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Hydrogen as a Catalyst for Sustainability: Decoding the Value Chain of a Low-Carbon Future

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Abstract

The escalating global demand for energy, propelled by rapid economic expansion and population growth, has intensified dependence on fossil fuels, resulting in heightened greenhouse gas emissions and accelerated resource depletion. This pressing scenario underscores the urgent need to transition from conventional energy systems to renewable energy alternatives. Hydrogen (H_2) has emerged as a clean energy fuel to facilitate a shift towards a lower carbon economy. Unlike carbon-based synthetic fuels, H_2 offers the potential for a carbon-neutral or even carbon-negative lifecycle when produced from renewable energy sources. This review provides a comprehensive and systematic analysis of the hydrogen economy, detailing its value chain from production to practical application and elucidating its potential to support decreasing carbon footprint. Herein, we discuss a variety of hydrogen production methodologies, including established techniques such as steam methane reforming and innovative approaches such as electrocatalysis, photocatalysis, biomass conversion, and non-thermal plasma-enhanced dry reforming of methane. Further, it discusses the key concept and governing parameters and emphasises its vital role in decarbonising key sectors. In addition, the review also examines hydrogen storage and transport technologies, including high-pressure compression, cryogenic liquefaction, and chemical carriers such as liquid organic hydrogen carriers (LOHCs) and metal hydrides, evaluating their technical feasibility and scalability. Furthermore, the study explores the applications of hydrogen in industrial processes, transportation, and power generation, highlighting its potential to substitute carbon-intensive energy sources. Finally, this review delineates key research and development priorities, underscoring the necessity for interdisciplinary efforts to establish H_2 as a foundational element of a sustainable, low-carbon energy system.

Keywords: Hydrogen, Generation, Storage, Utilization

1. Introduction

The increase in global population and economic development has led to a significant rise in energy demand, exerting considerable pressure on conventional energy resources. Power generation is essential for industrial growth and is critical in driving economic progress and technological advancements. However, the reliance on fossil fuels to fulfil this demand has resulted in resource depletion, energy security risks, and environmental challenges. Fossil fuels dominate global energy consumption, yet their limited availability and rapid depletion raise long-term sustainability concerns. Additionally, the combustion of fossil fuels contributes to the release of greenhouse gases, exacerbating climate change and underscoring the urgent need for a transition to cleaner energy alternatives. To address these pressing issues effectively, embracing hydrogen-based technologies, enhancing the integration of renewable energy sources, and investing in advanced energy storage systems is imperative. Their crosslinking with each other is vital for ensuring a sustainable and resilient clean energy infrastructure supporting future economic and technological growth. The key drawbacks of consuming these traditional resources (fossil fuels) are CO_2 emissions and increased global warming [1].

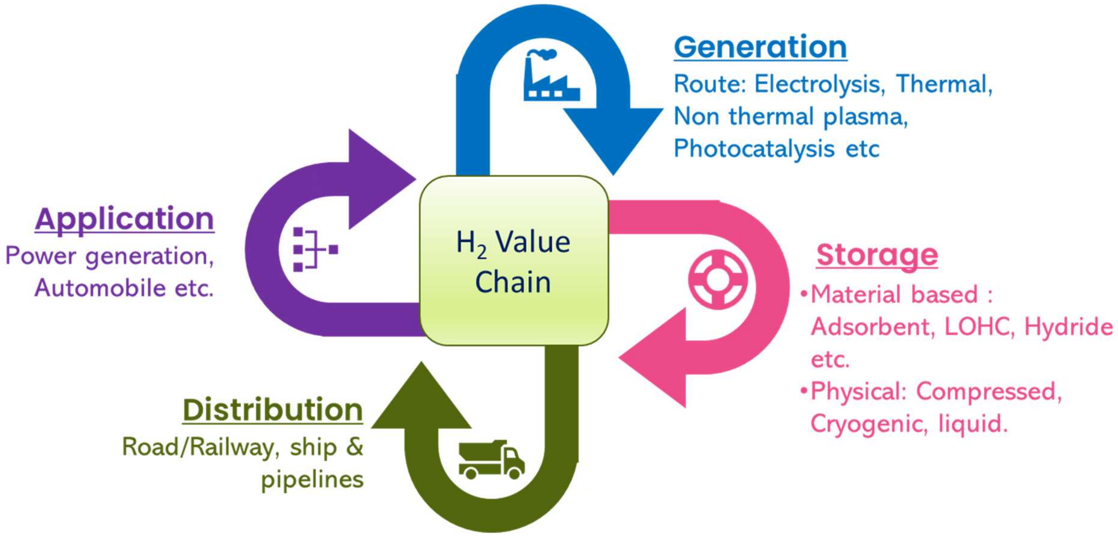


Figure 1. Schematic illustration of the hydrogen value chain

Renewable energy resources are the most promising candidates for replacing these conventional resources because of increased environmental problems. Hydrogen, the most abundant element in the universe, is the cornerstone of the global transition to clean energy. Molecular hydrogen gas (H_2) is an attractive fuel. It has the highest gravimetric energy density (142 MJ/kg), and its combustion byproduct is pollution-free water, making it an excellent energy carrier and a potential candidate for future low-carbon energy systems. Thus, they are considered essential chemicals, but their generation, storage, distribution, and further application, generally called as hydrogen value chain (**Figure 1**), are vital for decarbonising the industry and fulfilling the net zero target. Traditional production methods, such as steam methane reforming (SMR), are carbon-intensive and contribute ~830 Mt of CO_2 emissions annually [2]. Green hydrogen produced via renewable energy-powered electrolysis or novel pathways such as NTP offers a sustainable alternative. Another emerging pathway is photocatalytic hydrogen evolution, which has attracted tremendous interest because it generates green hydrogen based on solar radiation. However, the process is highly complex, as many factors influence photocatalytic hydrogen evolution. At the same time, novel photocatalysts, such as MOFs, perovskites, conjugated polymers, carbon-based materials, quantum dots, and others, face challenges such as stability and scalability.

In contrast, thermo-chemical pyrolysis and gasification are existing approaches in industries and play a dominant role in H_2 production, with costs in the range of 1.34–2.27 $/kg. Hydrogen storage is a critical aspect of the hydrogen economy, influencing its viability for energy applications. Storage methods include compressed gas, liquid hydrogen, metal hydrides, and chemical carriers such as ammonia and liquid organic hydrogen (LOHCs). Although compressed and liquid hydrogen offer direct storage solutions, they require high pressures (350–700 bar) or cryogenic temperatures (−253°C), leading to energy-intensive processes. Solid-state storage in metal hydrides and chemical carriers provides safer and more compact alternatives but faces challenges related to kinetics and reversibility. Advancements in storage materials and system integration are essential for enhancing efficiency and enabling large-scale hydrogen deployment before efficient hydrogen distribution, essential for the widespread adoption of hydrogen-based energy systems. H_2 can be transported through pipelines, compressed gas or liquid hydrogen tankers, and chemical carriers such as ammonia or liquid organic hydrogen carriers (LOHCs). Pipelines represent the economically efficient option for large-scale distribution. However, retrofitting existing infrastructure presents notable challenges that must be addressed. Cryogenic liquefaction and compression enable long-distance transport but incur high energy costs. Advancements in hydrogen carriers and storage technologies are essential to overcome logistical barriers and ensure a reliable supply chain. As a clean energy carrier, hydrogen can replace fossil fuels in hard-to-abate industries such as steelmaking, cement production, and chemical manufacturing, where direct electrification is challenging. In the transport sector, hydrogen fuel cells offer a viable alternative to heavy-duty trucks, maritime shipping, and aviation, reducing reliance on carbon-intensive fuels. In addition, hydrogen can be blended with natural gas or used in dedicated hydrogen turbines for low-carbon power generation. Coupled with carbon capture and storage (CCS) or produced via renewable-powered electrolysis, hydrogen has the potential to enable profound emission reduction across the energy system. However, achieving net zero requires overcoming the challenges related to hydrogen production scalability, cost reduction, infrastructure expansion, and energy efficiency improvements. Strategic policy frameworks, technological

