluents or desalinated water, thereby supporting circular water management alongside clean fuel production.[136] This coupling enables the recovery of water, energy, and valuable by-products, effectively transforming linear treatment facilities into circular biorefineries. Additionally, the integration of life cycle optimisation and resource recovery models provides tools to quantify trade-offs and maximise system sustainability.[134]

The hydrogen production sector thus plays a pivotal role in circular bioeconomy development by enabling the transformation of waste into energy, promoting resources regeneration, and contributing to decarbonisation efforts across industries and urban systems.[135,136] This systemic integration of hydrogen production routes within a circular framework is illustrated in Fig. 12.

11. Green hydrogen and circular economy: a bibliometric analysis

For the bibliometric analysis, an advanced literature search was conducted in the Web of Science Core Collection database[137] using the keywords “Green Hydrogen” and “circular economy”, which resulted in a total of 428 articles. The bibliometric analysis of these publications was performed using the VOSviewer software (Version 1.6.19).[138,139] The analysis was based on the co-occurrence of terms, with the unit of analysis set as all keywords. A full counting method was applied, and the minimum number of keyword occurrences was set at five. Out of 2709 identified keywords, 172 met this threshold. The network visualization generated by VOSviewer grouped these keywords into four distinct clusters, representing the major research themes within the field (Fig. 13).

Cluster 1 (Red colour with 60 items) is the core cluster emphasizing green hydrogen technologies and their integration with circular economy principles. It includes keywords such as "hydrogen, green hydrogen, energy, circular economy, life cycle assessment, storage, gas, renewable energy". The presence of life cycle assessment indicates the increasing focus on sustainability evaluation of hydrogen production and utilization. Similarly, the keywords storage and renewable energy highlight ongoing challenges in energy systems integration and the critical role of hydrogen as an energy carrier for decarbonization. The cluster 2 (Green Colour with 47 items) primarily reflects the technological and materials science aspects of hydrogen production. It consists of keywords such as "water, conversion, performance, degradation, electrolysis, oxidation, reduction, nanoparticles, kinetics". The occurrence of electrolysis and performance underscores the significance of process optimization, while oxidation, reduction, and kinetics emphasize the fundamental reaction mechanisms. The repeated occurrence of nanoparticles demonstrates active research into nanomaterial-based catalysts for improving electrolysis efficiency and durability. Cluster 3 (Blue Colour with 37 items) is centred on biological and biomass-based hydrogen production pathways. It incorporates keywords such as "biohydrogen production, biomass, biodiesel, anaerobic digestion, DF, resource recovery, lignocellulosic biomass". The presence of DF and anaerobic digestion reflects growing interest in biotechnological approaches, whereas resource recovery links these processes directly to the principles of the circular economy. Similarly, lignocellulosic biomass and biodiesel highlight the valorization of agricultural and organic waste streams for hydrogen generation. Cluster 4 (Yellow Colour with 28 items) highlights sustainability, valorization, and green chemistry approaches. It comprises keywords such as "sustainability, carbon oxidation, water valorization, recovery, pretreatment, extraction, lignin, cellulose, green chemistry". The combination of pretreatment, lignin, and cellulose demonstrates a strong emphasis on biomass valorization, while water valorization and recovery indicate resource-efficient processing. The keyword green chemistry connects these efforts to

