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Review

Power-to-hydrogen: A review of applications, market development, and policy landscape

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Abstract: As a result of the shift to low-carbon sustainable energy systems, hydrogen is now a major energy carrier. With an emphasis on hydrogen generation, storage, applications, infrastructure development and policy landscape, this review examines the “power-to-hydrogen” pathway. While hydrogen constitutes 75% of the universe’s mass, scalable terrestrial production remains challenging, with electrolysis efficiencies currently at 60–80% and costs at \$3–8/kg for green hydrogen. Key applications span steelmaking (reducing 7% of global CO_2 emissions) and fuel cells (reaching 60% energy efficiency). Storage solutions, including 700-bar compressed tanks and metal hydrides, face density and safety hurdles. Infrastructure demands \$15 trillion in investment by 2050 for pipelines and refueling stations. Policy levers like carbon pricing (<\$100/ton CO_2) and research and development (R&D) subsidies are critical to accelerate deployment. The carbon price, subsidies, and further research will all influence the direction of hydrogen in the future. Notwithstanding the obstacles, policy, technological, and infrastructure advancements can fully realize hydrogen’s potential to revolutionize the world’s energy system. From both global and universal perspectives, this review seeks to raise public understanding of hydrogen’s critical role in a sustainable energy future.

Keywords: Hydrogen generation; energy storage; infrastructure development; sustainable energy; policy and regulation

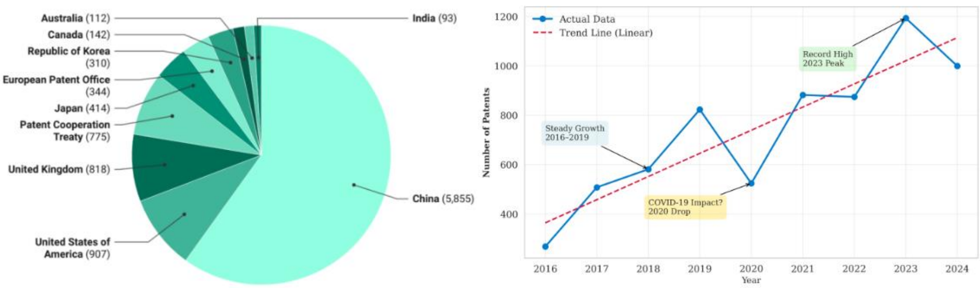
1. Introduction

Hydrogen has emerged as a critical energy carrier in the transition from fossil fuels, offering versatile applications across industry, transportation, and power generation [1–3]. While renewable hydrogen production shows promise for sustainable energy systems [4], scaling to meet projected global demand in the International Energy Agency (IEA)'s Net Zero by 2050 scenario which is 530 Mt H_2 by 2050 [5], requires us to overcome technical challenges (electrolyzer's efficiency, infrastructure, safety), economic barriers (cost competitiveness), and policy gaps. Ongoing advancements in electrolysis, storage (density/safety), and the integration of infrastructure aim to position hydrogen as a cornerstone of decarbonization efforts.

The trend in patent filings serves as an indicator of the growing importance of hydrogen technology. The filing of more patents indicates that governments, businesses, and researchers are investing a substantial amount of money in creating novel hydrogen solutions. According to the study by Martinez-Burgos et al. [6], water dissociation is currently the only commercially viable method for producing green hydrogen, with ongoing advancements in materials and catalyst recycling. A more recent comprehensive review conducted by Yang et al. [7] analyzed 5471 green hydrogen patents from 2002 to 2022, focusing on water electrolysis technologies and system operations' classifications. They found that system operation technologies make up 53% of the patents, suggesting that companies are prioritizing system integration and control strategies over green hydrogen production.

Updated data on green hydrogen patents published by the World Intellectual Property Organization (WIPO) [8] and shown in Figure 1 highlight significant innovation and growth in the field of sustainable energy technologies. China stands out as the dominant player, with a staggering 5855 patents, indicating its leadership in the development of green hydrogen technologies. In contrast, the United States follows with 907 patents, while other countries such as the United Kingdom (818 patents) and Japan (414 patents) show notable contributions. The Patent Cooperation Treaty (PCT) filings, at 775 patents, suggest international collaborations and an emerging global interest in the technology. The Republic of Korea (310 patents), Canada (142 patents), Australia (112 patents), and India (93 patents) also demonstrate significant, though smaller, participation in the space. Over the years, the number of green hydrogen patents has experienced a steady increase, particularly evident from 2020 to 2024. After a relatively moderate 2020 with 524 patents, the filings surged in 2021 (882 patents) and continued with high numbers in 2022 (874 patents), reaching a peak in 2023 with 1193 patents, before slightly dipping to 999 patents in 2024. This rising trend reflects growing global interest in clean energy solutions, with countries striving to secure technological leadership and intellectual property in the emerging green hydrogen sector. The data suggest an accelerating global effort to innovate in hydrogen production, storage, and utilization technologies, driven by the need to address climate change and transition to renewable energy.

The early growth phase (2016–2019) shows patent filings rising steadily from 268 to 823, reflecting growing investment in hydrogen technologies as clean energy solutions gained traction. The 2020 disruption stands out as a 36% year-over-year decline (823 to 524), likely caused by pandemic-related research and development (R&D) delays and shifting priorities in the energy sector during the COVID-19 lockdowns. Most strikingly, the post-pandemic surge (2021–2023) demonstrates remarkable acceleration, peaking at 1193 filings in 2023—a 36% increase over pre-pandemic levels—as nations and corporations doubled down on hydrogen as a cornerstone of decarbonization strategies. The sustained upward trend confirms hydrogen's rising importance in the global energy transition, with recent filings consistently exceeding historical levels despite macroeconomic challenges. These trends underscore how hydrogen innovation has weathered global disruptions while maintaining strong momentum toward clean energy solutions.



(a) Patent filings by country and authority in green hydrogen technologies.

(b) Yearly increase in green hydrogen patents from 2016 to 2024.

Figure 1. (a) Global distribution of green hydrogen patents by country and patent authority and (b) annual growth in hydrogen patents (2016–2024) [8].

Table 1 classifies a selection of recent review papers on hydrogen technologies on the basis of their key themes and contributions to the field. It covers a range of topics, including hydrogen as a clean energy carrier [9], long-distance transport via liquid hydrogen [10], mobility with liquid organic hydrogen carriers (LOHCs) [11], and various hydrogen applications [12], and storage and transportation methods [13]. It also addresses hydrogen's application in specific sectors such as power generation, aviation, maritime shipping [14], and large-scale infrastructure systems [15]. Additionally, it highlights green hydrogen technologies, emphasizing their technoeconomic analysis and integration with other systems for enhanced energy flexibility and security [16]. Corigliano et al. [17] demonstrated that molten carbonate fuel cells in biogas-to-energy systems can enhance cogeneration efficiency by utilizing CO_2 at the cathode. Recently, Genovese et al. [18] developed a model for producing multiple e-fuels, such as H_2, e-CH_4, e-NH_3, and e-CH_3OH (1 ton/day each), for hard-to-electrify transport, requiring 1 ton of H_2, 7 tons of CO_2, and 4.6 MWh of renewable energy per ton. Hydrogen production (58 kWh/kg) and liquefaction (12.3 kWh/kg) were identified as major energy demands.

Each paper's focus on the technological advancements, challenges, and future directions is categorized to provide a comprehensive overview of hydrogen research across different applications and scales. Buchner et al. [19] highlighted that public acceptance of green hydrogen plants in Germany is influenced by factors such as trust in project managers, risk/benefit perception, and experience with green hydrogen. These factors have a positive impact on the acceptance of these plants. Recently, Shan and Kittner [20] discussed the economic viability of clean hydrogen, emphasizing that while existing tax credit designs can make green hydrogen economically viable, a new allocation method prioritizing specific demand sectors could further boost adoption. Roucham et al. [21] presented a bibliometric analysis of green hydrogen and renewable energy research, noting an impressive annual growth rate of 93.56% in the field, with China, Germany, India, and Italy leading the way. Finally, Eckl et al. [22] focused on the underutilization of oxygen produced during electrolysis in green hydrogen projects, stressing the potential benefits of electrolytic oxygen over traditional oxygen production methods like cryogenic distillation and swing adsorption.

Table 1. Classification of selected hydrogen review papers on the basis of the themes and key areas of contribution.

Paper	Theme	Key area of contribution
Zhang et al. [9]	Hydrogen as a clean energy carrier	Hydrogen technologies from production to utilization. Identifying challenges and future opportunities for hydrogen across sectors.
Berstad et al. [10]	Liquid hydrogen in long-distance transport	Value chain analysis of liquid hydrogen, emphasizing energy efficiency, cost, and the impact of boiloff ratios on transport.
Singh et al. [11]	Hydrogen storage and mobility with liquid organic hydrogen carriers	Safe, economical, and compact storage and transportation of hydrogen using liquid organic carriers, including a discussion of their properties and applications.
Otto et al. [12]	Hydrogen carriers for various applications	Analyzes different hydrogen carriers (e.g., ammonia, methane) and evaluates their suitability for diverse applications like power generation, aviation, and trucking.
Yang et al. [13]	Hydrogen infrastructure and technology overview	State-of-the-art technologies for hydrogen storage and transportation, comparing physical- and material-based storage and offering infrastructure recommendations.
Van Hoecke [14]	Hydrogen for the maritime industry	Explores hydrogen's use in maritime shipping, focusing on storage challenges and the development of a new infrastructure for hydrogen bunkering in shipping.
Muthukumar et al. 15]	Large-scale hydrogen storage and infrastructure for sustainability	Reviews large-scale hydrogen storage systems and infrastructure for integrating hydrogen into sustainable energy systems, especially in developing countries.
Kourougianni et al. [16]	Green hydrogen technologies and system integration	Provides a detailed review of green hydrogen energy systems (GHES), focusing on technoeconomic aspects and integration with other technologies to enhance energy flexibility, resilience, and security. Covers generation, storage, utilization, and future research directions.
Buchner et al. [19]	Public acceptance of green hydrogen plants in Germany	Factors like trust in project managers, risk/benefit perception and experience with green hydrogen have a positive impact on the acceptance of green hydrogen plants.
Shan and Kittner [20]	Economic viability of clean hydrogen	The existing tax credit designs can make green hydrogen economically viable. A new tax credit allocation method could increase adoption of green hydrogen.
Roucham et al. [21]	Bibliometric analysis of green hydrogen and renewable energy research between 2018 and 2022	Annual growth in green hydrogen research, averaging 93.56% per year. China, Germany, India, and Italy are identified as the leading nations in this research field among 76 countries.
Eckl et al. [22]	State-of-the-art oxygen production technologies	Many green hydrogen projects do not fully utilize the oxygen produced during electrolysis. The potential of electrolytic oxygen in comparison with traditional methods like cryogenic distillation and swing adsorption.

While there is an extensive body of research on hydrogen, encompassing both review papers and technical studies [23–26], some fundamental questions have yet to be tackled in the literature. First, can hydrogen production overcome its energy intensity without exacerbating environmental trade-offs? What technologies or circular approaches could decouple scalability from carbon emissions? Second, while storage material limitations persist, which emerging solutions, from cryogenic composites to chemical carriers, offer the most viable pathways for global hydrogen trade? Third, how will cost dynamics and geopolitical risks shape hydrogen's commercialization? Are regional or global strategies better suited to mitigate financial and supply chain vulnerabilities? Fourth, what can pilot projects teach us about retrofitting the existing energy infrastructure for hydrogen? How can production facilities be standardized yet adaptable to diverse energy landscapes? What lessons can be drawn from ongoing global initiatives to build hydrogen production facilities, distribution networks, and refueling systems? Fifth, how do regulatory frameworks, spanning safety standards, subsidies, and international partnerships, shape hydrogen's trajectory? What policy instruments are most effective in bridging the gap between R&D and large-scale deployment? Sixth, how will hydrogen integrate with renewable energy to stabilize grids, store excess energy, and decarbonize sectors? What role will it play in the global energy transition? Finally, how can hydrogen's role in decarbonization and energy storage be optimized without overburdening transition timelines? What milestones define its roadmap to net zero dominance?