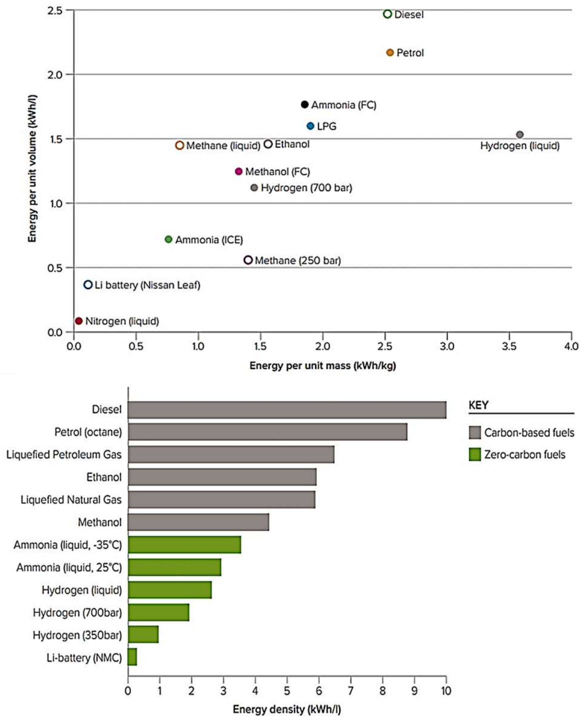


Figure 2. Comparison of Energy density (kWh/l) vs. energy per unit mass (kWh/kg) (top) and energy density of carbon and zero-carbon-based fuels (bottom). Image taken from reference [4] with permission

advancements, and international collaborations are essential for unlocking the full potential of hydrogen in a sustainable and decarbonised global economy. Further, India's National Green Hydrogen Mission (NGHM), with its significant ₹19,744 crore investment, is an example of sustainable development efforts to establish hydrogen as a linchpin of decarbonization [3].

2. Hydrogen Properties

Hydrogen has unique physicochemical properties, such as having the highest energy per unit mass of approximately 3.7 kWh/kg (**Figure 2** top). Furthermore, it compares other fuels used as automotive fuels and carbon- and non-carbon-based energy densities. However, its volumetric energy density is relatively low, at just 0.089 g/L in gaseous form under standard conditions. This low density necessitates high-pressure compression (350–700 bar) or liquefaction at −253°C for practical storage and transportation. In addition, hydrogen is colourless, odourless, and non-toxic; however, it has a wide flammability range (4–75% in air) and low ignition energy, requiring careful handling. Its high diffusivity allows for rapid dispersion, which reduces the risk of explosion in the open air. Additionally, hydrogen has a low boiling point (−252.9°C) and melting point (−259.2°C), creating cryogenic challenges that impact its applications. These properties significantly influence the use of hydrogen in fuel cells, combustion processes, and hydrogen-based industrial reactions, thereby highlighting the need for advanced storage and distribution technologies.

Another primary concern is hydrogen embrittlement, in which hydrogen diffuses into metal pipelines and storage containers, weakening their structural integrity and increasing the risk of cracking and failure. This issue is particularly critical in high-pressure pipelines and storage systems, where prolonged exposure can accelerate material degradation. As known, H_2 low energy density by volume requires both high-pressure compression and cryogenic liquefaction, which requires substantial energy input and specialised infrastructure. The next challenges associated with H_2 leakage are significant due to its small molecular size, which facilitates its escape through the distribution infrastructure's seals, channels, and microscopic pores. Additionally, the absence of a dedicated H_2 pipeline network, in contrast to the well-established infrastructure for natural gas, restricts the potential for large-scale deployment. To address this limitation, alternative hydrogen transportation methods, including liquid organic hydrogen carriers (LOHCs) and ammonia-based storage solutions, are being explored for their feasibility in long-distance and large-volume hydrogen transport. Addressing these challenges will require advancements in materials science, pipeline coatings, and efficient hydrogen carrier technologies to ensure a safe and cost-effective distribution.

3. Hydrogen Production Technologies

Hydrogen production can be categorised into two groups based on raw materials: fossil fuels and renewable resources, such as biomass and water. We primarily considered biomass or water when producing hydrogen from renewable sources. Using biomass as feedstock, the processes can be divided into two subcategories: thermochemical and biological [5]. Thermochemical technologies include pyrolysis, gasification, liquefaction, combustion, and plasma catalysis. On the other hand, the main biological processes for hydrogen production are photolysis and fermentation. The second category of renewable technologies focuses on methods that generate hydrogen through water-splitting processes. These methods include electrolysis, thermolysis, photocatalysis, and photoelectrolysis using water as the only input material. Different pathways for hydrogen production are shown in **Figure 3**. Additionally, hydrogen production methods are commonly classified using a colour coded system that categorises hydrogen based on its production method.

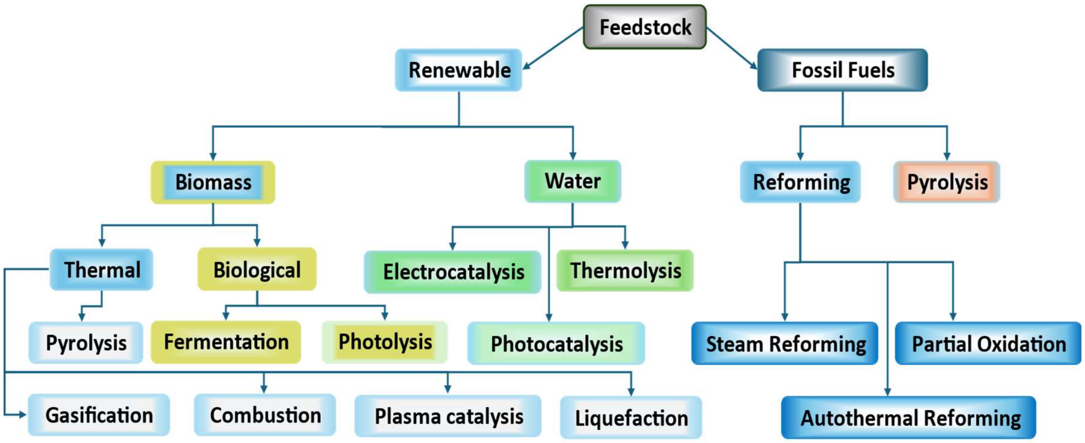


Figure 3. Schematic Illustration of various hydrogen generation processes.

a) **Gray Hydrogen** is primarily produced from natural gas through steam methane reforming (SMR) without carbon capture, producing emissions of approximately 9 to 10 kilograms of CO_2 for every kilogram of hydrogen produced. Although this method of hydrogen production is the most common today, it significantly contributes to carbon emissions.

b) **Blue Hydrogen** is derived from steam methane reforming (SMR) or auto-thermal reforming (ATR) with carbon capture, utilisation, and storage (CCUS). This process can reduce CO_2 emissions by up to 90%. It provides a transitional solution while green hydrogen is being developed, but its effectiveness depends on the efficiency and infrastructure of CCUS.

c) **Green Hydrogen** is produced through water electrolysis using renewable energy sources (solar, wind, hydro) with zero direct CO_2 emissions. It is considered the most sustainable option, but its cost remains high ($3–6 per kg of H_2) because of expensive electrolysers and renewable electricity.

d) **Turquoise Hydrogen** is generated through methane pyrolysis and natural gas is thermally decomposed into hydrogen and solid carbon. This process avoids CO_2 emissions but requires further development for large-scale implementation.

e) **Pink (or Purple) Hydrogen** is usually produced through electrolysis powered by nuclear energy; this process offers a low-carbon alternative with stable baseload electricity. However, challenges persist, such as high nuclear infrastructure costs and effective waste management.

f) **Yellow Hydrogen** is produced through electrolysis using grid electricity, which has a carbon footprint that varies based on the energy mix. If renewable energy powers the process, it qualifies as green hydrogen; otherwise, it may produce emissions.

g) **White Hydrogen** is naturally occurring geological hydrogen in underground reservoirs. It is currently in the early exploration stage and has the potential to be a sustainable hydrogen source if the extraction becomes viable.

h) **Black/Brown Hydrogen**, produced from coal gasification, emits significant levels of CO_2 and is the most carbon-intensive form of energy. Owing to environmental concerns, this is an obsolete technology.