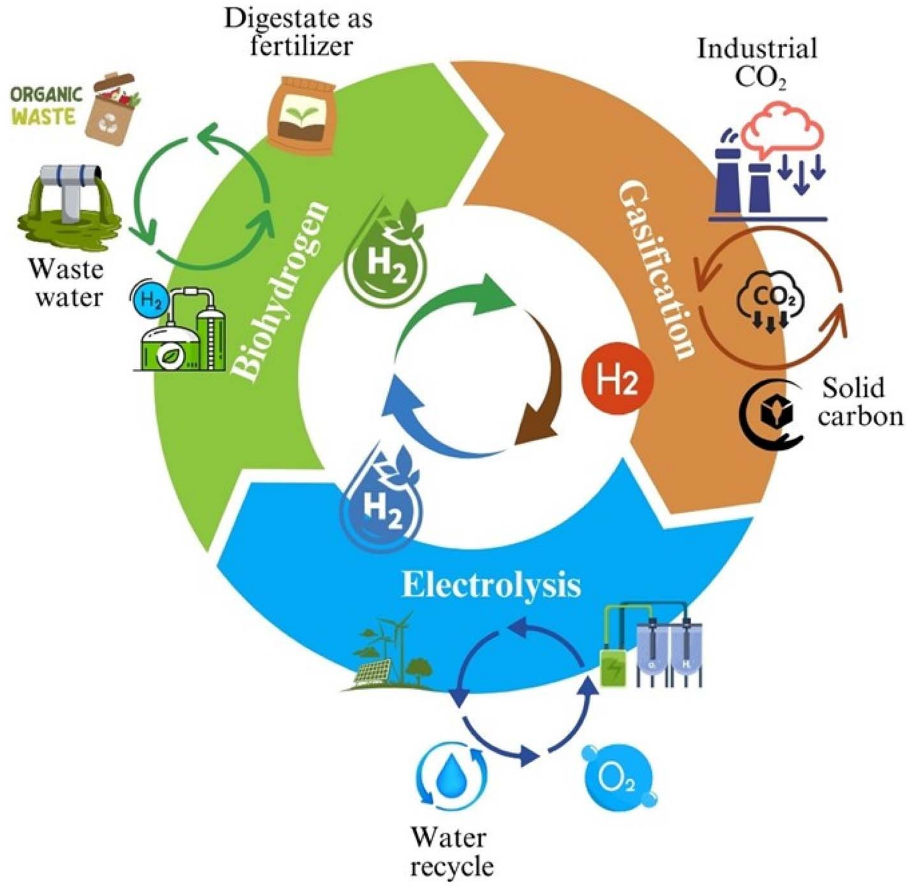

Fig. 12 Circular integration of hydrogen production technologies in the bioeconomy.

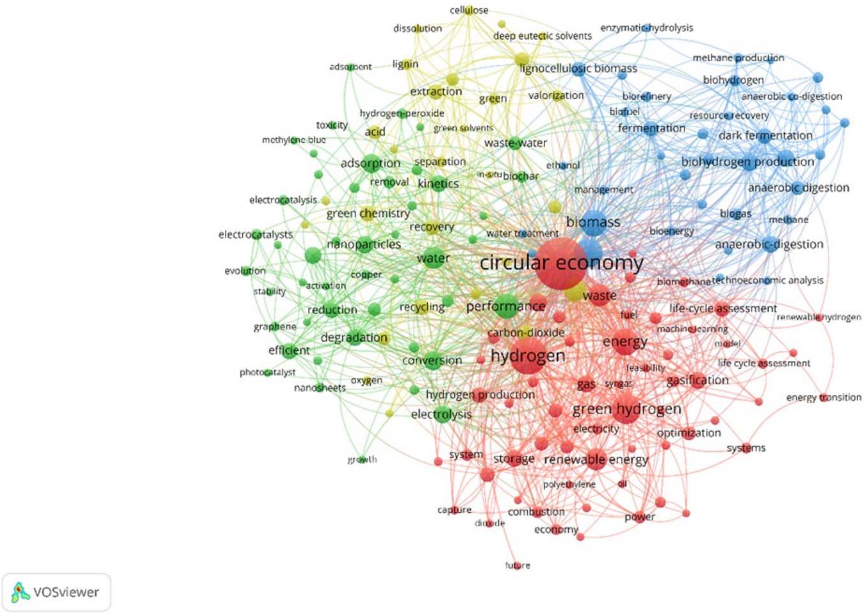

Fig. 13 Co-occurrence network of keywords.

environmentally benign and circular methodologies for hydrogen and by-product utilization.