By answering these open questions, this review aimed to fill a significant knowledge gap in the current literature and guide the strategic planning required for the large-scale deployment of hydrogen technologies. While existing reviews have explored individual aspects of hydrogen's potential, this review synthesizes critical interdependencies across production, storage, infrastructure, and deployment, highlighting gaps in scalability, policy coherence, and system integration. We provide a unified assessment of how technological innovation, regulatory frameworks, and international collaboration must converge to accelerate the hydrogen economy's transition from theory to global reality.

The review begins by exploring hydrogen in the universe, highlighting its abundance and crucial role in cosmic processes. It then transitions to its significance on Earth, emphasizing hydrogen's essential role in sustaining life. Moving forward, the review delves into the diverse applications of hydrogen before addressing the challenges and considerations associated with its widespread adoption. It further investigates the current state of hydrogen production, storage, and market development, followed by an analysis of the ongoing efforts in hydrogen infrastructure development. The review also examines the policy and regulatory landscape shaping hydrogen's future. Finally, it looks ahead to the future of hydrogen in the global energy market, offering insights into its potential to transform energy systems worldwide. With a global and universal perspective, this review aims to reach a broad audience, fostering greater public awareness of hydrogen's vast potential.

The review employs a structured methodology to synthesize current knowledge on hydrogen's role in the global energy transition. The methodology is described by Figure 2. The research scope was defined to focus on hydrogen-related developments until 2024, with emphasis on renewable hydrogen, technological scalability, policy frameworks, and market dynamics. Relevant literature was retrieved from major academic databases including Scopus, Web of Science, and Google Scholar using targeted keywords. Inclusion criteria comprised peer-reviewed publications addressing renewable hydrogen, energy applications, and quantitative analyses, while studies focused on gray or blue hydrogen, nonenergy uses, or purely theoretical discussions were excluded. Following an initial screening of the titles and abstracts, full-text articles were reviewed for relevance and data richness. The selected studies were then systematically categorized into key thematic areas: (i) Hydrogen in the universe, (ii) theoretical frameworks for hydrogen transitions, (iii) critical barriers to scalability, (iv) production and commercialization pathways, (v) infrastructure development, (vi) policy and regulatory landscape, and (vii) future integration within the global energy system. This thematic structuring facilitated a comprehensive synthesis of interdisciplinary insights, visually supported by a workflow diagram to guide the reader through the review's logic.

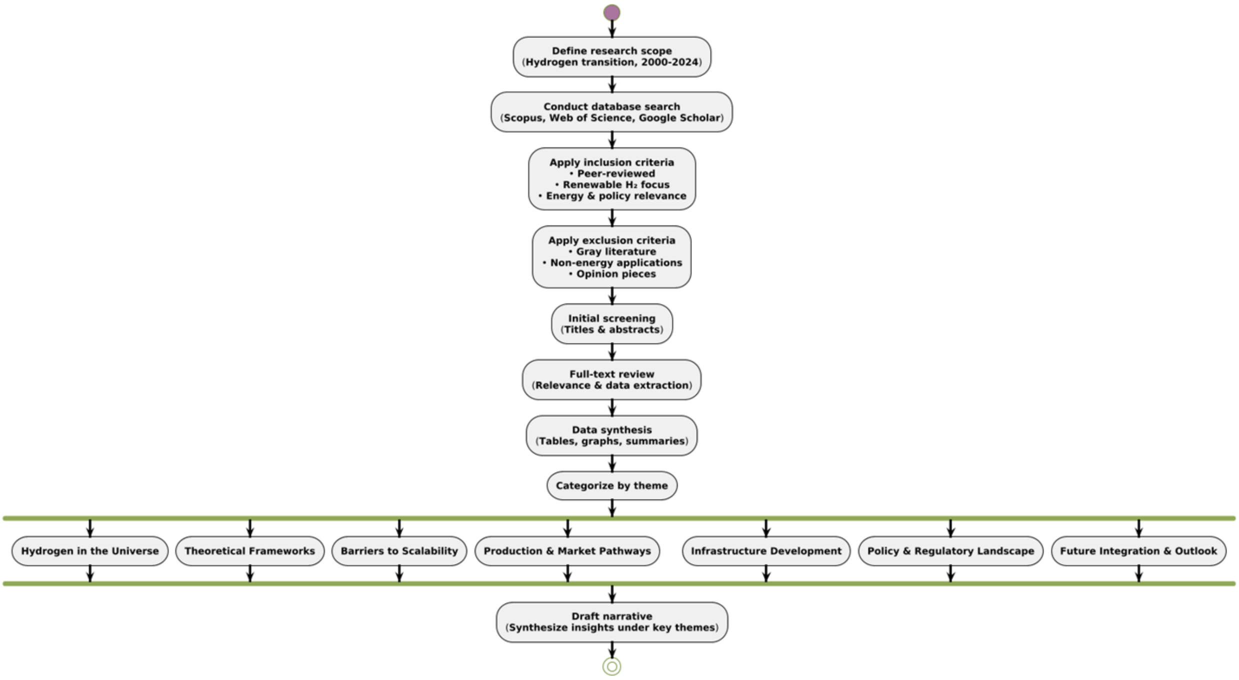


Figure 2. Workflow diagram of the methodological framework adopted for the systematic literature review.

2. Hydrogen in the universe: Ample and playing a key role

About 75% of the universe's mass is made up of hydrogen, making it the most prevalent chemical element in the cosmos. Astrophysical measurements and simulations that consider the makeup of stars, nebulae, galaxies, and interstellar gas provide the basis for this figure. Hydrogen makes up the majority of the visible matter in the cosmos, which is found in stars. The most prevalent element in stars is hydrogen, which serves as the main fuel for nuclear fusion in the cores of these bodies. The gas that fills the gaps between galaxies (intergalactic gas) and stars (interstellar gas) is likewise primarily hydrogen. The two main forms of this gas are ionic (H+) and atomic (H). The simplest form of hydrogen, the lightest of the chemical elements, is made up of a single proton and an electron. Since it is simpler to generate in the early phases of the formation of the universe, especially during the primordial nucleosynthesis that occurred just minutes after the Big Bang, this feature explains why it is present in the universe in large numbers. In contrast, all other elements (such as oxygen, carbon, nitrogen, etc.) make up a very minor portion of the observable universe's mass, with helium accounting for around 24% of it. It is crucial to remember that while hydrogen makes up a portion of the universe's observable matter, dark matter and dark energy—which together account for roughly 27% and 68% of the universe's mass—are also made up of atoms of hydrogen. The sun is the sole star in the solar system, with 74% of hydrogen undergoing fusion, even though some planets in the system, like some of the outer gas giants like Jupiter and Saturn, have large amounts of hydrogen in their atmospheres [27,28].

It is natural to think that hydrogen could be brought back from other stars or planets or even from other galaxies. However, we cannot really expect such missions, at least so far. The idea of bringing hydrogen from other stars or planets back to the Earth makes for good science fiction, but it has little practical significance. Robert and Forward [29] examined the viability of several technologies for interstellar travel in a review study. The paper described two primary strategies, namely high-risk and high-speed missions employing cutting-edge techniques like beamed power, antimatter, or interstellar ramjets, and long, slow trips using "worldships" powered by current nuclear technologies. According to the study, within a human lifetime, exploration of nearby star systems might be possible at rates between 0.1 and 0.3 times the speed of light. Beyond the capabilities of current technology, interstellar travel presents enormous hurdles. Nanoprobes can be used for robotic flybys, but advances in physics, biology, and space medicine are needed for human missions.

Relying on biological advancements, slow missions such as generation ships are feasible but questionable [30]. Given the difficulties mentioned, there would be comparable scientific and technological barriers to bringing hydrogen from other star systems to Earth. Transporting hydrogen from our solar system or another galaxy would necessitate major improvements in propulsion energy efficiency, and the capacity to preserve hydrogen's integrity over extended distances. In this context, in order to increase the viability and efficiency of hydrogen-fueled space missions, Wade et al. [31] presented a novel technique for in-space hydrogen harvesting for the STAR-H2 reactor concept, which may allow for more extensive and productive space exploration. The system may collect hydrogen from space and use it as fuel for propulsion systems by employing a nuclear reactor to produce the energy needed to produce hydrogen. Overall, transporting hydrogen over such great distances would probably be a long way off, given the uncertain and slow nature of interstellar missions, which are similar to generation ships. The transmission of hydrogen from other stars is still a theory until advances in physics and space medicine are made.

3. Theoretical frameworks for hydrogen transitions

Hydrogen's potential as an energy vector must be understood through established transition theories that explain technological adoption and systemic change. The multilevel perspective (MLP) [32] frames hydrogen technologies (e.g., green electrolysis, fuel cells) as niche innovations challenging the fossil fuel regime, driven by landscape pressures like decarbonization mandates and energy security crises. Meanwhile, technological innovation systems (TIS) theory [33] identifies functional barriers to hydrogen's maturation, including:

- ✓ Knowledge development (R&D gaps in storage);
- ✓ Market formation (lack of H_2 refueling infrastructure);
- ✓ Policy alignment (inconsistent subsidies vs. carbon pricing).

A sociotechnical systems lens [34] highlights the interdependencies between hydrogen's technical feasibility (e.g., pipeline retrofitting) and social acceptance (e.g., public resistance to H_2 hubs). Path dependence [35] explains why legacy energy systems resist transition, exemplified by the "chicken-or-egg" stalemate between hydrogen vehicles and refueling networks. These theories collectively predict nonlinear adoption trajectories, where hydrogen's scalability depends on simultaneous advances in technology, policy, and user practices [36].

Important theoretical frameworks for examining hydrogen transitions in energy systems are depicted in Figure 3. Four main theories support the central role of hydrogen as a transformative energy vector. The multilevel perspective (MLP) positions hydrogen technologies as niche innovations disrupting the dominant fossil fuel regime under pressure from global decarbonization and energy security challenges. Technological innovation systems (TIS) theory identifies systemic barriers, including gaps in research and development, weak market formation, and inconsistent policy signals. The sociotechnical systems approach emphasizes the interaction between technical feasibility, such as he infrastructure, and social acceptance, including public resistance to hydrogen's deployment. Path dependence highlights how the existing energy infrastructures hinder transition, exemplified by mutual reliance between hydrogen vehicles and refueling networks.