One of the emerging pathways is Photocatalytic hydrogen evolution, which uses light energy to initiate a chemical reaction that leads to hydrogen evolution, involves light absorption by semiconductor/ photocatalyst materials, leading to the splitting of water molecules and the formation of hydrogen and oxygen gases via redox reactions at the conduction band (CB) and valance band (VB) region respectively [6]. An effective photocatalyst typically consists of redox properties that expedite the required chemical processes and a light-collecting antenna for solar energy absorption. Next, photoexcited electrons (e^-) and holes (h^+) along the thermodynamic potential of reactions process the redox reaction. The photocatalyst absorbs UV–Vis light from the sun or other illumination sources. The photoexcited electrons go to the conduction band (CB), forming electron-hole pairs with holes in the valence band (VB). The energy gap, or band gap, the difference between VB and CB, determines how much light is absorbed or whether the catalyst is photoactive or UV-active. In a photocatalytic water-splitting system, photoexcited electrons and holes move to the surface of the photocatalyst after light illumination and act as reducing and oxidising agents, respectively. Upon contact with water, whether on the surface of the photocatalyst or within the cocatalyst, the ensuing oxidation and reduction processes are initiated, as described in the equation below. In a photocatalyst (PC), the absorption of photons leads to the generation of electron-hole pairs, initiating the process of water splitting (R1).

$$\mathbf{PC + 4h\nu \rightarrow 4e^- + 4h^+} \qquad \mathbf{R1}$$

The oxidation half-reaction occurs at the anode, where water molecules are oxidised to oxygen and protons (R2).

$$\mathbf{2H_2O + 4h^+ \rightarrow O_2 + 4H^+} \qquad \mathbf{R2}$$

Simultaneously, at the cathode, the reduction half-reaction facilitates hydrogen evolution(R3) as follows:

$$\mathbf{4H^+ + 4e^- \rightarrow 2H_2} \qquad \mathbf{R3}$$

The overall water-splitting reaction (OWS) (R4) can be represented as:

$$\mathbf{2H_2O + 4e^- + 4h^+ \rightarrow 2H_2(g) + O_2(g)} \qquad \mathbf{R4}$$

To proceed, the energy input must overcome the standard Gibbs free energy change ($\Delta G°$) of 237 kJ mol^{-1}, corresponding to an electrochemical potential of 1.23 eV. As a result, the band gap of the photocatalyst must be at least 1.23 eV (approximately 1000 nm) to enable thermodynamically favourable water splitting. However, a band gap closer to the visible range is perceived to harvest 45% of the light falling on the earth's surface. At the same time, most studies focused only on UV light active photocatalyst, which contributes only 5% of the light spectrum. However, nanostructuring efficient photocatalysts for hydrogen (H_2) evolution remains a significant challenge, requiring a balance between optimal light absorption, thermodynamic potential difference, and redox activity [7]. Photocatalytic hydrogen (H_2) production holds significant promise for sustainable energy conversion but encounters several limitations. For Instance, higher band gap, the recombination of electrons and hole pairs, catalyst recyclability, and the prolonged hours of reactions in the presence of cocatalysts and sacrificial reagents for higher yields. Furthermore, the higher thermodynamic potential to proceed with the non-spontaneous reaction, ineffective charge carriers' dynamics, formed gas separation and unfavourable anode-cathode reactions impede overall efficiency. Over the past two decades, various strategies have been investigated to address these obstacles, including band gap engineering, metal/ metal or nonmetal doping, heterojunction formation, surface modification, and the development of core-shell nanostructures. Notably, enhancing charge separation and catalytic activity by incorporating cocatalysts, defect engineering, and Z-scheme or type II configurations has demonstrated promising results in improving performance. Optimising reaction conditions, enhancing catalyst design, and improving reactor configurations are crucial for minimising kinetic losses and enhancing charge transfer dynamics[6]. In addition, advanced light-harvesting strategies, such as elevating plasmonic behaviours, can be leveraged to enhance light-harvesting effects. Nanostructuring with different catalyst combinations for tailoring catalyst properties enhances photocatalytic H_2 evolution that can be further optimised for practical, clean energy applications. Meanwhile, electrocatalysis remains a well-established hydrogen production method, with alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOEC) being the most widely deployed technologies[8]. In PEM electrolysers, water oxidation at the anode generates protons (H^+) and oxygen(R7), while the protons migrate through the membrane to the cathode, forming hydrogen gas(R8). In contrast, alkaline and SOEC electrolysers introduce water at the cathode, where it is reduced to hydrogen gas and hydroxide ions (OH^-)(R6), with hydroxide ions migrating to the anode for oxygen evolution(R5). The key reactions for each system are as follows.

Alkaline and SOEC Electrolysis
Anode Reaction

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \qquad \textbf{R5}$$

Cathode Reaction

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \qquad \textbf{R6}$$

PEM Electrolysis
Anode Reaction

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad \textbf{R7}$$

Cathode Reaction

$$4H^+ + 4e^- \rightarrow 2H_2 \qquad \textbf{R8}$$

Electrolysis allows the production of high-purity hydrogen directly from water; however, its efficiency and energy consumption vary depending on the technology used. Commercial alkaline electrolysers can achieve annual hydrogen production rates of up to 380,000 kg with a system energy consumption of approximately 53.4 kWh/kg of hydrogen (H_2) and an efficiency of 73%. Solid Oxide Electrolysis Cells (SOEC) differ from alkaline and Proton Exchange Membrane (PEM) electrolysis systems operating at elevated temperatures[9]. This allows for partial replacing electrical energy with thermal energy, resulting in higher efficiency. However, the requirement for high temperatures (typically above 700°C) poses challenges for material durability. Electrolysis is one of the cleanest methods for H_2 production and reducing energy consumption and improving system longevity are critical areas for further research and development. Hydrogen can also be produced from fossil fuels via hydrocarbon reforming and pyrolysis [10,11]. Numerous chemical techniques are employed in hydrocarbon reforming, including steam reforming, partial oxidation, and autothermal steam reforming (as discussed with the reaction equation). Partial oxidation (POx) serves as a traditional method for hydrogen production, which involves the conversion of hydrocarbons, steam, and oxygen into hydrogen and carbon oxides. The catalytic POX process operates at approximately 950°C and can utilise a range of feedstocks, from methane to naphtha. Conversely, the non-catalytic POX process necessitates higher temperatures, specifically between 1150°C and 1315°C, making it suitable for processing heavier hydrocarbons such as heavy oil and coal. Hydrocarbon reforming reaction, usually used in the chemical process plant as a broader category of hydrogen production, facilitates the transformation of hydrocarbon into hydrogen through steam and oxygen as reactants. In the steam reforming (SR) process, hydrocarbons react with steam to yield hydrogen and carbon monooxides (R10), while partial oxidation entails the reaction of hydrocarbons with oxygen(R9). Next, autothermal reforming integrates both processes, effectively balancing the endothermic and exothermic reactions to enhance overall efficiency. The steam reforming consists of three fundamental steps: generating synthesis gas (syngas), the water-gas shift (WGS) (R11) reaction to produce additional hydrogen, and subsequent purification through methanation (R12) or various gas separation techniques. The raw materials for this process can range from methane, natural gas, and other methane-containing gases to various combinations of light hydrocarbons, including ethane, propane, butane, pentane, and light and heavy naphtha. If the feedstock contains organic sulfur compounds, a desulfurisation step is necessary before the reforming process to prevent poisoning of the reforming catalyst, which is typically nickel-based.

Reforming Reactions

1. Catalytic Reforming:

$$\mathbf{C_nH_m+(n/2)O_2 \rightarrow nCO+(m/2)H_2} \qquad \textbf{R9}$$

2. Noncatalytic Reforming

$$\mathbf{CH_4 + nH_2O \rightarrow nCO + (m + n)\ H_2} \qquad \textbf{R10}$$

Water-Gas Shift (WGS) Reaction

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2} \qquad \textbf{R11}$$

Methanation Reaction

$$\mathbf{CO + 3H_2 \rightarrow CH_4 + H_2O} \qquad \textbf{R12}$$

Thermochemical technologies primarily involve pyrolysis and gasification. Both processes yield various gaseous products, including methane (CH_4) and carbon monoxide (CO), which can be further processed to produce additional H_2 through steam reforming and water-gas shift (WGS) reactions. In addition to these methods, combustion and liquefaction are considered less preferable. Combustion results in low hydrogen production and emits polluting byproducts, whereas liquefaction requires challenging operational conditions, ranging from 5 to 20 MPa, in the absence of air [12].