The analysis indicates that research on green hydrogen and the circular economy is primarily focused on advancing clean energy systems, improving technological efficiency, and developing innovative production methods. Alongside these technological advancements, increasing attention is being given to biological pathways and waste-to-energy processes, which align hydrogen production with circular economy principles.[140] Sustainability considerations, including resource recovery and environmentally friendly processing, further highlight the integration of green hydrogen research within broader circular economy frameworks. This research field is evolving from technology-centered studies toward a more holistic approach that combines energy innovation, biotechnology, and sustainable resource management.

12. Hydrogen economy and industrial symbiosis

The hydrogen economy is increasingly recognised as a cornerstone of the global transition to sustainable energy systems, with its successful deployment hinging not only on technological innovation but also on systemic integration across industrial ecosystems. Industrial symbiosis (IS) the collaborative exchange of materials, energy, and information between co-located industries has emerged as a key enabler for embedding hydrogen production and use within circular and resilient industrial frameworks.[141] In this context, green hydrogen serves as a dual vector: both a clean energy carrier and a facilitator of industrial ecology through cross-sectoral synergies.

IS supports hydrogen economy development by enabling the reuse of by-products and waste heat, optimising the consumption of water, energy, and raw materials, and minimising emissions across interconnected production chains. For example, in eco-industrial parks, waste oxygen and heat from electrolysis processes can be recovered and repurposed in adjacent manufacturing systems, such as cement, steel, or chemical production, thereby increasing resource efficiency and lowering the net carbon footprint of hydrogen systems.[142] Similarly, water recovered from industrial processes, including those in gas-to-liquid and liquefied natural gas operations can be reused in hydrogen electrolysis, reducing freshwater dependency in arid regions.

Moreover, a hydrogen-integrated industrial network enables the valorisation of CO_2, biogas, and biomass residues, creating multiple pathways for the circular conversion of carbon-rich waste into clean fuels. The strategic coupling of hydrogen hubs with ports, chemical clusters, and renewable generation sites enhances not only sustainability but also economic resilience.[143] Together, the hydrogen economy and IS form a synergistic model that advances multiple Sustainable Development goals (SDGs), particularly those related to clean energy (SDG7), sustainable industry (SDG9), responsible production (SDG12), and climate action (SDG13). The systemic integration of hydrogen production into IS networks is visualized in Fig. 14.

13. Green hydrogen and sustainable development goals

13.1. Green hydrogen and the 2030 agenda: a strategic alignment

Green hydrogen is rapidly gaining global attention as a key technology for achieving the United Nations' 2030 Agenda for Sustainable Development. Produced through electrolysis powered by renewable energy, green hydrogen offers a clean and versatile alternative to fossil fuels. It aligns directly with SDG 7 (Affordable and Clean Energy) and plays a critical role in SDG13 (Climate action) through its application in decarbonizing hard to abate sectors such as ammonia, steel, shipping, and aviation.[10,143,144] Green hydrogen also supports SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation and Infrastructure) through the expansion of electrolyser manufacturing, renewable energy integration, and the development of new infrastructure for transport and storage.[145] In water-scarce regions, coupling electrolysis with desalination supports SDG6 (Clean water and sanitation), While applications in clean mobility and urban decarbonization contribute to SDG11 (Sustainable Cities and Communities) and SDG12 (Responsible Consumption and Production).[10,145] Recent global policy milestones, including the COP28 outcomes and the Dubai Agreement, have reaffirmed the role of green hydrogen in achieving the 1.5 °C target and advancing SDG17 (Partnerships for the Goals).[144] Fig. 15 illustrates the multi-SDG alignment of green hydrogen.

13.2. Green hydrogen contributions to key SDGs

Green hydrogen is uniquely positioned to contribute to a wide array of SDGs, with direct and indirect benefits across environmental, economic, and social domains. The following sub-sections highlight how green hydrogen supports some of the most critical SDGs, as discussed in the recent sustainability and hydrogen literature. The cross-cutting contributions of green hydrogen to various SDGs are illustrated in Fig. 15.