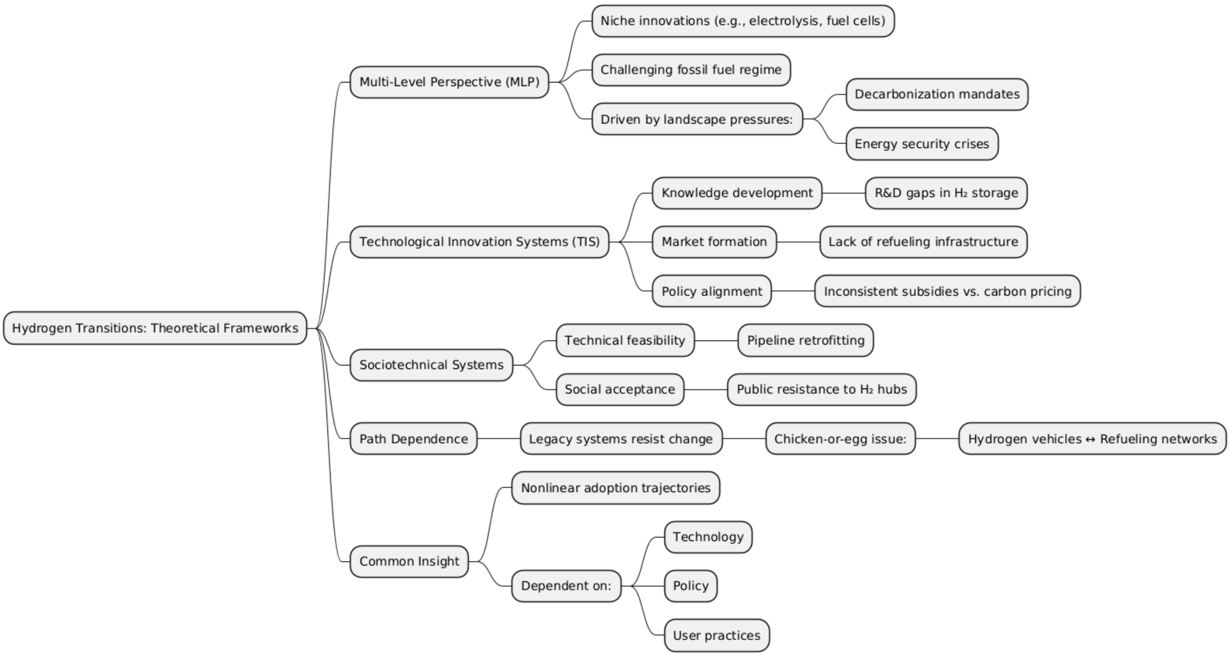


Figure 3. Theoretical frameworks guiding hydrogen energy transitions.

These frameworks underscore that hydrogen adoption is nonlinear and contingent on coordinated progress in technology, policy, and societal engagement.

4. Challenges and considerations for hydrogen: Critical barriers to scalability

4.1. Energy-intensive production: Technological and environmental trade-offs

Despite being essential to the energy shift towards more sustainable solutions, hydrogen generation is still energy-costly, which poses a significant obstacle to its large-scale feasibility. The environmental benefits of current technologies are limited because they are all energy-intensive and frequently produce CO_2.

As displayed in Figure 4, steam methane reforming [37] is the most popular method of producing hydrogen, which involves reacting methane (CH_4) with water vapor to produce hydrogen and carbon dioxide (CO_2). While this method is popular because it is relatively inexpensive, it uses a lot of energy to heat the reactors to high temperatures (800–1000 °C) and produces a lot of CO_2, which makes it unsustainable in the long run unless carbon capture and storage (CCS) solutions are employed.

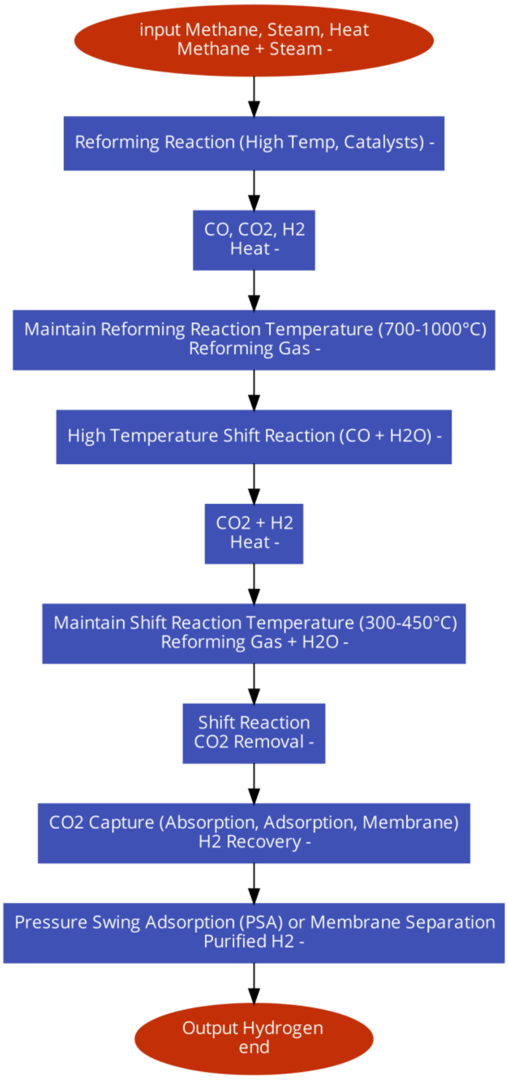


Figure 4. Steam methane reforming (SMR) process for hydrogen production.

Coal gasification [38], as displayed in Figure 5, is the process of heating coal in an oxygen-free atmosphere to create syngas, which can then be used to extract hydrogen. Similar to methane reforming, this process uses a lot of energy, produces CO_2 emissions, and necessitates extremely high temperatures, rendering it unsustainable over time. In pyrolysis [39], hydrocarbons are broken down at high temperatures to create hydrogen. In addition to requiring high temperatures and a lot of energy, this process may be less polluting than methane reforming if it is combined with renewable hydrocarbons. Using an electric current, electrolysis [40] separates water (H_2O) into hydrogen (H_2) and oxygen (O_2). Although this approach uses a lot of energy, it is cleaner if the electricity is generated using renewable resources [41] like solar or wind.

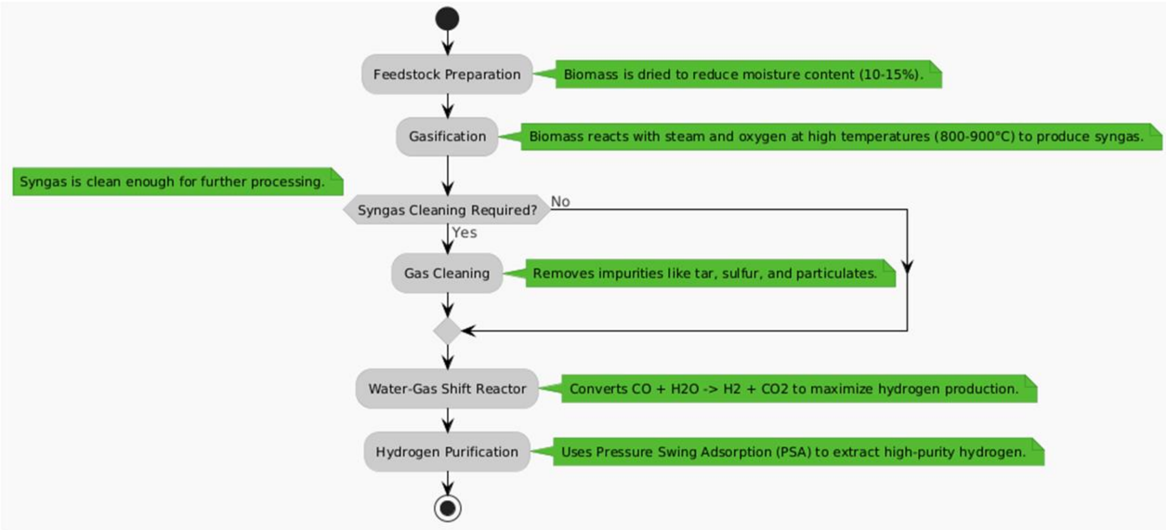


Figure 5. Gasification process for hydrogen production.

The efficiency of electrolysis is normally around 60–80%, implying that a large quantity of electrical energy is required to produce a significant amount of hydrogen. Hydrogen produced by electrolysis is commonly called "green hydrogen" (Figure 6) if the electricity originates from renewable sources; however, production remains expensive on a large scale due to the energy intensity of this method.

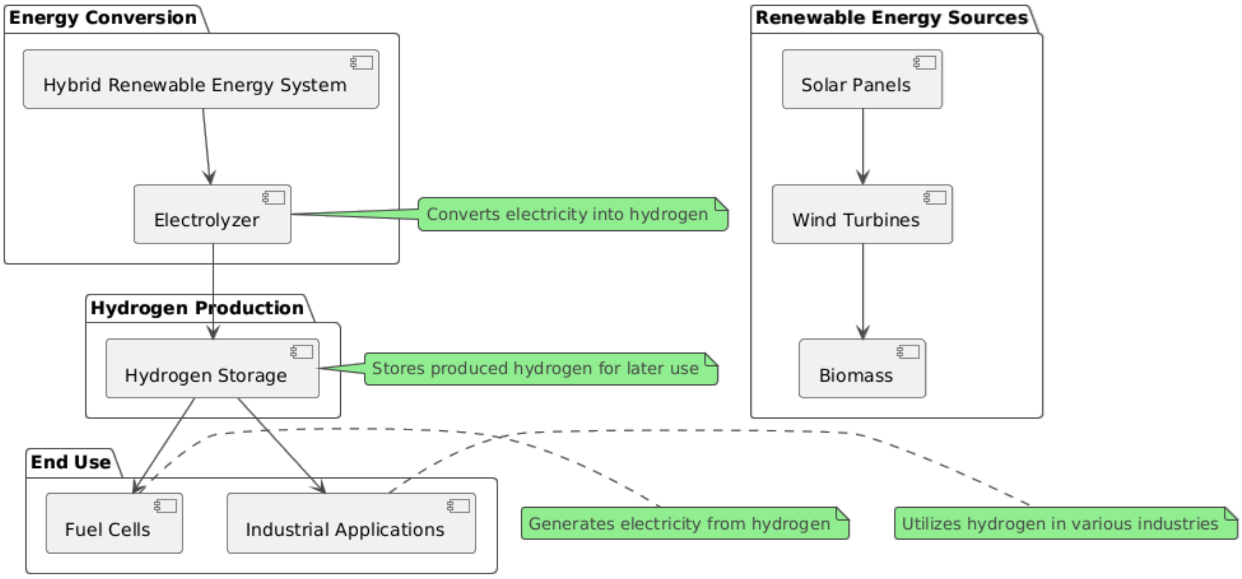


Figure 6. Schematic of green hydrogen production from renewable energy sources.

Figure 7 shows a heat map based on the domains of research into green hydrogen in 2024 and 2025 in relevant journals that publish cutting-edge research on hydrogen technologies, fuel cells, and energy systems, among other related topics. The bibliometric analysis was conducted using VOSviewer software with data extracted from the Web of Science Core Collection. Our search query targeted publications (2024) containing the terms "green hydrogen" in the titles, abstracts, or keywords. For multiauthor papers with international collaborations, we employed fractional counting to ensure equitable attribution: Each country received proportional credit based on its contribution to authorship. Only peer-reviewed articles and reviews were included, with careful normalization of citation counts to account for varying publication dates within the study period. The heat map visualization specifically represents citation density, where warmer colors indicate a higher citation frequency per unit of area, providing a quantitative assessment of research impact across geographical regions. The methodology established bibliometric practices while addressing the unique challenges of tracking emerging hydrogen technologies. The figure shows that green hydrogen is an interdisciplinary field that spans environmental science, electrolysis, chemistry, economics, electrical engineering, renewable energy, material science, process engineering, automotive engineering, and sustainable development, as evidenced by the high-citation research domains that have been identified. Because they tackle the societal and technological obstacles associated with the development of green hydrogen, these subjects are essential.