Biomass pyrolysis is a thermochemical process that generates liquid oils, solid char, and gaseous compounds by heating biomass to temperatures between 650 K and 800 K at pressures of 0.1 to 0.5 MPa. This process occurs without oxygen, except in cases where partial combustion is permitted to supply the required thermal energy. On the other hand, biological H_2 production processes operate under ambient temperature and pressure, making them inherently energy efficient. These processes utilise renewable energy sources that are virtually inexhaustible and contribute to waste recycling using organic waste as feedstock. The primary biological pathways for H_2 generation include direct and indirect bio-photolysis, photofermentation, dark fermentation, and multistage (sequential) dark and photofermentation processes. Bio-photolysis is a biological mechanism that leverages photosynthetic principles observed in plants and algae for H_2 production. Unlike higher plants, which only reduce carbon dioxide (CO_2) owing to the absence of H_2 producing enzymes, certain algae possess hydrogenase and nitrogenase enzymes that can generate molecular hydrogen under specific conditions. For example, green algae, such as Chlamydomonas reinhardtii, can produce hydrogen through direct bio-photolysis, where water molecules are split into protons and oxygen during photosynthesis. The protons are then converted into molecular H_2 by the hydrogenase enzyme. However, hydrogenase is highly sensitive to oxygen and requires strict oxygen control below 0.1% to sustain hydrogen production. Moreover, at full sunlight intensity, nearly 90% of the photons captured by the photosynthetic apparatus (chlorophyll and associated pigments) remain unused, resulting in efficiency limitations. Indirect bio-photolysis, primarily facilitated by cyanobacteria (blue-green algae), occurs in two stages. In the first stage, photosynthetic activity produces glucose, as shown in the following reaction (R13-14):

$\mathbf{12H_2O + 6CO_2 + \{light\ energy\} \rightarrow C_6H_{12}O_6 + 6O_2}$ **R13**

In the second stage, glucose is further broken down to yield hydrogen:

$\mathbf{C_6H_{12}O_6 + 12H_2O + \{light\ energy\} \rightarrow 12H_2 + 6CO_2}$ **R14**

This process relies on enzymes hydrogenase and nitrogenase, achieving hydrogen production rates comparable to green algae. However, indirect bio-photolysis is still largely conceptual, with an estimated capital cost of $135 per square meter and a projected hydrogen production cost of approximately $10 per gigajoule, or $1.42 per kilogram of H_2. Despite their potential, biological methods for H_2 production face several challenges including low conversion efficiency, oxygen sensitivity of key enzymes, and scalability constraints. Future advancements in genetic engineering, reactor design, and metabolic optimisation may improve the feasibility of these methods for large-scale hydrogen production.

Plasma catalysis has emerged as a promising approach for hydrogen production, leveraging non-thermal plasma (NTP) to drive chemical reactions at relatively low bulk temperatures [13,14]. The interaction between the plasma-generated reactive species and catalytic surfaces facilitates enhanced reaction kinetics, lowers energy barriers, and enables hydrogen generation from diverse feedstocks, including water, hydrocarbons, ammonia, and biomass-derived gases. Plasma catalysis integrates the benefits of plasma-induced radical formation with those of heterogeneous catalysis, creating an efficient route for H_2 production. Depending on the nature of the feedstock, different reaction pathways can be employed:

Plasma-Catalytic Water Splitting

In this process, water molecules undergo dissociation in the plasma environment, leading to the formation of H_2 (R15) and oxygen radicals. These reactive species subsequently interacted with the catalyst, enhancing the reaction selectivity and improving the hydrogen yield (R16).

Overall Reaction
$\mathbf{2H_2O \rightarrow 2H_2 + O_2}$ **R15**

Activation Pathway
$\mathbf{e^- + H_2O \rightarrow H^\bullet + OH^\bullet + e^-}$ **R16**

Plasma-Catalytic Methane Reforming (Dry Reforming (R17) & Steam Reforming (R 18))

Dry Reforming:
$\mathbf{CH_4 + CO_2 \rightarrow 2H_2 + 2CO}$ **R17**

Steam Reforming
$\mathbf{CH_4 + H_2O \rightarrow 3H_2 + CO}$ **R18**

The above reactions can be activated from plasma or non-thermal plasma, which reduces the need for high temperatures compared with conventional thermocatalytic reforming. Plasma-catalytic ammonia Decomposition and Plasma-assisted NH_3 decomposition (as shown in reaction R19) allow for efficient hydrogen production at lower temperatures than traditional thermal-based catalytic processes.

$\mathbf{2NH_3 \rightarrow N_2 + 3H_2}$ **R19**

High energy plasma, usually called the 4th state of matter, offers several advantages for hydrogen production. It enables low-temperature activation, allowing reactions to proceed at reduced temperatures compared to conventional thermal catalytic processes, eventually lowering the energy requirement. The high-energy electrons in non-equilibrium reaction pathways help overcome activation barriers and facilitate alternative reaction mechanisms. In addition, plasma catalysis can integrate into the hydrocarbon processing unit's operation. Their ease of continuous feedstock treatment, such as ammonia and biomass-derived gas processing. The interaction between plasma-generated reactive species and catalytic surfaces mainly enhances reaction kinetics, improves selectivity, and boosts overall catalytic performance [15]. Despite these advantages, plasma catalysis needs continuous temperature and pressure control to use plasma efficiently. That may hinder its widespread industrial application. Energy efficiency remains critical because plasma generation requires significant power input at a specific frequency, such as over 50 kHz. Furthermore, catalyst stability under plasma conditions is oxidised or sintered, which affects long-term

Table 1. Comparison of Hydrogen Production Processes with advantages, disadvantages and TRL levels.

Process	Efficiency (%)	Major Advantages	Major Disadvantages	Technology Readiness Level (TRL)
Steam Reforming (SR)	74–85	Advanced technology with established infrastructure.	CO_2 is a byproduct of fossil fuel use.	9
Partial Oxidation (POx)	60–75			8–9
Autothermal Reforming (ATR)	60–75			8–9
Methane Pyrolysis	~50	Emission-free, reduced-step procedure.	Carbon byproducts, dependence on fossil fuels.	6–7
Biomass Pyrolysis	35–50	Environmentally friendly, abundant, and affordable raw materials.	Tar formation, varying hydrogen yield, and seasonal changes in feedstock availability.	5–6
Biomass Gasification	40–65			6–7
Bio-photolysis	10	CO_2 consumed, O_2 is the only byproduct and operates under mild conditions.	Requires sunlight, low H_2 yield, O_2 sensitivity, and controlled temperature.	3–4
Dark Fermentation	60–80	CO_2-neutral process effectively aids in waste recycling.	Lower yield and conversion efficiency. require large reactor volume.	4–5
Photofermentation	0.1	CO_2-neutral methods can use organic waste and wastewater.	Requires sunlight, low conversion efficiency, O_2 sensitivity.	3–4
Electrolysis	40–60	No emissions with renewable sources, proven technology, integrates with RES.	Low efficiency, high capital costs.	8–9
Thermolysis	20–45	Clean, sustainable, abundant feedstock, O_2 as the only byproduct.	Material corrosion, high capital costs.	4–5
Photo-electrolysis	0.06	Emission-free, abundant feedstock, O_2 as the only byproduct.	Requires sunlight and low apparent quantum yield	3–4

performance. The next challenge is the scalability for higher flow rates, which needs advancements in reactor design and optimisation of plasma discharge catalyst interactions. Addressing these issues requires the development of robust catalysts, improved reactor configurations and enhanced process integration strategies. Nonetheless, Plasma catalysis is a promising pathway for sustainable hydrogen production, particularly in decentralised and renewable energy-integrated systems. Next, in **Table 1**, we compare the various H_2 production processes' efficiency, significant advantages and disadvantages, and the corresponding Technology Readiness Level (TRL). However, continued research and technological advancements are essential to overcoming existing limitations and revamping the full potential of the H_2 economy.