13.2.1 SDG 6 – clean water and sanitation. Green hydrogen deployment can be aligned with sustainable water use through integration with desalination systems and non-freshwater sources, offering opportunities in arid regions if water-energy nexus assessments are included. As highlighted by Peyerl and van der Zwaan (2024),[145] careful management is crucial to avoid stress on freshwater systems, particularly in the global south. These practices support Target 6.3 (water quality and reuse), Target 6.4 (water-use efficiency) and Target 6.5 (integrated water resources management).

13.2.2 SDG 7 – affordable and clean energy. Green hydrogen provides a clean, storable energy carrier that decarbonizes electricity, industry, and transport while enhancing renewable integration by absorbing excess solar and wind power. According to Mneimneh *et al.* (2023),[143] these systems offer significant advantages for universal energy access in remote areas. This contributes to Target 7.1 (affordable energy access), Target 7.2 (increasing renewable share), and Target 7.b (expanding infrastructure in developing countries).

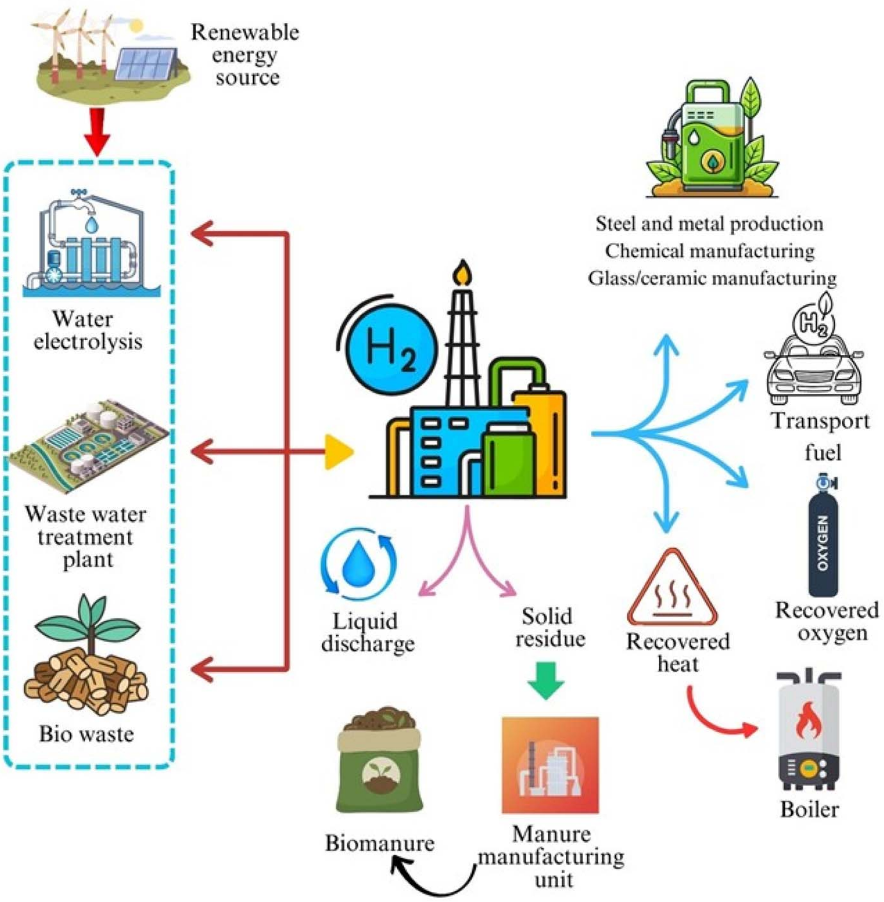

Fig. 14 Illustration of green hydrogen integration within an IS network.

Fig. 15 Green hydrogen's systemic contributions to the UN SDGs.