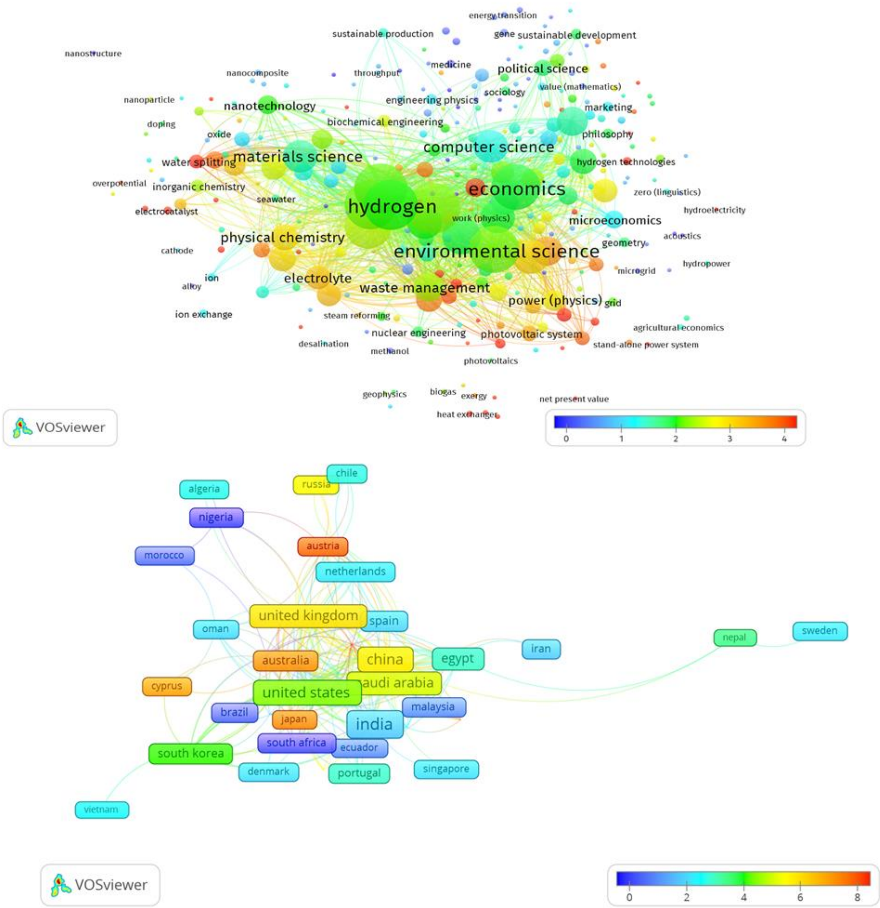


Figure 7. Visualization of green hydrogen research on 2024 through a normalized citation heat map.

For example, whereas material science concentrates on developing effective and long-lasting materials for fuel cells and electrolyzers, electrolysis is crucial for the environmentally sustainable production of hydrogen. For the entire hydrogen generation process to limit carbon emissions, environmental science and renewable energy are essential. Studies on economics and sustainable development are essential for determining the viability and long-term effects of using hydrogen in a variety of industries, such as transportation and industry. Aiming for a more sustainable and emission-free future, automotive engineering also contributes significantly to the integration of hydrogen fuel cells into transportation networks.

By investigating these topics, scientists are tackling not just the technological challenges of green hydrogen but also the infrastructure, policy, and economic prerequisites necessary for broad adoption. The figure also presents a citation heat map visualizing the frequency of citations of research papers related to hydrogen in different countries. The map indicates a clear global distribution of citations, with a notable concentration in United Kingdom, Japan, Australia, and the Middle East, particularly in countries like Saudi Arabia and Qatar, where several papers have garnered over six citations on average. Additionally, other significant contributors to the field include China, Poland, and South Korea. A further cluster of citations can be seen in countries like the USA and Russia. This distribution suggests that green hydrogen research is being actively pursued across various regions, with some countries leading in terms of citation impact, indicating their prominent role in advancing this area of study.

Hydrogen is commonly classified into several types according to the production methods and environmental impact. Green hydrogen, produced via electrolysis powered by renewable energy (e.g., solar or wind), is a zero-emission energy source. In contrast, gray hydrogen, derived from natural gas without carbon capture and storage (CCS), generates high CO_2 emissions, while blue hydrogen also uses natural gas but incorporates CCS to reduce emissions. Turquoise hydrogen, produced through methane pyrolysis, yields solid carbon instead of CO_2, lowering greenhouse gas emissions. The least sustainable option, black/brown hydrogen, is derived from coal gasification and emits significant CO_2. Nuclear energy enables the production of both purple hydrogen (via high-temperature steam electrolysis) and pink hydrogen (through nuclear-powered electrolysis). Yellow hydrogen is generated via solar-powered electrolysis, offering another renewable alternative. Lastly, white hydrogen occurs naturally in geological formations but remains rarely utilized and is considered a form of "fossil hydrogen".

The prescribed methods exhibit significant trade-offs between efficiency, cost, and environmental impact, shaping their viability for energy transitions. Green hydrogen, while producing zero emissions (0.1–1 kg CO_2/kg H_2), faces efficiency losses (50–70% electrolyzer efficiency) and high costs ($4–6/kg) due to dependence on renewable energy. Blue hydrogen reduces emissions (0.8–2 kg CO_2/kg H_2 with CCS) but incurs 20–40% energy penalties for carbon capture and risks methane leakage (3.5% leakage negates the climate benefits). Gray hydrogen remains the cheapest ($1–2/kg) but is environmentally unsustainable (10–12 kg CO_2/kg H_2), perpetuating fossil lock-in. Turquoise hydrogen (methane pyrolysis) avoids CO_2 but requires high temperatures and markets for solid carbon byproducts. Nuclear-derived hydrogen (pink/purple) offers baseload power but faces public acceptance hurdles and high capital costs ($3,000/kW). Finally, yellow hydrogen (solar electrolysis) suffers from intermittency, needing storage integration. Lifecycle analyses show that green H_2's carbon footprint is 80–90% lower than that of gray H_2 but remains 2–3 more water-intensive. In terms of economic scalability, blue H_2 may bridge the transitions, but cost reductions in electrolyzers (<$500/kW by 2030) could tip the scales toward green H_2.

Figure 8 presents a diverse array of global green hydrogen and related projects, highlighting variations in the scale, products, and geographic distribution. Most projects focus on hydrogen (H_2) production, though ammonia and synfuels are also significant products, with ammonia being particularly prominent in regions like Mauritania and Brazil. Projects vary widely in size, from large-scale initiatives like the Western Green Energy Hub in Australia (producing over 7200 kt H_2/y) to smaller ones such as Hynet Northwest in the UK (producing 810 kt H_2/y). Countries like Australia, Mauritania, and the United States are leading in hydrogen production, reflecting their favorable renewable energy resources, while regions like Chile and Germany contribute through more moderate-scale projects. The focus on ammonia in several projects suggests its growing role as a hydrogen carrier for export, with synfuels also emerging as an important sector in regions like South Africa. Overall, the table underscores the figure trend toward scaling up green hydrogen production, with a focus on both hydrogen and ammonia as key products for sustainable energy transition.

The listed projects in the IEA's projects database [42] represent some of the world's largest and most ambitious green hydrogen initiatives, each aiming to revolutionize the global energy landscape by leveraging renewable sources for hydrogen production.

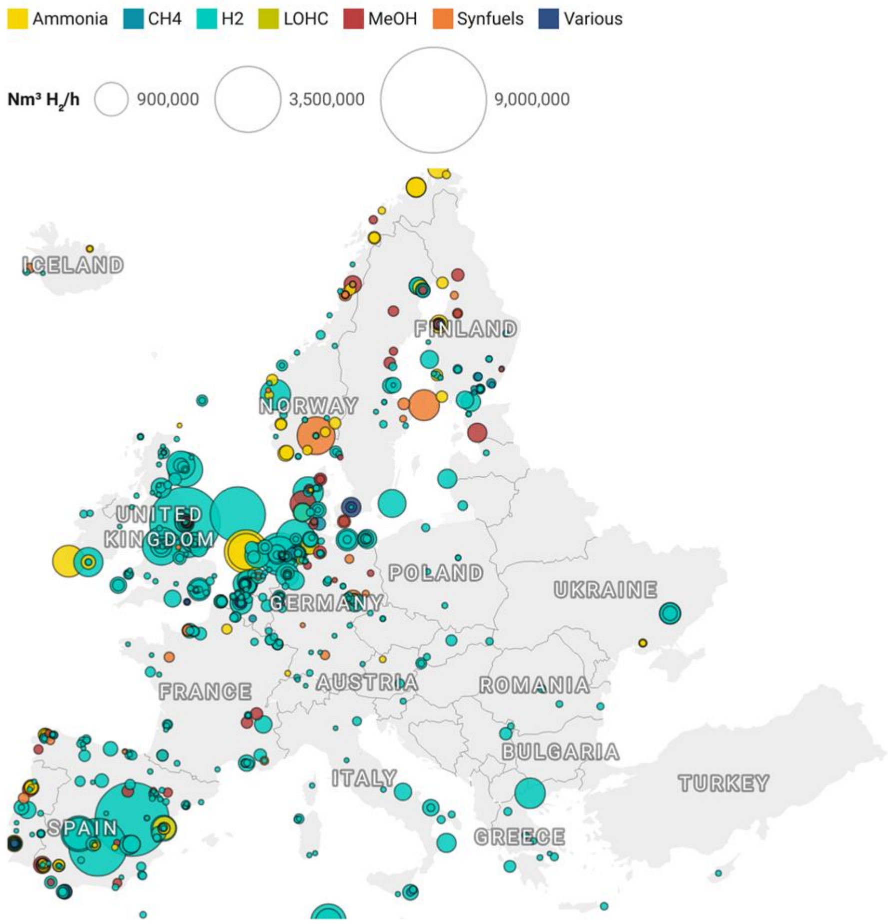


Figure 8. Byproducts and normalized capacity of green hydrogen projects (data from IEA [42]).

At the forefront is the Western Green Energy Hub in Australia, which stands as the largest, with a projected production capacity of 7202.88 ktH_2/y, focusing on ammonia production using various renewable energy sources through electrolysis. Following closely is Megaton Moon in Mauritania, with a capacity of 6063.87 ktH_2/y, which will produce hydrogen (H_2) through electrolysis, tapping into the country's vast renewable resources. Other significant players include ACME SCZONE Green Ammonia Plant in Egypt and the Mauritania & BP-Nassim Project, both of which also harness electrolysis technology for large-scale ammonia and hydrogen production, reflecting the growing importance of renewable hydrogen for industrial applications, particularly in sectors like fertilizers and transportation fuels. In Europe, Spain's Lacq Hydrogen and FertigHy Second Plant aim to advance hydrogen production by using solar photovoltaic (PV) and proton exchange membrane (PEM) electrolysis technologies, respectively, while the UK's H21 Leeds City Gate—Teesside Hydrogen is leveraging natural gas with carbon capture, utilization, and storage (NG with CCUS) to produce hydrogen as part of its low-carbon transition. Similarly, South Africa's Secunda SAF Project—Phase II is focused on producing synfuels from green hydrogen, an innovative approach to decarbonize the fuel industry. Additionally, Brazil's Green Energy Park and Hydrogen City in the United States are making strides in integrating electrolysis technology with renewable energy, contributing significantly to the global supply of green hydrogen. Notably, projects like Fortescue Metals' Rio Negro in Argentina and Adani H_2 in India are tapping into their respective countries' renewable resources to produce hydrogen for various industrial uses, emphasizing the global spread of green hydrogen initiatives. These projects collectively indicate enormous potential for scaling up green hydrogen production, which is critical in decarbonizing industries such as ammonia manufacturing, steel production, and long-distance transport, thus helping to meet the targets set in global climate agreements. By employing cutting-edge electrolysis and PEM technologies and capitalizing on solar, wind, and other renewable sources, these projects are laying the foundation for a sustainable and low-carbon future.