Developing H_2 generation technologies requires a comprehensive approach integrating catalyst and reactor design, simulation-driven optimisation, in situ analytical techniques, techno-economic evaluation, life cycle assessment (LCA), process integration, and regulatory compliance. This development seeks to enhance reaction kinetics, optimise process intensification, and ensure economic feasibility. Developing highly active and durable catalysts, including nanostructured materials, doped metal oxides, and transition metal phosphides, is crucial for enhancing catalytic efficiency, selectivity, and operational stability. Next, an in-depth understanding of plausible reaction mechanisms, such as intermediate formation, charge transfer dynamics, and rate-determining steps, are crucial for enhancing catalytic overall performance. Besides this, theoretical and computational approaches such as density functional theory (DFT) calculations and microkinetic modelling will aid in identifying active sites and adsorption energetics, facilitating the rational design of catalyst facets[16]. Further, process modelling and simulation using tools like ASPEN Plus, COMSOL Multiphysics, and computational fluid dynamics (CFD) also play a key role in optimising reactor operation configurations for elevating energy efficiency[17]. As a result, such techniques improve mass and heat transfer characteristics, enhancing reactor performance in thermochemical, electrochemical, and plasma-assisted hydrogen production systems. Furthermore, techno-economic analysis (TEA) and life Cycle Assessment (LCA) are essential for evaluating the commercial viability of H_2 production, considering factors such as capital expenditure (CAPEX), operational costs (OPEX), and overall economic feasibility study. In general, overall minimization of overall carbon footprint for H_2 generation technologies is desired as indicated in **Figure 4** for further development.

Investigation using current state-of-the-art tools and techniques such as In-situ characterisations of Fourier Transform Infrared spectroscopy (FTIR), Electron Paramagnetic Resonance (EPR), and Near-Ambient Pressure X-ray Photoelectron Spectroscopy NAP-XPS are also crucial for ensuring operational catalysts stability and optimising H_2 production efficiency. Such analysis helps identify the key parameters

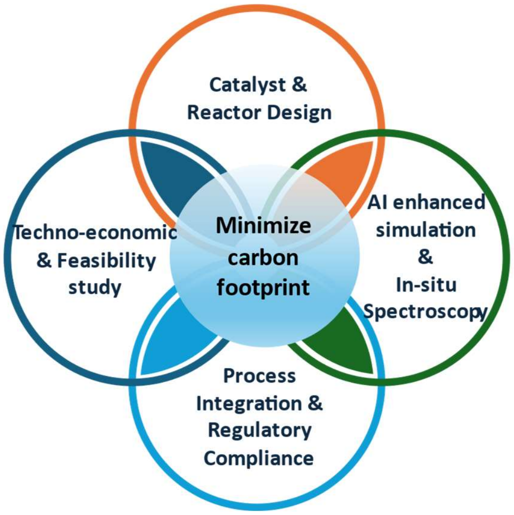


Figure 4. Minimisation of overall carbon footprint for hydrogen generation technologies.

and the effect of different available feedstock qualities on the reaction condition. Also, it is important to elucidate the reaction mechanism for hydrocarbons, ammonia, and biomass-derived gas decomposition under the influence of various reaction conditions and correlate with the overall economic viability of hydrogen production. Further, transitioning from laboratory-scale research to pilot-scale validation and industrial deployment requires comprehensive testing of catalyst performance, process stability, and energy efficiency under realistic conditions. By advancing reactor designs, optimising processes, and incorporating sustainability assessments, H_2 production technologies can be scaled into economically viable and environmentally sustainable solutions, supporting the growth of the H_2 economy. After analysis of thermos economic analysis, it desired to process the residue or by-product without impacting the environment. Also, following the environmental constraint set by the Intergovernmental Panel on Climate Change. To ensure sustainability, LCA analysis should be checked for environmental footprint calculations, considering greenhouse gas emissions, energy consumption, and resource utilisation. Reactor design remains pivotal, requiring advancements in structured catalysts, microreactors, and modular systems for decentralised H_2 production. The selection of reactor materials must consider thermal stability, corrosion resistance, and mechanical strength to withstand high-temperature and reactive environments. Energy efficiency is essential for optimising H_2 production, with strategies including waste heat recovery, process intensification through membrane separation, and integration with renewable energy sources. These approaches not only improve H_2 yield but also reduce overall energy consumption, contributing to a more sustainable and cost-effective hydrogen production process.

4. Hydrogen Storage

Recently, the world has turned to H_2 as a promising candidate for several industrial applications, including transportation, electricity generation, and long-term energy storage. However, efficiently storing H_2 presents significant challenges due to its low volumetric energy density and high diffusivity. Traditional storage methods, such as compressed gas tanks and cryogenic liquid H_2 tanks, are commonly used but have limitations. These include concerns about long-term storage, such as embrittlement, energy-intensive liquefaction processes, and potential leakage due to hydrogen's small molecular size. Several advanced H_2 storage methods are being explored, as shown in **Figure 5**, to address these challenges, categorised into physical, phase, and material-based, which are further classified into different sections. However, emerging options include underground storage, metal and complex hydrides, metal-organic frameworks (MOFs), and liquid organic hydrogen carriers (LOHCs). Underground storage in geological formations, such as salt caverns, provides a viable option for large-scale and long-duration H_2 storage[18]. However, significant capital investment, proximity to suitable geological sites, and careful management are required to prevent contamination of the stored gas. Metal and complex hydrides can chemically absorb and release H_2, allowing for high volumetric storage densities of up to 6 wt.% when using compounds like $MgCl_2$. Nonetheless, their slow-release kinetics and high thermal activation requirements pose practical challenges. Metal hydrides, such as MgH_2 and $LaNi_5$, show promising hydrogen capacities of 6–7 wt.%, but the cyclic adsorption and desorption process results in decreased efficiency with each cycle [19,20]. Emerging metal-organic frameworks (MOFs) use exceptionally high surface areas exceeding 10,000 m^2/g to enhance physisorption-based storage. However, prolonged adsorption and desorption remain challenging.

While MOFs are recognised for their high surface area and microporous structures that facilitate H_2 adsorption, their practical application is limited by the low operating temperatures needed for effective adsorption and innovative material designs to optimise performance under ambient conditions. Integrating metal hydride (MH) storage into Power-to-Power (P2P) systems offers significant advantages in H_2-based energy storage. The MH tank, positioned between an electrolyser and a fuel cell or hydrogen internal combustion engine, operates at outlet pressures of approximately 30 bar, eliminating the need for additional compression. This is a distinct advantage over compressed gaseous hydrogen (CGH_2) storage systems. The desorption pressure associated with metal hydride (MH) storage aligns effectively with the inlet pressure requirements of proton exchange membrane (PEM) fuel cells, which typically range from 3 to 5 bar. This compatibility facilitates the direct supply of hydrogen without excessive pressurisation, thereby enhancing system safety, reducing maintenance requirements, and minimising overall costs by eliminating the need for high-pressure components [21]. Moreover, MH storage is characterised by high volumetric energy density and scalability, making it suitable for small-scale residential energy storage applications and large-scale seasonal hydrogen reserves. Its capacity to retain hydrogen without losses further underscores its viability for medium- to long-term storage applications. In residential energy systems, overall efficiency is of paramount importance. A conventional power-to-gas-to-power (P2P) configuration comprises an electrolyser, a fuel cell, and a hydrogen storage unit, each contributing to efficiency losses at various stages of the energy conversion process. Nonetheless, system efficiency may be optimised by harnessing the reaction heat generated during hydrogen absorption and desorption.

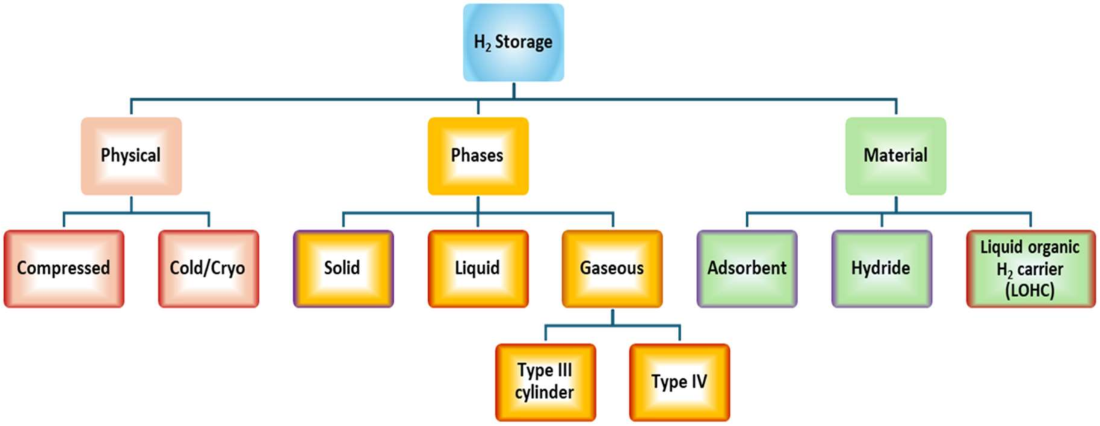


Figure 5. Schematic illustration of Hydrogen Storage in various categories.