13.2.3 SDG 8 – decent work and economic growth. Hydrogen development fosters green industrialization and job creation across the supply chain, including manufacturing and maintenance. Li *et al.* (2023)[85] emphasize that the hydrogen economy could generate millions of jobs. These outcomes align with Target 8.2 (technological innovation), Target 8.3 (productive employment and MSMEs), and Target 8.5 (full employment and equal pay).

13.2.4 SDG 9 – industry, innovation, and infrastructure. Green hydrogen decarbonizes hard-to-abate industries like steel and chemicals, driving low-carbon innovation. Infrastructure for production and transport stimulate investment in energy corridors and industrial hubs. As Peyerl and van der Zwaan (2024)[145] point out, this value chain builds resilient infrastructure globally, aligning with Target 9.1 (sustainable infrastructure), Target 9.4 (resource-efficient industry), and Target 9.5 (enhanced scientific research).

13.2.5 SDG 11 – sustainable cities and communities. Hydrogen contributes to urban sustainability through clean public transport, heating, and backup power. As shown by Martinez de Leon *et al.* (2024),[146] it complements urban decarbonization by reducing air pollution in densely populated areas. These advancements address Target 11.2 (sustainable transport systems) and Target 11.6 (reducing environmental impact/air quality).

13.2.6 SDG 12 – responsible consumption and production. Green hydrogen enables resource efficient industrial practices and circular material use. Whether from renewables or waste biomass, it reduces fossil fuel dependence and minimizes waste. As discussed by Peyerl and van der Zwaan (2024),[145] integrating hydrogen into circular strategies utilizing off-gases or organic resides reinforces sustainable production. This supports Target 12.2 (resource management), Target 12.4 (chemical/waste management), Target 12.5 (waste reduction), and Target 12.a (Sustainable technology adoption).

13.2.7 SDG 13 – climate action. Hydrogen is core to global climate strategies for meeting net-zero targets by replacing fossil fuels to enable significant GHG reductions. According to Mneimneh *et al.* (2023),[143] green hydrogen can contribute up to 20% of required emissions reductions by 2050. These benefits contribute to Target 13.1 (climate resilence), Target 13.2 (national policy integration), and Target 13.3 (climate education).

13.2.8 SDG 17 – partnerships for the goals. The international nature of hydrogen trade necessitates global collaboration between technology providers, investors, and developing nations. As emphasized by Peyerl and van der Zwaan (2024),[145] cooperation in innovation, standards, and financing is key to equitable participation. This aligns with Target 17.6 (technological cooperation), Target 17.7 (environmentally sound technology transfer), and Target 17.9 (capacity-building).

14. Conclusion

This review set out to address a central question: how can green hydrogen, aligned with green chemistry and circular economy principles, be deployed strategically to deliver a low-carbon, resource-efficient, and socially inclusive energy future? The analysis demonstrates that green hydrogen is not a universal substitute for fossil fuels, but a targeted enabler of deep decarbonisation, industrial symbiosis, and multi-SDG alignment when applied in appropriate sectors and regions.

Across the hydrogen value chain, key advances were identified in biohydrogen, electrolysis (PEM, AEL, SOEC), photocatalysis, and waste-derived routes such as glycerol reforming. When integrated with renewable energy and evaluated through life-cycle performance, these pathways can reduce carbon intensity while limiting toxic intermediates and waste generation. Storage options—including compressed and liquefied hydrogen, chemical carriers, and porous materials present complementary trade-offs in safety, recyclability, and system flexibility. Policy frameworks such as India's National Green Hydrogen Mission and emerging international trade initiatives highlight the importance of coordinated governance, credible certification, and targeted incentives for effective scale-up.

The real-world implications are substantial but conditional. Green hydrogen can decarbonise hard-to-abate sectors, support grid flexibility, valorise industrial by-products, and create skilled employment across economies. At the same time, its deployment must be carefully managed to avoid inefficient energy use and unintended environmental trade-offs.