4.2. Storage and transport: Material and infrastructure hurdles

Hydrogen's low volumetric energy density (0.0107 MJ/L at STP vs. 32 MJ/L for gasoline) necessitates costly compression (350–700 bar) or liquefaction (–253 °C), consuming 15–30% of its energy content [43]. Composite tanks (Type IV) reduce weight but face permeation losses (>1% per day) and require costly carbon fiber reinforcement [44]. Alternative carriers like ammonia (NH_3) and liquid organic hydrogen carriers (LOHCs) mitigate transport challenges but introduce energy penalties: Ammonia synthesis consumes 12–15% of H_2's energy, while LOHC dehydrogenation requires 500–600 °C heat [45]. Metal hydrides (e.g., MgH_2, $NaAlH_4$) offer solid-state storage but suffer from slow kinetics (<2 wt% reversible capacity at temperatures lower than 150 °C). Advanced porous materials and changing regulatory frameworks are examples of emerging technologies for the storage and transportation of hydrogen. With a useable density of 14.4 g/L at 77 K, metal–organic frameworks (MOFs) like NU-1501 show promise in storing hydrogen; nevertheless, their practical uses are severely limited by their dependence on cryogenic temperatures. Due to their higher potential for leakage, many repurposed natural gas networks may not be eligible for future hydrogen service under the European Union's draft Hydrogen Infrastructure Package, which places strict limits on the allowable hydrogen loss for pipelines at less than 0.1%. Overall, the area of hydrogen transport is intricate and demands close attention to both the technical and financial issues. Although useful in certain situations, the current approaches should be improved to guarantee large-scale, safe, affordable, and sustainable transportation.

5. Hydrogen production, storage, and market development: Pathways to commercialization

5.1. Production: Cost dynamics and policy levers

The global debate over efficient energy sources has brought attention to hydrogen and fuel cells as promising emerging technologies, as noted by da Silva Veras et al. [46]. The competitiveness of existing production technologies is one of the obstacles to the widespread adoption of hydrogen technology, despite its potential. However, hydrogen has major environmental advantages, including lower air pollution and carbon cycle stability, and may be produced from both renewable and nonrenewable sources. In a similar vein, Yue et al. [47] stressed the significance of extensive hydrogen use, especially in areas with a wealth of renewable energy. They contended that the development of new hydrogen markets in industries such as industry, transportation, and aviation depends on appropriate legislative backing. Furthermore, Liu et al. [48] drew attention to the continuous difficulties in the production and storage of hydrogen, emphasizing that the high expense and storage needs continue to be major obstacles. They contend that developments in hydrogen storage materials and photocatalytic water breakdown are essential for further study. The potential of hydrogen as a clean substitute for fossil fuels, particularly in transportation, was further emphasized by Qureshi et al. [49], who also pointed out that the existing techniques of producing hydrogen are still not economically viable.

The production process and regional variables, especially feedstock costs, have a substantial impact on the levelized cost of hydrogen (LCOH). The least expensive option is gray hydrogen, which is made from natural gas without carbon capture and costs between $1.20 and $2.50 per kilogram. However, the price of gray hydrogen is very sensitive to the price of natural gas. At $2/kg to $3/kg, blue hydrogen, which includes carbon capture and storage (CCS), is somewhat more costly. CCS adds $0.5/kg to $1/kg. Due in large part to the high capital cost of electrolyzer equipment, green hydrogen, which is produced by electrolysis using renewable electricity, remains the most costly at $3.5/kg to $6/kg. Policy interventions are narrowing this gap. The US's Inflation Reduction Act (IRA) subsidies ($3/kg for green H_2) could reduce LCOH to less than $1/kg by 2030, while the EU's carbon pricing (more than $102/ton CO_2) favors electrolysis in high-renewable regions. However, grid congestion and renewable intermittency could increase LCOH by 20–30% in decentralized systems.

5.2. Storage materials: From lab-scale to industrial adoption

Significant advancements have been achieved in the field of hydrogen storage throughout the years, especially in an effort to increase the technology's safety, durability, and efficiency. Depending on the storage method (physical, chemical, or solid-state), different materials are used to store hydrogen. Current research and development is centered on materials such as metal hydrides, clathrates, metal-organic frameworks (MOFs), and activated carbon, with an emphasis on enhancing their cost-effectiveness and storage capacity. Activated carbon can adsorb hydrogen molecules at low pressures and temperatures because of its high surface area. It is among the most widely used substances for physical adsorption of hydrogen. Another promising material is carbon nanotubes (CNTs), which can store hydrogen through adsorption at high pressures due to their high surface area and superior mechanical qualities. Graphene is also able to store hydrogen through adsorption thanks to its exceptional surface area. Metal-organic frameworks (MOFs) are porous structures made up of metal ions bonded by organic ligands. They are efficient for storing hydrogen because of their tunable porosity, which allow them to absorb large amounts of hydrogen at moderate pressures. Metal hydrides, in which hydrogen atoms are chemically bound to the metal, can be formed by intermetallic alloys such as sodium (Na), magnesium (Mg), nickel (Ni), and lanthanum (La). Through chemical absorption, these materials store hydrogen, which is then released when heated. Despite models indicating a lower capacity than Department of Energy (DOE) standards, carbonaceous materials like clathrates have emerged as a promising candidate of hydrogen storage that has focused on materials such as metals, MOFs, and carbonaceous materials [50].

Numerous studies have also focused on the process of hydrogen molecules interacting with a material's interior or surface through adsorption and desorption. The hydrogen atoms can be absorbed in different ways. Physisorption usually takes place at low temperatures and pressures and involves weak interactions (van der Waals forces) between hydrogen molecules and the material surface. Chemisorption results in more stable storage, frequently at higher temperatures, when stronger chemical bonds are formed between the hydrogen atoms and the material's surface.

Additionally, hydrogen atoms can enter a material's bulk and occupy interstitial sites, as in metals or alloys. With an emphasis on local characterization techniques that look at surface and nanostructural interface effects, Sun et al. [51] evaluated a variety of characterization techniques used to analyze hydrogen's absorption and desorption in materials. They emphasized how these methods can be used to investigate and comprehend materials that store hydrogen.

Recent breakthroughs in destabilized hydrides (e.g., $LiBH_4$-MgH_2 composites) enable 8–10 wt% reversible storage at 200–300 °C, though the cycle life remains at <1000 iterations. MOFs with open metal sites (e.g., Ni_2(m-dobdc)) show promise for ambient-temperature storage (2.5 wt% at 100 bar), but scalability is hindered by the costs of ligand synthesis. As an example o findustrial uptake, Toyota's 2025 Mirai FCEV will use Type III tanks (700 bar) with 5.6 wt% capacity, while HyStorPor projects tested depleted gas reservoirs for underground H_2 storage at >98% purity. Overall, hydrogen storage remains expensive, particularly when using cryogenic methods or advanced solid storage materials. In terms of efficiency, the conversion, storage, and release of hydrogen result in energy losses. Increasing the efficiency of these processes is critical for making this technology viable on a large scale. The infrastructure for hydrogen storage and delivery is currently immature, necessitating major investment to enable its integration into the global energy grid.

5.3. Market development: Geopolitical and financial risks

The cost of hydrogen today fluctuates greatly depending on the production technique, region, and market conditions. In general, hydrogen derived from fossil fuels (such as natural gas reforming) remains the most affordable, with prices achieving \$2.4/kg. Hydrogen production costs \$2/kg from carbon capture and storage, \$4/kg from electrolyzed water, \$3.6/kg from solar thermochemical techniques, and \$3.7/kg from wind [52]. The price of hydrogen may therefore fall as technologies evolve and markets develop, with the goal of making hydrogen a competitive choice for the energy transition. According to a recent analysis by Frieden and Leker [53], the primary cost trajectory for hydrogen production indicates that electrolysis costs will decrease from \$6/kg in 2020 to \$3/kg by 2050. According to Brändle et al. [54], given the central assumptions, the minimal cost of producing hydrogen from renewable energy sources will drop to \$1.5/kg. It should be noted that the cost of hydrogen is mostly determined by the technique of generation. In this regard, Kamran and Turzyński [55] concluded that water electrolysis, despite being extremely efficient (55–80%), is expensive at 4.15–\$10.3/kg, whereas pyrolysis provides more cost-effective solutions with a yield of 25–65 g/kg.

Although long-term plans, like using 15% hydrogen to meet to reach carbon neutrality by 2050 [56], may sound ambitious, there are risks and difficulties involved that need be taken into account. First, plans for the development of new technologies, including renewable hydrogen, may be disrupted by unanticipated geopolitical events, like the crisis in Ukraine. For instance, the conflict in Ukraine has demonstrated how vulnerable Europe's energy supply is [57], which may cause long-term tensions to postpone or alter the priorities for investments in green technologies. Investments in energy infrastructure can be slowed down or the supply chains of raw materials required for hydrogen generation disrupted by armed conflicts, economic sanctions, and shifts in international relations. Second, the effects of international health emergencies like COVID-19 have shown how brittle long-term strategies can be when unexpected world events occur [58]. In addition to causing a worldwide economic downturn, the health issue has interfered with the energy transition and infrastructure initiatives in numerous areas. Some energy projects' implementation has been delayed as a result of budgets being reallocated to crisis management. Furthermore, the pandemic has made workforce, supply chain, and mobility issues worse, which has slowed advancements in a number of industries, including energy. Finally, long-term policy choices can be impacted by unexpected changes in public opinion, national or international priorities, and changes in administrations.

The goals set for 2050 may be impacted by a change in political objectives, whether as a result of a change in leadership or evolving energy requirements [59]. A fresh financial crisis, for instance, would cause governments to refocus their attention from the energy transition to other pressing economic issues. The projected 2050 hydrogen economy, which aims for a 10–15% global energy share, is fraught with financial and geopolitical hazards. Given that China controls 80% of the rare earth elements necessary for electrolyzers' catalysts, supply chain risks are apparent. Furthermore, current investment levels are insufficient because, in order to meet the IEA's net zero ambitions, annual spending on hydrogen infrastructure must quadruple to $130 billion by 2030. Project delays, like the repurposing of Nord Stream 2, highlight ongoing permission and regulatory obstacles, even though the EU's REPowerEU initiative, which aims to produce 10 million tons of renewable hydrogen by 2030, has been sparked by the crisis in Ukraine.

6. Development of hydrogen infrastructure

6.1. Hydrogen production facilities

Facilities for producing hydrogen are essential to the shift to renewable energy, as various regions use a variety of strategies to satisfy their energy needs. For instance, Fragiacomo and Genovese [60] evaluated a PEM hydrogen production system in Southern Italy that uses a variety of renewable energy sources, including solar, wind, and geothermal. The hydrogen is used for natural gas grid injections and mobility. The advantages of hydrogen for the economy and environment are shown by its financial and emissions analysis. For their financial analysis, the authors considered a power purchase agreement range of €50–100/MWh and evaluated scenarios allocating 25–100% of daily hydrogen production to mobility applications. With an emphasis on the Black Sea, which is abundant in hydrogen-sulphide H_2S, Seker and Aydin [61] used multiplecriteria decision-making (MCDM) techniques to choose the ideal location for a hydrogen sulfide decomposition plant in Turkey. The strategic significance of site selection for the best possible hydrogen production is shown by this study. The potential of hydrogen as a universal energy carrier for energy storage and transportation, especially in underdeveloped areas, was examined by Kirichenko and Kirichenko [62], who proposed hydrogen cryogenic storage and transport systems as workable ways to balance regional energy imbalances. For energy redistribution, the authors advocated for hydrogen as a universal energy carrier, with cryogenic storage (using RSV-1,400 tanks: 10^6 L capacity) and transport via cryogenic tankers. Together, these studies demonstrate the increasing significance of renewable resource-powered hydrogen production facilities, their viability from an economic standpoint, and their potential to mitigate regional energy imbalances and reduce carbon emissions. The hydrogen production projects database published by the IEA [63] includes all projects that have been put into service globally since 2000 to create hydrogen for energy or to mitigate the effects of climate change. It encompasses programs that aim to either lower emissions related to the production of hydrogen for current uses or use hydrogen as an industrial feedstock or energy carrier in future applications that could be a low-emission technological choice.