The heat produced during the charging phase (absorption) and waste heat from the electrolyser can be redirected for residential heating or integrated into thermal energy storage systems. Similarly, the waste heat from the fuel cell can be effectively harnessed during the discharging phase (desorption). Despite MH storage exhibiting lower efficiency than battery-based energy storage systems, its scalability and compact design offer advantages for medium- to long-term hydrogen storage applications. While MH storage's slower H_2 release kinetics is generally not a limiting factor for a steady energy supply, a small buffer storage system may be necessary to accommodate peak power demands. Similar considerations apply to off-grid hydrogen storage systems reliant on renewable energy sources, where stability and energy density are key parameters.

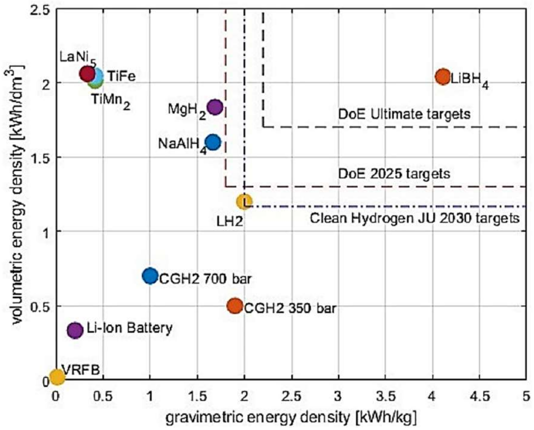


Figure 6. Volumetric and gravimetric energy densities of storage systems such as metal hydrides and others. Image taken from [22] with permission.

For backup power applications, seasonal variations of sunlight availability are crucial for energy storage. However, MH storage's inherently slower hydrogen release kinetics presents a challenge. As a result, batteries are more suitable for short-duration backup power applications. A hybrid system that integrates metal hydride (MH) storage with a smaller battery may provide an optimal solution for extended backup durations ranging from several days to weeks. Such configuration prefers MH storage's high volumetric energy density and scalability while ensuring immediate response capabilities. However, addressing regulatory constraints related to large-scale hydrogen storage is desired. The implementation of large-scale metal hydride storage systems is accompanied by the need for extensive administrative and regulatory approvals, therefore increasing the complexity of their deployment [22]. Despite these challenges, hydrogen storage based on metal hydrides remains a promising long-term solution, particularly for decentralised, off-grid, and industrial applications, due to its inherent safety, efficiency, and scalability. Complex metal hydrides are notably advantageous for mobile applications because of their high hydrogen storage capacity and relatively low weight. In addition, concerns are associated with MH toxicity and flammability.

Nonetheless, practical challenges hinder the widespread adoption due to lesser efficiency under actual operating conditions. The reversible hydrogen storage capacity is significantly lower than theoretical predictions, often decreasing each cycle. Moreover, the multi-step dehydrogenation and hydrogenation processes necessitate elevated temperatures and pressures, resulting in slow kinetics and diminished reversibility. Ongoing research efforts are concentrated on developing advanced catalysts and alternative reaction pathways to overcome these limitations. Next, thermal management is critical to MH storage configurations' viability. Efficient heat exchange mechanisms maintain operational stability and enhance hydrogen release and uptake rates. Currently, technologies based on complex hydrides are not yet commercially mature and require further fundamental research and process optimisation to facilitate large-scale implementation. An advantage of lithium-based metal hydrides is their less abundant raw material and recyclability performance, making them a sustainable alternative to conventional high-pressure H_2 storage in carbon-fibre-reinforced tanks. As industries increasingly adopt circular economy principles and prioritise life-cycle carbon footprint reduction, these attributes could drive broader adoption of MH storage solutions for medium- to long-term H_2 applications. Consequently, greater emphasis should be placed on developing efficient recycling processes and end-of-life studies to enhance the sustainability of metal hydride technologies. Improved recycling methods could also reduce manufacturing costs for MH-based storage tanks, thereby increasing their competitiveness with alternative hydrogen storage technologies and facilitating their commercialisation within the H_2 energy sector.

5. Hydrogen Distribution

Efficient H_2 transport is critical to a sustainable hydrogen economy, necessitating cost-effective, high-capacity, and safe storage and distribution methods. Among available technologies, Liquid Organic Hydrogen Carriers (LOHCs) provide a promising solution due to their reversible hydrogenation and dehydrogenation cycles, which enable safe, long-distance transport without the need for cryogenic liquefaction or high-pressure storage (shown in **Figure 7**). LOHCs chemically bind H_2 under moderate temperature and pressure conditions during hydrogenation and release it via dehydrogenation at the point of use. These processes, however, require significant energy input, which can be minimised through heat integration and catalyst optimisation to improve overall efficiency and economic viability. The feasibility of LOHC-based transport largely depends on hydrogenation and dehydrogenation efficiencies, which are influenced by carrier losses, separation inefficiencies, and catalyst stability. The primary cost drivers in hydrogenation include solvent losses and the energy-intensive separation of accumulated byproducts, while in dehydrogenation, the high cost of noble metal catalysts poses a significant challenge. Advancements in low-cost, high-performance catalysts with reduced deactivation rates and lower reaction temperatures are essential to enhance the process efficiency. Optimising heat recovery between exothermic and endothermic dehydrogenation can significantly reduce the overall energy demand and improve the hydrogen yield. LOHCs such as dibenzyl toluene, perhydro-N-ethyl carbazole, and methylcyclohexane exhibit 5–7 wt% H_2 storage capacities, making them competitive with alternative H_2 storage methods. Their low vapour pressure, non-toxic nature, and chemical stability enhance operational safety and compatibility with existing petrochemical infrastructure, facilitating large-scale implementation. For transoceanic transport, LOHCs are advantageous over compressed or liquefied hydrogen, minimising H_2 losses due to boil-off and enabling continuous supply chains for industrial and mobility applications. **Table 2** presents LOHC couples discussed in this Perspective, along with their hydrogen storage capacity, standard Gibbs free energy (ΔG°), and standard redox potential (E°)[23].

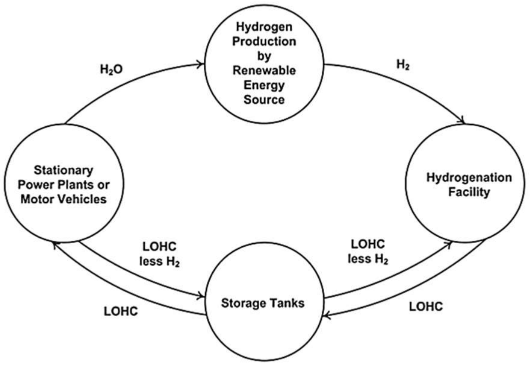
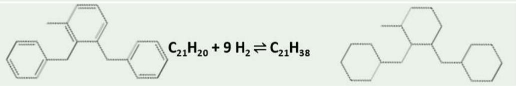
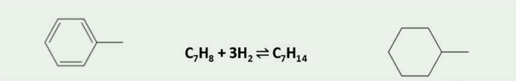
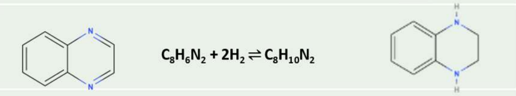
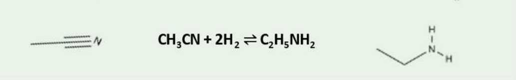
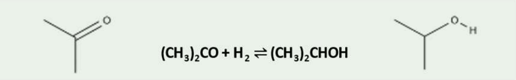
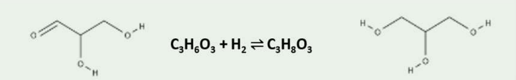
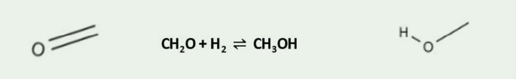
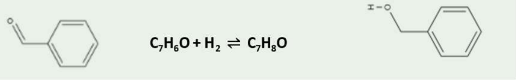
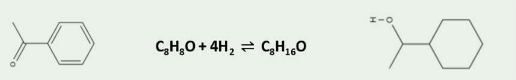
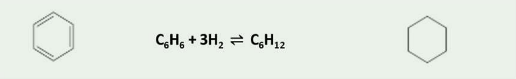


Figure 7. Schematic Illustration of LOHC supply chain.