Critical limitations remain. High production costs, dependence on scarce catalyst materials, infrastructure readiness, and water availability—particularly in arid and semi-arid regions—represent first-order constraints. Without robust life-cycle assessment and systems-level planning, large-scale hydrogen deployment risks shifting environmental burdens toward resource depletion, toxicity, and land use pressures.

Future research should therefore prioritise:

- Catalyst innovation to reduce reliance on critical and hazardous materials.
- Integration of electrolysis with non-freshwater and wastewater resource.
- Scalable storage and transport solutions with minimal energy penalties.
- Harmonised international certification and safety standards.
- Multi-criteria sustainability metrics extending beyond carbon to include toxicity, circularity, and socio-economic equity.

The evidence indicates that green hydrogen, when designed, governed, and deployed within clear sustainability boundaries, can form a cornerstone of a resilient net-zero energy system. Its success will depend on aligning chemistry-driven innovation with policy realism and systems integration, enabling climate mitigation alongside a just and resource-efficient energy transition.

Author contributions

Debajyoti Kundu: conceptualisation, methodology, writing – original draft; writing – review & editing, supervision. Arun Barathi, Kumari Pooja, Madhava Surya, Samuel Jacob, Apurba Koley, Palas Samanta, Vineet Kumar, Anjani Devi Chintagunta, N. S. Sampath Kumar: writing – original draft. Srinivasan Balachandran, Hari Singh: writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

ACGIH	American conference of governmental industrial hygienists
ACH	Air changes per hour
ADP	Abiotic depletion potential
AEL	Alkaline electrolysers
AEM	Anion exchange membrane
ATR	Autothermal reforming
AWE	Alkaline water electrolysis
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CED	Cumulative energy demand
CFD	Computational fluid dynamics
CGH_2	Compressed gaseous hydrogen
CHP	Combined heat and power
CLSR	Chemical looping steam reforming
COD	Chemical oxygen demand
COFs	Covalent organic frameworks
DF	Dark fermentation
DOE	Department of energy
E-factor	Environmental factor
EoL	End-of-life
EROI	Energy return on investment
ETA	Event tree analysis
FCEVs	Fuel cell electric vehicles
FMEA	Failure modes and effects analysis
FTA	Fault tree analysis
GHG	Green house gas
GW	Gigawatt
HAZOP	Hazard and operability study
HER	Hydrogen evolution reaction
HRT	Hydraulic retention time
IDLH	Immediately dangerous to life or health
IRENA	International renewable energy agency
IS	Industrial symbiosis
ISO	International organisation for standardisation
LCA	Life cycle assessment
LCOH	Levelised cost of hydrogen

LCSA	Life cycle sustainability assessments
LFL	Lower flammable limit
LH_2	Liquefied hydrogen
LOHCs	Liquid organic hydrogen carriers
MCFCs	Molten carbonate fuel cells
MECs	Microbial electrolysis cells
MMT	Million metric tonnes
MOFs	Metal–organic frameworks
NFPA	National fire protection association
NGHM	National green hydrogen mission
OER	Oxygen evolution reaction
P2H2P	Power-to-hydrogen-to-power
PAFCs	Phosphoric acid fuel cells
PC	Photocatalytic
PEC	Photoelectrochemical
PEM	Proton exchange membrane
PEMFCs	Proton exchange membrane fuel cell
PF	Photofermentation
PFSA	Perfluorosulfonic acid
PGMs	Platinum group of metals
PLI	Production-linked incentives
PMI	Process mass intensity
POX	Partial oxidation
PV-EC	Photovoltaic-electrochemical
SMR	Steam methane reforming
SOECs	Solid oxide electrolyser cells
STH	Solar-to-hydrogen
TLV	Threshold limit value
USD	United states dollar
VFAs	Volatile fatty acids

Data availability

All relevant data supporting this study are provided within the manuscript. This review does not include primary research results, software, or code, and no new data were generated or analysed as part of this work.

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