Projects that are being planned or built are also featured. The report outlines a wide range of hydrogen production projects globally, showcasing the diversity in the projects' scope, technology, and expected production capacities. These projects are spread across various countries, including the Netherlands, Norway, Sweden, Spain, and the USA, with implementation timelines spanning from operational to early-stage feasibility and concept phases, with expected completion dates ranging from 2021 to 2030. The projects employ different hydrogen production technologies, primarily electrolysis methods such as PEM (proton exchange membrane), SOEC (solid oxide electrolysis cells), and other types of electrolysis, powered by renewable energy sources like solar PV, offshore wind, and grid electricity. The main product across most projects is hydrogen (H_2), although some focus on other products like ammonia and synfuels, such as the Norsk e-Fuel project in Norway. The hydrogen production capacities vary greatly, from small-scale projects like the ARIES project in the USA, which produces 1 ktH_2/y, to massive initiatives like the NorthH_2 project in the Netherlands, which targets 4000 ktH_2/y. This wide variation in scale and technology reflects the global trend toward green hydrogen and its diverse applications in energy storage, transportation, and industrial processes. Furthermore, the projects illustrate the international commitment to advancing hydrogen as a key element in the transition to cleaner energy systems, with a focus on integrating renewable energy sources and achieving significant reductions in carbon emissions. The main product in most cases is hydrogen (H_2), though some projects, like Power2Met, produce methanol (MeOH) or methane (CH_4). The production capacities vary, with smaller projects like the H_2One projects in Japan producing minimal hydrogen, while larger initiatives such as the Fukushima Hydrogen Energy Research Field in Japan and Guangdong Synergy Hydrogen Power Technology in China produce significantly higher amounts, reaching up to 1.69 ktH_2/y and 0.60 ktH_2/y, respectively. Overall, data from the IEA database [63] on hydrogen production projects highlights the strategic efforts across different regions to scale up hydrogen production, optimize renewable energy's integration, and contribute to global sustainability goals.

6.2. Distribution and refueling networks

Recent advances have expanded hydrogen use beyond traditional fuel cells to direct combustion in gas turbines (with Mitsubishi achieving 30% hydrogen co-firing in 2023) and aviation applications (e.g., Airbus's hydrogen-powered A380 test flights). Key research focuses on overcoming combustion challenges like NO_x emissions through ultra-lean burn technologies and cryogenic storage solutions for mobility. The US DOE's 2024 Hydrogen Shot program targets \$1/kg H_2 for fuel applications, driving innovations in high-density storage materials (metal-organic frameworks) and anion exchange membrane fuel cells for heavy transport. However, the transfer of hydrogen from production locations to end consumers in a variety of industries require distribution and refueling networks, which are crucial elements of the hydrogen economy. In order to provide a consistent supply of hydrogen fuel, the infrastructure needed for hydrogen distribution consists of a variety of pipelines, storage facilities, liquefaction plants, and refueling stations. Particularly useful for moving huge amounts of hydrogen over long distances, pipelines are sometimes regarded as the most economical way to distribute the gas, particularly when linking industrial customers and fuelling stations with centralized production facilities. However, there are obstacles to overcome in the construction of a comprehensive network of hydrogen pipelines, such as the high initial capital expenditure and the requirement for specialist materials to manage the specific characteristics of hydrogen.

Although they have higher logistical expenses, alternatives like tube trailers and liquid hydrogen tankers are used in areas where pipelines are not practical. Supporting hydrogen-powered vehicles requires the construction of hydrogen refueling stations, which should be placed in key areas to optimize user accessibility.

Globally, there are currently more than 160 hydrogen refueling stations, which provide a basis for increasing hydrogen mobility. By utilizing local resources and pre-existing infrastructure, programs such as the US Department of Energy's Regional Clean Hydrogen Hubs (H_2Hubs) seek to improve the efficiency of both production and delivery. All things considered, encouraging the use of hydrogen as a clean energy carrier and accomplishing more general decarbonization objectives in the energy sector depend on building a strong hydrogen distribution network. On the other hand, utilizing the existing infrastructure to support the shift to a hydrogen economy, the gas pipelines in Algeria and Tunisia offer a substantial possibility for the transportation of green hydrogen. According to studies, current natural gas pipelines may be modified to carry hydrogen because they can manage mixtures of natural gas and hydrogen with the right adjustments [64,65]. In order to maintain pipelines' integrity under hydrogen service circumstances, advanced surface treatments can reduce problems such embrittlement. In North Africa, Algeria is positioned as a competitive producer of green hydrogen due to its abundance of renewable resources, especially solar energy, which also offers considerable economic advantages when using the country's existing gas infrastructure for transportation [66,67]. With the current pipeline network and the possibility for low-cost hydrogen generation, Algeria may become a major supplier of hydrogen to Europe. Reusing pipelines is a strategic priority for the EU, which is interested in importing hydrogen from North Africa due to the need to satisfy its climate pledges and diversify its energy sources. Even though the current infrastructure is a viable route for hydrogen transportation, obstacles like the requirement for regulatory alignment and funding for the production of renewable energy are still crucial to achieving this potential.

6.3. Global hydrogen infrastructure initiatives

With large investments and projects under way in numerous countries, global hydrogen infrastructure initiatives are quickly changing to accommodate the growing hydrogen economy. As part of a larger €4.6 billion initiative to accelerate the development of renewable hydrogen technology, the European Commission has committed nearly €2 billion through its first hydrogen auction—part of a broader €4.6 billion European Hydrogen Bank initiative—to stimulate the market and accelerate the deployment of renewable hydrogen technologies across its member states. Germany, aiming to future-proof its energy mix, has launched tenders for 12.5 GW of hydrogen-ready power plants, which will initially run on natural gas before transitioning fully to hydrogen, aligning with its 2035 decarbonization goals.

With approximately 1.5 million tons of blue hydrogen capacity anticipated to reach final investment decisions in 2025, the US is positioned to become a potential leader in this industry. Meanwhile, forecasts suggest that the supply of clean hydrogen in the country might expand dramatically. By 2025, the US is expected to reach 1.5 million tons of blue hydrogen production capacity, supported by tax incentives such as the 45 V production tax credit of up to \$3/kg for clean hydrogen. Furthermore, cross-border projects that cover the whole hydrogen value chain—from production and storage to distribution and application—are being made possible by cooperative initiatives like the Clean Hydrogen Joint Undertaking, guaranteeing a comprehensive approach to infrastructure development. Events like the World Hydrogen Summit 2025 give industry participants a forum to collaborate and exchange ideas, accelerating the development of hydrogen projects around the world. The foundation for a strong hydrogen infrastructure is being laid by these initiatives, which are crucial for reaching decarbonization targets and facilitating the global shift to sustainable energy systems.

7. Policy and regulatory landscape

7.1. Key standards and considerations for producing green hydrogen

To guarantee environmental sustainability and efficiency, several standards must be followed throughout the manufacturing of green hydrogen [68]. Water quality, electrolyzer technology, renewable energy sources, and regulatory frameworks are all covered by these standards. For green hydrogen to be produced successfully and widely used, several components must be integrated. The main guidelines and factors to be taken into account when producing green hydrogen are listed in Table 2. First, the production of green hydrogen must be supplied by renewable energy sources like solar and wind power, which are crucial for lowering carbon emissions and dependency on fossil fuels. Second, the selected electrolyzer must be efficient, and the energy consumed per kilogram of hydrogen produced can be used to assess the electrolyzers' efficiency. In this context, the design of membrane electrode assemblies (MEA) in electrolyzers and electrocatalysts has a significant impact on the efficiency of hydrogen production. The durability of anion exchange membrane water electrolyzers (AEMWE) and the high cost of noble metal catalysts should be taken into account [69]. Third, given the high water demand for large-scale hydrogen production, it is important that the water used for electrolysis comes from sustainable and noncompetitive sources. High-purity water, with a resistivity of more than 1 MΩ cm, sodium and chloride concentrations below 5 μg/L, and a total organic carbon content below 50 parts per billion, is required for proton exchange membrane water electrolyzers (PEMWEs). While freshwater with a total dissolved solid (TDS) content of less than 0.5 g/kg is typically used [70], alternatives such as desalinated, recycled, brackish, or seawater are being explored, especially in regions where freshwater supplies are limited. Fourth, maximizing renewable energy's integration with hydrogen production would ensure efficient generation, considering load balancing, grid stability, and storage. Green hydrogen must help reduce emissions in sectors like manufacturing, transportation, and heating, supporting net zero carbon goals. Robust hydrogen frameworks are being implemented by governments around the world. For example, the US'd Inflation Reduction Act (IRA, 2022) offers a \$3/kg tax credit for clean hydrogen (<0.45 kg CO_2e/kg H_2) through to 2033, and the EU's Renewable Energy Directive III (RED III, 2023) requires 42.5% renewable hydrogen in industry by 2030 with strict hourly green power matching starting from 2030 [71]. Japan's Basic Hydrogen Strategy (2023) aims to deliver 3 Mt/year by 2030 with \$17 billion in subsidies, whereas Germany's H_2Global project (2021) subsidizes imports through an auction mechanism worth €900 million. EU-wide origin guarantees are established by the CertifHy scheme (2022), which classifies hydrogen as low-carbon (<3.0 kg CO_2e/kg) or renewable (<1.5 kg CO_2e/kg).

As shown in Table 2, the standards for green hydrogen production can be systematically ranked by importance to guide prioritization in policy and investment decisions. The highest priority is the renewable energy source requirement, as it fundamentally defines the "green" nature of hydrogen. Without verifiably additional renewable electricity, hydrogen cannot qualify as truly low-carbon. Close behind are certification schemes and the efficiency of electrolysis, which ensure market credibility and technical viability, respectively. Environmental lifecycle assessments (LCAs) provide the necessary but secondary safeguards on sustainability, while safety standards, though essential, represent baseline requirements rather than differentiators in green hydrogen's value proposition. This hierarchy reflects a critical insight: Meeting top-tier standards (renewable sourcing and certification) is non-negotiable for climate benefits, whereas other components optimize an already compliant system. Policymakers should use this ranking to allocate resources, ensuring stringent enforcement of renewable electricity criteria before addressing lower-priority technical refinements.

Table 2. Green hydrogen production: Key components ranked by importance, with visual emphasis on critical requirements (the five-star system explicitly shows decision-making priorities).

Category	Key standards and requirements	Priority level
1. Renewable energy source (core requirement for "green" designation)	•Electricity source: Must use additional renewable energy (solar, wind, hydropower, geothermal) •Carbon footprint: ≤1 kg CO_2e/kg H_2 (aligned with EU RFNBO (European Union for Renewable Fuels of Non-Biological Origin) criteria)	★★★★★
2. Certifications (market credibility)	•Guarantees of origin (GO): Mandatory tracking of renewable energy inputs •EU clean hydrogen certification: Compliance with lifecycle emissions thresholds	★★★★
3. Electrolysis efficiency (technical feasibility)	•Energy use: ≤50 kWh/kg H_2 (PEM electrolyzers) •System losses: <10% (grid-to-hydrogen conversion)	★★★★
4. Environmental standards (sustainability)	•Lifecycle assessment (LCA): Must cover water use, electrolyzer production, and end-use emissions •Water sourcing: Noncompetitive/recycled water prioritized	★★★
5. Safety and technology (operational risks)	•ISO 14687: Hydrogen purity standards [72] •ISO/TS 19880-1: Safety protocols for storage/transport [73]	★★

Fifth, lifecycle assessment (LCA) of the process considering factors like water use, renewable energy production, and electrolyzers' lifecycle impacts must ensure that the environmental benefits of green hydrogen outweigh any negative effects throughout its production and use. Finally, safety regulations for its production, storage, and transportation are crucial. Standards like ISO 14687 for hydrogen quality [74] and ISO/TS 19880-1 for refueling stations [75] ensure the safety, quality, and compatibility of hydrogen technologies. To guarantee the sustainability of hydrogen generation, international standards concentrate on technological and environmental constraints [76]. Green hydrogen production standards are still being developed, but obstacles like the high cost of technology and the requirement for regulatory frameworks still exist. These issues should be resolved to reach green hydrogen's full potential as a sustainable energy source.