For transoceanic transport, LOHCs are advantageous over compressed or liquefied hydrogen, minimising H_2 losses due to boil-off and enabling continuous supply chains for industrial and mobility applications. **Table 2** presents LOHC couples discussed in this Perspective, along with their hydrogen storage capacity, standard Gibbs free energy (ΔG°), and standard redox potential (E°) [23]. For a comparison of the LOHC couples, the ΔG° per mole of H_2 transferred (ΔG° relative) is also included. An example of an LOHC couple is the dibenzyltoluene/ perhydrodibenzyltoluene pair (H0-DBT/H18-DBT). An example of an LOHC couple is the dibenzyltoluene/ perhydrodibenzyltoluene pair (H0-BT/H18-DBT). The H0-DBT/H18-DBT couple offers a hydrogen storage capacity of 6.24 wt %, making it an efficient system for reversible hydrogenation and dehydrogenation cycles. Another notable advantage of the H0-DBT/H18-DBT couple is its extensive liquid range, characterised by melting points (MPs) below −30 °C and boiling points (BPs) exceeding 350 °C. This property ensures stability and ease of handling across various operating conditions. Nonetheless, a major limitation of the dibenzyl toluene (DBT)-based liquid organic hydrogen carrier (LOHC) system is its substantial energy requirement during the thermo-chemical dehydrogenation (TCD) process, which adversely impacts the overall efficiency of H_2 storage and release.

Table 2. LOHC Couples and Properties. Data taken from the ref[23] with permission.

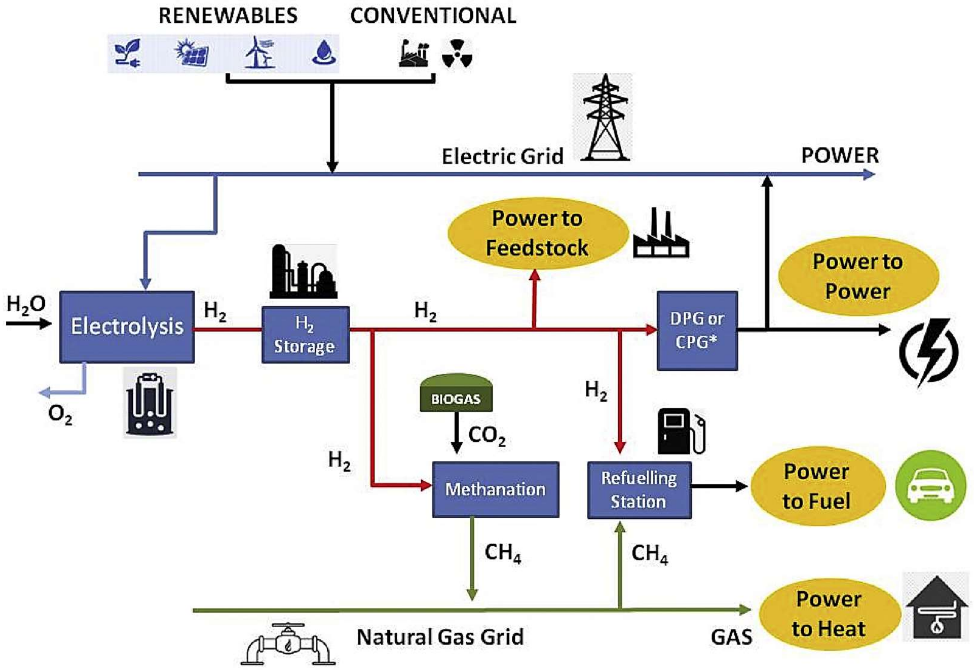
No.	LOHC Pair	Reaction	H Loading (wt%)	ΔG° (kJ/mol)	ΔG° relative (kJ/mol H2)	E° (V vs SHE)
1	Dibenzyltoluene (H0-DBT)/Perhydrodibenzyltoluene (H18-DBT)	 $C_{21}H_{20} + 9\ H_2 \rightleftharpoons C_{21}H_{38}$	6.24	-260.04	-28.89	0.15
2	Toluene/Methylcyclohexane (MCH)	 $C_7H_8 + 3H_2 \rightleftharpoons C_7H_{14}$	6.17	-93.35	-31.12	0.16
3	Quinoxaline (QX)/1,2,3,4 -tetrahydroquinoxaline (THQ)	 $C_8H_6N_2 + 2H_2 \rightleftharpoons C_8H_{10}N_2$	2.99	-38.59	-19.3	0.1
4	Acetonitrile/Ethylamine	 $CH_3CN + 2H_2 \rightleftharpoons C_2H_5NH_2$	8.96	-50.15	-25.08	0.13
5	Acetone/Isopropanol (IPA)	 $(CH_3)_2CO + H_2 \rightleftharpoons (CH_3)_2CHOH$	3.35	-22.73	-22.73	0.12
6	Glyceraldehyde (GA)/Glycerol (GL)	 $C_3H_6O_3 + H_2 \rightleftharpoons C_3H_8O_3$	2.19	-37.3	-37.3	0.19
7	Formaldehyde/Methanol	 $CH_2O + H_2 \rightleftharpoons CH_3OH$	6.3	-56.17	-56.17	0.29
8	Benzaldehyde/Benzyl alcohol	 $C_7H_6O + H_2 \rightleftharpoons C_7H_8O$	1.87	-27.5	-27.5	0.14
9	Acetophenone/1 -cyclohexylethanol	 $C_8H_8O + 4H_2 \rightleftharpoons C_8H_{16}O$	6.3	-98.34	-24.58	0.13
10	Benzene to Cyclohexane	 $C_6H_6 + 3H_2 \rightleftharpoons C_6H_{12}$	7.20	-98.97	-32.99	0.17

Furthermore, the necessity of purifying the H_2 gas produced during dehydrogenation to eliminate potential impurities or byproducts adds complexity and increases operational costs [23]. Despite these challenges, the dehydrogenation process has yielded promising results, achieving methylcyclohexane (MCH) conversion rates exceeding 95% and toluene selectivity surpassing 99%. Additionally, hydrogen and toluene yields have been reported to exceed 95%. These findings highlight the efficiency and viability of the LOHC system as a hydrogen storage and transport solution at a demonstration scale. To enhance the commercial feasibility and scalability of this technology, further advancements in catalyst design, process optimization, and energy integration strategies are essential. Generally, unsaturated organic molecules that undergo reversible hydrogenation reactions can be classified as LOHC molecules.

Some liquid organic hydrogen carriers (LOHC) are more promising than others due to factors like thermodynamic properties. The carbon footprint associated with using LOHCs for hydrogen transport can be significantly reduced by incorporating renewable energy or nuclear power into the hydrogenation and dehydrogenation processes. Furthermore, advancements in carbon-free shipping technologies are expected to decrease emissions further, making LOHCs a viable low-carbon alternative for global hydrogen logistics. A system-level techno-economic analysis (TEA) identifies several key parameters that affect cost-effectiveness and energy consumption in H_2 transport: the rate of hydrogen transport, catalyst costs, and separation efficiency. Future research should concentrate on developing catalysts to lower reaction temperatures and increase turnover rates, implementing advanced separation techniques to minimise solvent losses and enhance hydrogen purity, exploring heat integration strategies to improve energy efficiency and reduce utility costs, integrating with renewable energy sources to decrease emissions and to improve sustainability, and conducting large-scale pilot projects to validate process performance and scalability. By addressing these technological and economic challenges, LOHCs have the potential to transform hydrogen transport, enabling efficient, safe, and cost-effective distribution within regional and global H_2 supply chains.

6. Hydrogen Utilization and End-Use Applications

Hydrogen utilisation is pivotal in advancing decarbonisation efforts across multiple sectors, including industry, transportation, and power generation. **Figure 8** highlights the diverse H_2 production pathways and their integration into different sectors, showcasing hydrogen's versatility as an energy carrier. Hydrogen utilisation presents a transformative approach to reducing CO_2 emissions across diverse end-use applications and industrial systems [24,25]. In the "power-to-feedstock" paradigm, H_2 is a critical building block for producing low-carbon chemicals, such as ammonia for fertilisers or methanol for plastics, supplanting fossil-derived inputs and slashing associated emissions. The "power-to-power" scheme uses H_2 as an energy storage medium, produced via electrolysis from renewable energy sources such as wind



* DPG = Decentralized Power Generation (e.g., fuel cells or microturbines). CPG = Centralized Power Generation (e.g., turbines).