7.2. Government policies supporting the hydrogen economy

With several nations putting strategic frameworks in place to increase hydrogen production and utilization, government policies supporting the hydrogen economy are crucial for easing the transition to a low-carbon future. In the United States, the National Clean Hydrogen Strategy and Roadmap lays out a comprehensive plan to achieve large-scale clean hydrogen production by 2030, 2040, and 2050, with a focus on cooperation between federal agencies, industry, and local communities to meet decarbonization goals [77]. The Bipartisan Infrastructure Law further supports this initiative by providing tax credits for clean hydrogen production and funding regional hydrogen hubs. Targeting a rise in hydrogen consumption to 20 million tons annually by 2050 and making significant investments in green transformation projects, Japan's revised Basic Hydrogen Strategy seeks to build a strong domestic hydrogen market while boosting its competitiveness internationally [78]. By focusing on decarbonizing current hydrogen production and extending its role across several industries through subsidies and regulatory assistance, the European Union has also made notable progress with its Hydrogen Strategy and REPowerEU plan [79]. In order to guarantee that hydrogen production is in line with sustainability objectives, the International Renewable Energy Agency (IRENA) highlights the necessity of explicit regulatory structures and guarantees of origin on a global scale. These concerted efforts show how hydrogen's potential to decarbonize various industries while promoting economic growth and energy security is becoming increasingly recognized.

7.3. International collaborations in hydrogen research

A number of initiatives, including the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), aim to promote cooperation among nations to advance clean hydrogen technologies and fuel cells, improving energy security and sustainability. Crowdhelix launched the Hydrogen Helix, which brings together experts from across the hydrogen value chain, including researchers and industry leaders, to accelerate innovation in hydrogen technologies and foster collaborative projects like the GH_2 initiative, which aims to develop a CO_2-free hydrogen production process using solar energy. Additionally, nations like Australia are fortifying their ties through programs like the Commonwealth Scientific and Industrial Research Organisation (CSIRO)'s Hydrogen Industry Mission, which focuses on international research collaboration to bolster the global hydrogen economy. Furthermore, through initiatives like the CSIRO Hydrogen Industry Mission, which focuses on international research collaboration to support the global hydrogen sector and contribute to net zero objectives, nations like Australia are fortifying their relationships. By coordinating research activities among participating nations and guaranteeing efficient information and resource sharing, the International Energy Agency's Hydrogen Technology Collaboration Program further aids these initiatives. In addition to improving research capacities, these partnerships aid in the standardization of technologies and the development of interoperable systems, which are necessary for a hydrogen economy that is competitive in terms of cost and ultimately pave the way for a sustainable energy future.

7.4. Hydrogen standards and safety regulations

To guarantee the safe production, storage, and use of hydrogen as an energy source, safety rules and standards are essential. As the uses of hydrogen extend beyond more conventional sectors like chemical manufacturing and aerospace, several organizations, including the Department of Energy (DOE), are actively working to create thorough safety procedures and codes specific to hydrogen systems. This will fill in the regulation gaps. According to hazardous material handling protocols, the Occupational Safety and Health Administration (OSHA) issues rules for worker safety, and the National Renewable Energy Laboratory (NREL) keeps a database of pertinent safety requirements for hydrogen fuel cell systems. Furthermore, organizations like the International Organization for Standardization (ISO), which is creating worldwide standards for hydrogen technology to promote safe practices internationally, help to coordinate international activities. Regulatory agencies and industry stakeholders are working together to develop consensus standards that guarantee safety in hydrogen applications. Examples of these include the ATmospheres EXplosibles ATEX directives that set safety standards for equipment and workplaces where explosive atmospheres may occur, which regulate equipment used in potentially explosive atmospheres, and the National Fire Protection Association (NFPA) code for hydrogen technology safety in the U.S. Government agencies, business executives, and international organizations are working together to create a strong set of safety rules that will safeguard public health and encourage trust in hydrogen technologies as sustainable energy sources as their use increases.

7.5. Hydrogen subsidies and incentives

With global investments rising to about \$280 billion, hydrogen subsidies and incentives are becoming more and more important in propelling the expansion of the hydrogen economy. The United States is the main beneficiary, having set aside \$137 billion for qualified projects over the next 10 years through the Inflation Reduction Act (IRA). Clean hydrogen may now compete with hydrogen obtained from fossil fuels because to this act's generous tax credit of up to \$3 per kilogram for low-carbon hydrogen generation. Initiatives such as the Carbon Contracts for Difference (CCfD) program use fixed payments based on carbon savings to encourage the production of green hydrogen in Europe, even if the subsidies are around 27% lower than those in the US. Germany and other nations are also putting new subsidy schemes into place. Through initiatives like H_2Global, which allows green hydrogen imports into the EU through a two-auction system, nations like Germany are also putting creative subsidy structures into place, improving the market dynamics. To position themselves as leaders in the global hydrogen market, countries like Japan and India are creating their own strong frameworks for hydrogen development and providing significant subsidies for infrastructure construction and production. As more countries publish their hydrogen strategies, collaborative efforts and competitive incentives are projected to form a lively international hydrogen environment, ultimately driving a move towards sustainable energy options.

8. The future of hydrogen in the global energy market

8.1. Hydrogen's role in decarbonizing the energy sector

As a flexible energy carrier that can ease the switch from fossil fuels to renewable energy sources, hydrogen is essential to the decarbonization of the energy sector. It is expected that by 2050, hydrogen will make up 3–20% of total energy consumption as nations work to achieve net zero goals. The demand for hydrogen worldwide is also predicted to rise by up to 15 times from 2020 levels. Among its many uses, it improves the grid's stability and flexibility by serving as a storage option for surplus renewable energy produced by wind and solar power. Emissions can be cut by up to 11% without requiring a large amount of new infrastructure by incorporating hydrogen into current energy systems, such as by mixing it with natural gas in pipelines. Furthermore, where electrification alone might not be enough, hydrogen is crucial for decarbonizing hard-to-abate sectors like heavy industries and transportation. For example, hydrogen can serve as a clean fuel for aviation and maritime transportation and can take the place of fossil fuels in high-temperature industrial processes. Globally, significant government incentives and expenditures are being made to assist the development of hydrogen technologies, which are essential for increasing output and cutting costs. In the end, hydrogen is positioned as a pillar in the worldwide endeavor to attain a sustainable and decarbonized energy environment due to its capacity to supplement renewable energy sources and offer a clean substitute for fossil fuels.

8.2. Integration with renewable energy systems

Hydrogen serves as a vital bridge connecting intermittent renewable energy sources, including solar and wind, and the energy needs of many industries as the world moves toward decarbonization. Hydrogen, a versatile storage medium that can handle the unpredictability of renewable energy supply, can be produced by electrolyzing excess renewable electricity. Energy generated during periods of peak renewable generation can be stored and used later when demand is high or renewable output is low thanks to this feature, which enables efficient supply and demand management. This integration is demonstrated by projects like "power to gas" technology, which injects hydrogen into the already existing natural gas infrastructure to enable a gradual shift to a hydrogen-based economy without requiring major infrastructure upgrades.

Additionally, research suggests that combining the generation of hydrogen with renewable energy systems can result in significant financial advantages, such as lower energy production costs and improved system efficiency. The European Commission highlights that in order to improve the overall efficiency of renewable energy systems and decarbonize energy-intensive businesses and transportation, renewable hydrogen is crucial. The potential for hydrogen to supplement renewable energy sources places it as a cornerstone of future energy systems, propelling both economic growth and environmental sustainability as nations invest in hydrogen infrastructure and technology.

Figure 9 describes an overarching strategy for dealing with the intermittent nature of renewable energy sources in relation to green hydrogen production. It commences with the user making a request for hydrogen production that is handled by the power management system (PMS). The PMS first checks whether there is energy for use from the renewable energy sources (RES), which include solar panels and wind turbines. If the energy levels are satisfactory, the PMS commands the RES to provide energy that is given to the electrolyzer (EL). The electrolyzer takes the supplied power and performs electrolysis, which separates water into hydrogen and oxygen. The hydrogen generated is transferred to hydrogen storage (HS) for later use. On the other hand, if the PMS notices that energy availability is low, the system keeps watching the energy levels and gets a low energy warning from the RES. In this case, the PMS informs the user that due to the supplied energy not being sufficient, the production of hydrogen cannot take place. In any case, and regardless of whether production takes place or not, the PMS informs the user at the end of the process, which ensures transparency and accountability. This approach demonstrates the need for the combination of renewable energy systems and hydrogen production systems to enhance productivity.

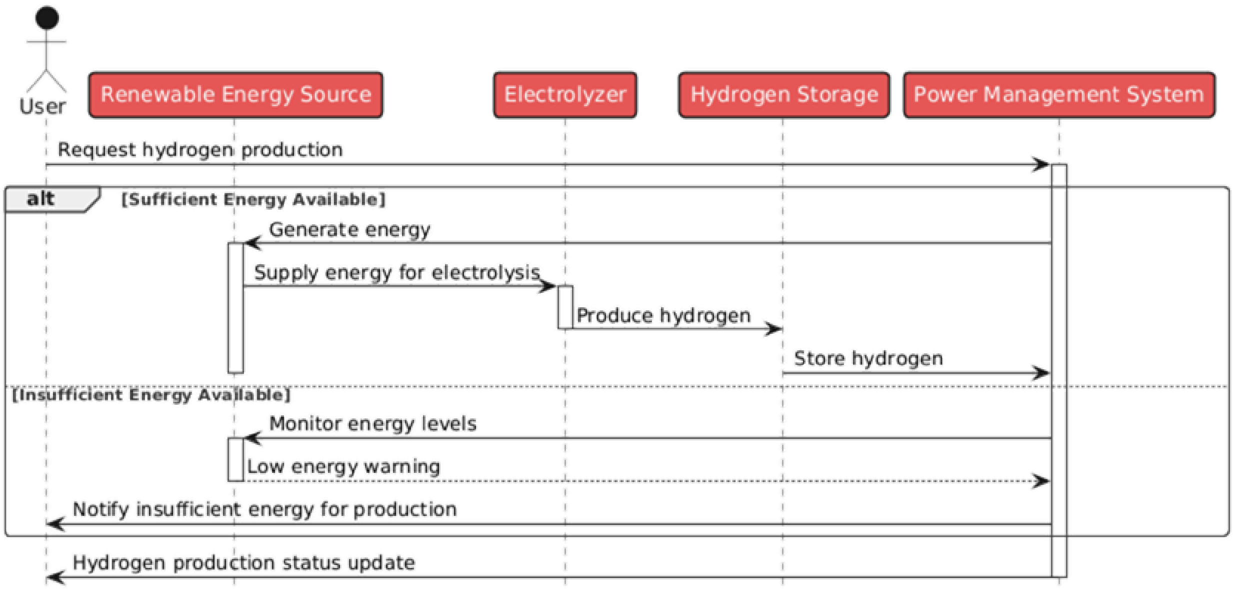


Figure 9. Managing intermittent renewable energy for efficient green hydrogen production.

8.3. Hydrogen in the context of the global energy transition

As a flexible and sustainable way to satisfy the urgent needs of decarbonization, hydrogen is becoming more and more acknowledged as a key component of the global energy transition. Hydrogen, especially green hydrogen made from renewable energy sources, is becoming a zero-emission substitute for fossil fuels as nations work to cut greenhouse gas emissions and fight climate change. This shift is crucial because hydrogen may drastically cut carbon emissions in a number of areas, such as manufacturing, transportation, and heating, by substituting clean hydrogen solutions—which only release water vapor when they burn—for conventional fossil fuels. Clean hydrogen has the potential to be a key component in reaching global climate goals, with the International Renewable Energy Agency (IRENA) projecting that it might make up as much as 12% of total energy consumption by 2050. Furthermore, by storing the extra renewable energy produced by solar and wind power, hydrogen improves the grid's flexibility and stability while mitigating the intermittency issues that these energy sources provide. Countries can take advantage of hydrogen's high energy density and storability to build a more robust and low-carbon energy infrastructure by incorporating it into their current energy systems, such as by using it in fuel cells or blending it with natural gas. The integration of hydrogen into the global energy landscape is expected to accelerate as investments in hydrogen technology rise, bolstered by advantageous regulations and incentives. This will spur economic growth and innovation while enabling a sustainable shift away from fossil fuels.

8.4. Hydrogen as an energy storage solution

The potential of hydrogen as an energy storage medium is becoming more widely acknowledged, especially when considering the integration of renewable energy sources such as solar and wind. The ability to store huge amounts of energy in a relatively compact form is one of the main benefits of hydrogen storage, which makes it appropriate for both short-term and long-term energy needs. By using excess renewable power to electrolyze water into hydrogen and oxygen, hydrogen can be created. This process effectively stores energy that would otherwise be squandered during times of high generation or low demand. By resolving the intermittent problems with renewable energy, this skill makes it possible to have a steadier and more dependent power source. Furthermore, hydrogen may be preserved in sizable subterranean caves and stored in a variety of forms, such as solid metal hydrides or pressurized gas, which enables seasonal storage that batteries are unable to offer. When necessary, hydrogen can be consumed in gas turbines or converted back into electricity using fuel cells, providing a flexible way to satisfy energy demands with only water vapor as a byproduct. With continued technological developments and falling production costs, hydrogen's function as an energy storage medium is gaining popularity as nations work to decarbonize their energy systems, making it a crucial component of a sustainable energy future.

8.5. Hydrogen's global energy roadmap: Scaling, integration, and net zero dominance

As displayed in Figure 10, three major stages will shape hydrogen's future in the global energy market: (1) 2024–2030: Scaling, whereby electrolyzer costs fall by 50% to $400/kW [80] and global capacity reaches 30–50 Mt/year [81], thanks to EU/US policies such as the $3/kg IRA tax credit and RED III's 42.5% renewable H_2 mandate; (2) 2031–2040: Integration, when hydrogen meets 5–10% of energy demand through retrofitted pipelines and ammonia-based global trade [82–83], with costs reaching $2–3/kg in sun-rich regions; and (3) 2041–2050: Net zero dominance, when H_2 accounts for 15% of final energy, assuming aggressive policy support [84], bolstered by more than 500 salt cavern storage sites and stringent hourly renewable matching. The $1.2 trillion funding gap and the requirement for 3000 TWh of excess renewable energy are critical hazards that call for coordinated policies such as H_2 blending requirements and R&D efforts focused on solid oxide electrolyzers (85% efficiency) and liquid carriers (6–7 weight percent density).

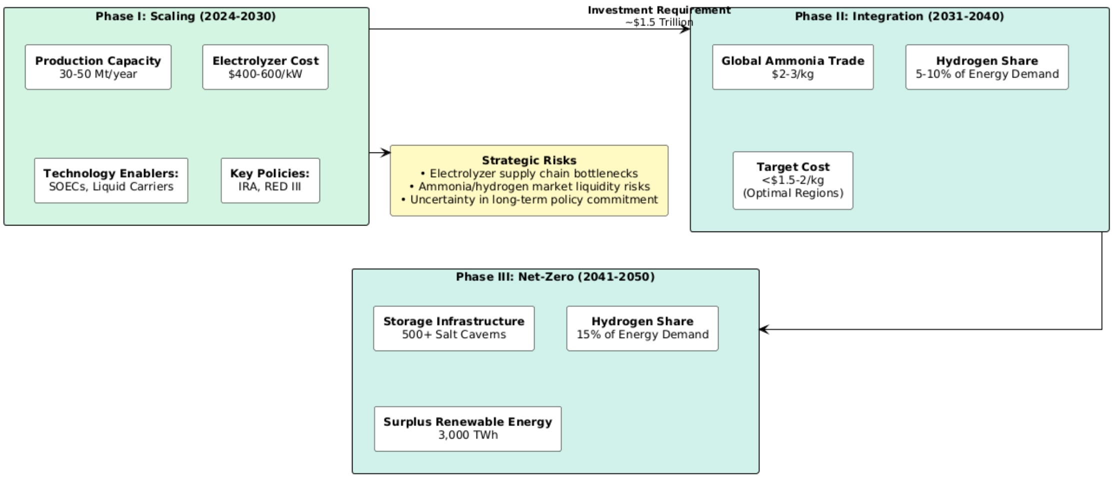


Figure 10. Clean hydrogen transition roadmap (2024–2050): Strategic phases and key milestones.

9. Conclusions

Hydrogen, the most basic and prevalent element in the universe, is essential for maintaining life and enabling many industrial and natural activities. It is a vital component of water and is necessary for life as we know it. It contributes to respiration, photosynthesis, and the production of energy in biological systems. Moreover, hydrogen is essential for the chemical reactions that support life on Earth, since it is also necessary for the synthesis of many organic molecules. Scientists and engineers have developed a number of techniques to extract hydrogen from these sources over time. One of the most popular methods is electrolysis, which divides water molecules into hydrogen and oxygen using electricity. However, when using fossil fuels, this approach is expensive and environmentally unsustainable due to its high energy consumption. Hence, green hydrogen has become more necessary as the need for clean, renewable energy has increased. From industry and transportation to power generation and storage, hydrogen provides a flexible option that may be applied in many different fields. For hard-to-decarbonize industries like heavy manufacturing and long-distance transportation, where fossil fuel alternatives have been scarce, it can be used as a clean fuel. Furthermore, considering the intermittent nature of renewable energy sources like solar and wind, hydrogen is a useful tool for balancing the supply and demand for renewable energy because to its efficient storage and transportation capabilities. This review reveals both its transformative potential and the systemic challenges that must be overcome to realize its role in the global energy transition.

✓ The exponential growth in green hydrogen patents—led by China (5855 patents), the US (907), and the EU (PCT: 775)—signals a competitive race for technological leadership. The 2023 peak underscores the acceleration of R&D, yet disparities in regional contributions highlight gaps in equitable global collaboration.

✓ Megaprojects like Australia's Western Green Energy Hub (7203 ktH_2/y) and Mauritania's Megaton Moon (6064 ktH_2/y) demonstrate hydrogen's industrial scalability, but their concentration in resource-rich regions raises questions about energy equity and supply chain resilience.

- ✓ While MOFs and LOHCs offer theoretical promise, real-world constraints persist: 30% energy loss in liquefaction, \$0.5–1/kg cost penalties for ammonia synthesis, and regulatory bottlenecks (e.g., the EU's 0.1% pipeline leakage limit).
- ✓ Policy interventions are narrowing the cost gaps: The US's IRA subsidies (\$3/kg) could slash green H_2 costs to less than \$1/kg by 2030, while the EU's carbon pricing (>\$102/ton CO_2) favors electrolysis. Grid intermittency and CCS adoption risks may still inflate LCOH by 20–30% in decentralized systems.
- ✓ Robust frameworks are emerging, from the US's IRA's tax credits to the EU's RED III mandate (42.5% renewable H_2 by 2030) and Japan's \$17 billion subsidies. However, fragmented standards (e.g., CertifHy's CO_2 thresholds) and uneven funding risk slowing global alignment.
- ✓ Hydrogen's trajectory is expected to progress through three phases: Scaling (2024–2030), where electrolyzer costs drop to \$400/kW due to strong policy support; integration (2031–2040), with hydrogen meeting 5–10% of energy demand via ammonia trade and retrofitted pipelines; and net zero dominance (2041–2050), where hydrogen supplies 15% of final energy, backed by 500+ salt cavern storage sites and solid oxide electrolyzers with 85% efficiency.
- ✓ Key challenges remain for hydrogen's future: A \$1.2 trillion infrastructure funding gap calls for public–private cooperation, trade-offs between storage methods and production models complicate deployment, and patent and project concentration risks exclude developing economies, raising concerns about global equity.

Hydrogen's future hinges on bridging these gaps through innovation, policy coherence, and global cooperation. As stars fuse hydrogen to power galaxies, humanity must now harness it to power a sustainable Earth, without replicating the inequalities of past energy transitions.

In light of the power-to-hydrogen technology and its wider uses, the following suggestions are made for further research in the field of hydrogen production.

- ✓ Although electrolysis is a promising technique for producing green hydrogen, there are still significant obstacles to overcome in terms of increasing its effectiveness and reducing costs. Current systems face energy losses of 20–40%, with PEM electrolyzers requiring 48–55 kWh/kg H_2 and alkaline systems needing 50–60 kWh/kg H_2. Future studies should concentrate on creating sophisticated catalysts, improving electrodes' composition, and investigating novel electrolyzer designs.
- ✓ Green hydrogen generation can be made more dependable and scalable by combining power-to-hydrogen technology with renewable energy sources like solar and wind. With global power to hydrogen capacity projected to grow from 0.3 GW (2023) to 50 GW by 2030, these integration technologies will determine whether green hydrogen can achieve its projected 10–15% share of global energy storage by 2040. The goal of research should be to better coordinate the production of hydrogen with the fluctuating nature of renewable energy sources. This might entail creating smart grids and cutting-edge energy management systems that facilitate hydrogen generation and economical energy utilization.
- ✓ Green hydrogen has a lot of potential, but its high manufacturing costs prevent it from being widely used. Future research should examine cost-cutting measures like economies of scale, new technology, and the improvement of hydrogen distribution and storage infrastructure. Reducing costs will also need the creation of financial and policy incentives, like carbon pricing or subsidies, to encourage the use of hydrogen generation technology.
- ✓ It will take a coordinated effort by businesses, governments, and academic institutions to successfully implement hydrogen technologies. In order to provide uniform rules and best practices

for the production, storage, and use of hydrogen, future research should concentrate on promoting international cooperation. Establishing global hydrogen supply chains that guarantee fair access to green hydrogen in both developed and developing economies may also be facilitated by cooperative efforts.

✓ The development of laws and regulations that support the hydrogen economy is crucial to its success. Prioritizing hydrogen production in the global shift to a low-carbon economy can also be achieved by investigating the role of hydrogen in national and regional decarbonization programs.

✓ Finally, gaining societal acceptance requires raising public knowledge and comprehension of hydrogen's contribution to the energy transition. In order to educate the public about the advantages of green hydrogen, its possible uses, and how it may help fight climate change, future efforts should include educational campaigns and initiatives. Increasing public confidence in hydrogen technology will hasten their implementation in a number of industries.

Use of AI tools declaration

The authors used AI tools solely for improving grammar and language style. All intellectual content, analysis, and conclusions are the authors' own.

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This work is dedicated to the soul of the late Professor Sassi Ben Nasrallah, in remembrance of his invaluable contributions and enduring legacy.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

R-B: Conceptualization, methodology, writing—original draft. M-H: Data curation, resources, formal analysis, visualization—review and editing. S-E: Supervision, formal analysis.

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