Figure 8. Schematic illustration of H_2 integration in energy production. Image taken from the ref [26] with permission

or solar power. This H_2 can be converted back into electricity through fuel cells, providing a zero-emission solution for stabilising electrical grids. In "power-to-fuel" applications, H_2 can be integrated with captured carbon dioxide (CO_2) to synthesise hydrocarbons, including synthetic methane and liquid fuels like kerosene. Such an approach offers sustainable alternatives for hard-to-abate sectors, including aviation and maritime transportation. The "power-to-heat" pathway employs H_2 combustion or catalytic oxidation to generate high-temperature heat for industrial applications, notably in steel and cement production, which have historically depended on coal or natural gas. By replacing fossil fuels with H_2, these industries can substantially decrease carbon emissions and enhance environmental sustainability. Green H_2, produced via water electrolysis powered by renewable energy sources, is a key enabler of this transition. This ensures that H_2 generation remains carbon-free, minimising environmental impact across the entire value chain. Beyond direct CO_2 emission reduction, power-to-fuel systems can integrate carbon capture technologies to enhance circularity by repurposing CO_2 rather than emitting it into the atmosphere. Similarly, power-to-heat applications utilise hydrogen's high energy density to meet industrial thermal demands without generating greenhouse gas byproducts.

However, challenges persist in scaling electrolysers, ensuring efficient H_2 storage at high pressures or cryogenic temperatures, and developing the necessary distribution infrastructure. Advances in catalysis, membrane technology, and system integration progressively address these limitations, improving efficiency and cost-effectiveness. H_2 adoption supports global decarbonisation efforts by displacing carbon-intensive energy sources and aligning with stringent climate policies. Expanding hydrogen's role in power-to-heat and related applications will require continued investment in research, innovation, and infrastructure development to enable its widespread deployment soon.

7. Future Perspectives

The hydrogen economy presents a transformative opportunity to establish a sustainable, low-carbon energy framework, yet its realisation hinges on overcoming significant scientific and logistical challenges through coordinated efforts. Addressing these challenges necessitates substantial investment in research and development to advance hydrogen production, storage, and utilisation technologies. Involving academia, industry, civil society, and policymakers is crucial to developing awareness towards society and young minds to work toward making an economically viable and scalable H_2 ecosystem. Future research should prioritise the development of advanced materials, such as nanostructured catalysts, high-performance membranes, and efficient H_2 storage solutions. Cutting-edge characterisation techniques will be pivotal in optimising these materials to enhance efficiency, safety, and durability.

A key focus area in this transition is improving hydrogen production methods, mainly electrolysis and integration of non-thermal plasma catalysis, which relies on renewable electricity to generate H_2. Each evolving technology must achieve higher energy efficiency, cost-effectiveness, and durability to meet large-scale demand. Integrating process intensification strategies, novel electrode or catalytic materials, and stack-level optimisations with various Technology readiness levels (TRL) will be essential for accelerating H_2 deployment and ensuring its role as a cornerstone of the future clean energy economy. Alternative approaches, such as photocatalysis utilising solar energy to dissociate water molecules and biohydrogen production via microbial metabolism, offer sustainable pathways but require rigorous industrial relevance optimisation. Non-thermal plasma catalysis, involving ionised gas to facilitate H_2 generation with minimal energy input, must be examined for a higher TRL level to achieve practical deployment. Integrating these diverse techniques with renewable energy sources can diversify the hydrogen supply while minimising carbon emissions.

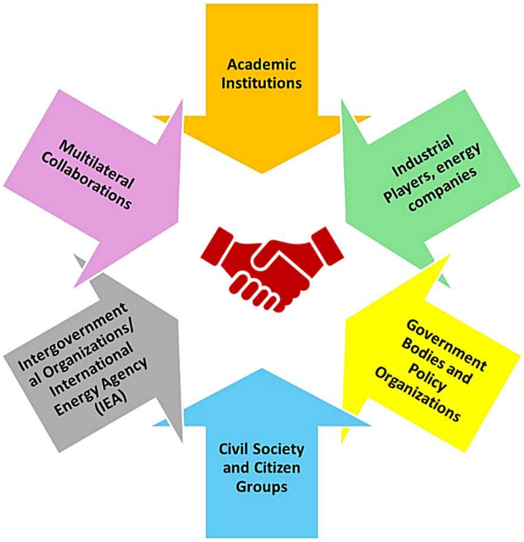


Figure 7. Illustration of the inclusion of various organisations working towards decarbonisation by strengthening the hydrogen value chain

Figure 7 conceptualises various organisations' collaborative efforts to advance the hydrogen economy. The figure illustrates the interconnected roles of industries, research institutions, policymakers, and financial sectors in enhancing the H_2 value chain. By fostering innovation in hydrogen production, storage, distribution, and utilisation across power, fuel, feedstock, and heat applications, these organisations contribute to global decarbonisation goals. Storage and transportation innovations are equally pivotal. Liquid hydrogen carriers, such as ammonia or liquid organic compounds, provide high energy density and safer handling, yet their synthesis, hydrogen release, and recycling processes require further development. Cost reduction in Type IV cylinders, lightweight, high-pressure vessels made from composite materials, is vital for economical storage and lowering hydrogen compression's energy intensity and expense. Expanding infrastructure, including pipelines and refuelling stations, will enable widespread adoption in applications such as chemical synthesis (e.g., ammonia and methanol production), grid-scale energy buffering, synthetic fuel generation for aviation and heavy transport, and industrial heat supply. This future relies on synergistic contributions from all stakeholders. Academia must spearhead breakthroughs in production technologies and material science while industry translates these findings into deployable systems, optimising costs and scalability. Civil society is crucial in raising awareness among younger generations to inspire engagement and innovation in hydrogen-related fields. Supported by multilateral cooperation such as the International Energy Agency (IEA), policymakers must establish robust frameworks offering funding, regulatory support, and global partnerships to accelerate infrastructure growth and ensure affordability. By addressing technical challenges, such as enhancing catalyst durability and membrane performance, this collective effort could position H_2 as a cost-competitive, low-emission energy carrier by 2050, significantly reducing global CO_2 emissions and paving the way for a resilient, eco-friendly energy future.

8. Conclusions

The hydrogen economy offers a promising transition pathway to a sustainable, low-carbon energy system. This review highlights various existing and emerging hydrogen production, storage, and utilisation technologies. Briefly discussed the various methods for hydrogen generation, including steam methane reforming (SMR), electrocatalysis, photocatalysis, biomass-to-hydrogen conversion, non-thermal plasma-enhanced dry reforming of methane (DRM), and water-gas shift (WGS) reactions. While SMR is currently the dominating industrial scale for hydrogen production, its carbon-intensive nature emphasises the urgent need for greener alternatives. For example, Electrocatalysis and photocatalysis are potential approaches to utilise renewable energy sources. Next, including non-thermal plasma in biomass-based hydrogen production can offer potential low carbon emissions. However, these emerging technologies require further efficiency, scalability, and cost-effectiveness advancements. Continued innovation and research development in this direction are desired to minimise the overall carbon footprint of the hydrogen value chain.

This review also highlighted various hydrogen storage methods, with hydrides playing a significant role due to their high storage capacity and safety, particularly for transportation applications. Liquid organic hydrogen carriers (LOHCs) emerged as a key solution for efficient clean energy transport and distribution, offering a practical means to handle hydrogen's low volumetric density. Looking ahead, the future perspectives section emphasises the necessity of advancing production technologies such as electrolysers, photocatalysis, and plasma catalysis alongside optimising storage systems like LOHCs and reducing costs for high-pressure cylinders. Collaborative initiatives involving academia, industry, civil society, and policymakers are essential for addressing hydrogen production's technical and economic challenges. By integrating these efforts, we can enhance the scalability and affordability of hydrogen. Such advancements are critical for facilitating the hydrogen economy's potential to reduce global CO_2 emissions significantly and to foster the development of a cleaner energy future.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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