

Review

Hydrogen in the Energy Transition: A System-Level Review of Production Pathways, Infrastructure, and Deployment Challenges

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Abstract

Hydrogen is increasingly recognized as a strategic energy carrier in global decarbonization pathways, particularly for hard-to-abate sectors such as steel production, chemicals, long-distance transport, and seasonal energy storage. However, its climate benefits depend strongly on the production pathway, infrastructure development, and system-level integration. To address this complexity, this review develops a systematic quantitative comparison framework that is applied consistently across major hydrogen production pathways. Each pathway is evaluated using five criteria: carbon intensity ($\text{kg CO}_2/\text{kg H}_2$), Technology Readiness Level (TRL, 1–10), process efficiency (% on an LHV basis), scalability potential, and compatibility with existing infrastructure. The resulting cross-pathway matrix enables evidence-based assessment of trade-offs rather than a purely sequential description of technologies. Four broad production categories are considered: fossil-based hydrogen, fossil-based hydrogen with carbon mitigation, nuclear-derived hydrogen, and renewable-based hydrogen. The review further examines the integration of hydrogen storage, transport, and end-use applications to identify key system constraints and infrastructure bottlenecks. Emerging approaches, including digital optimization and machine learning, are also discussed for enhancing the operation and control of hydrogen systems. The analysis indicates that while low-carbon hydrogen is essential for decarbonizing hard-to-abate sectors, its large-scale deployment remains constrained by technological, infrastructural, and investment-related challenges.

Keywords: hydrogen; energy transition; hydrogen infrastructure; decarbonization; machine learning

1. Introduction

The global energy system is changing rapidly, driven by climate change and the need to reach net-zero greenhouse gas (GHG) emissions. Industrial activity, transport and electricity generation are still the major sources of carbon dioxide (CO_2) emissions, being a risk for environmental sustainability, economic stability and energy security [1,2]. In this context, hydrogen has emerged as a key element of decarbonization strategies, thanks to its versatility and its capacity for complementarity with renewable energy sources (RES) [3]. Hydrogen as a long-duration energy carrier allows for the decoupling of the temporal and spatial aspects of energy supply and demand, thus supporting grid stability and potentially resolving some of the challenges of hard-to-electrify sectors such as heavy industry and long-distance transport [4,5]. When there is surplus renewable electricity, this excess can be converted into hydrogen via water electrolysis and stored for later use in



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energy storage, industrial processes or transportation fuels [6,7]. Furthermore, hydrogen can substitute fossil fuels in high-temperature industrial applications (e.g., chemical and cement industry) and help to decarbonize heavy-duty transport, maritime shipping and possibly aviation [8–14]. Hydrogen can be produced through a variety of technologies, including RES water electrolysis, fossil-based reforming with carbon capture and storage (CCS), biomass gasification and novel thermochemical processes [15–17]. The pathway chosen has a major impact on lifecycle emissions, cost and scalability. Efficient storage and transportation solutions such as compressed gas, liquefied hydrogen, underground storage and pipeline infrastructure connecting production sites with end-use applications are also needed for large-scale deployment [18–23]. Hydrogen has gained increasing strategic importance in recent years in national and international energy policies. Hydrogen roadmaps since 2020 have highlighted the importance of low-carbon hydrogen for meeting climate targets by mid-century, especially in hard-to-abate sectors [24–32]. Initial efforts were mainly focused on R&D, pilot projects and institutional building, while more recent efforts are increasingly focused on infrastructure development, industrial clusters and integrated hydrogen supply chains [33–40]. Hydrogen systems are expected to move towards large-scale deployment in the future with growing electrolyzer capacity, RES-hydrogen hubs and cross-border infrastructure networks [41–49]. Along with the technological development, digitalization and artificial intelligence (AI) are arising as important tools for optimization of hydrogen systems, giving predictive maintenance, better energy management and improved integration with renewable energy systems [50–53]. Such developments highlight the increasing importance of system-level approaches to the integration of hydrogen into future energy networks. The paper therefore provides a system-level review of the role of hydrogen in the energy transition, including production pathways, storage and transport infrastructure, end-use applications and regional deployment strategies. While many existing studies focus on individual technologies, this review integrates technological, infrastructural and policy perspectives, and points out emerging aspects such as digital optimization and machine learning (ML) applications in hydrogen energy systems. Existing studies in the field of hydrogen technology mainly focus on individual parts of the value chain, such as production routes, materials and electrolyzer design, storage technologies or end-use applications. In contrast, fewer studies cover the economic and policy dimensions, and machine learning-related research mainly focuses on electrolyzer control or fuel cell diagnostics separately. However, no study has yet comprehensively and systematically integrated the five key dimensions of production, infrastructure, end-use, policy and digital optimization into an integrated framework, considering their interdependencies. This fragmentation of the literature has led to a system-level analytical gap, such that single-technology studies are unable to identify cross-sector bottlenecks, such as the mismatch between the cost of green hydrogen production and the speed of infrastructure development or the dependence of machine learning-based optimization performance on data exchange between different actors in the value chain and regulatory frameworks.

This study aims to fill this gap by making four main contributions. First, a comprehensive comparative matrix is developed to assess the main hydrogen production pathways based on carbon intensity, technology maturity level (TRL), process efficiency, scalability and infrastructure compatibility. Second, system-level infrastructure constraints are analyzed by examining energy penalties, purity requirements and safety challenges. Third, hydrogen end-uses are competitively evaluated from a techno-economic perspective compared to alternatives such as direct electrification and CCS to identify areas of real advantage. Fourth, machine learning and digital optimization are considered as an integrated enabling layer across the entire value chain, and evidence on algorithms, data, KPIs and constraints is structured by application area. The study also distinguishes between proven

operational data, projects under development, announced scenarios and market forecasts to avoid unrealistic inferences. The hydrogen's evolving role in decarbonization from 2020 to 2030 is given in Figure 1.

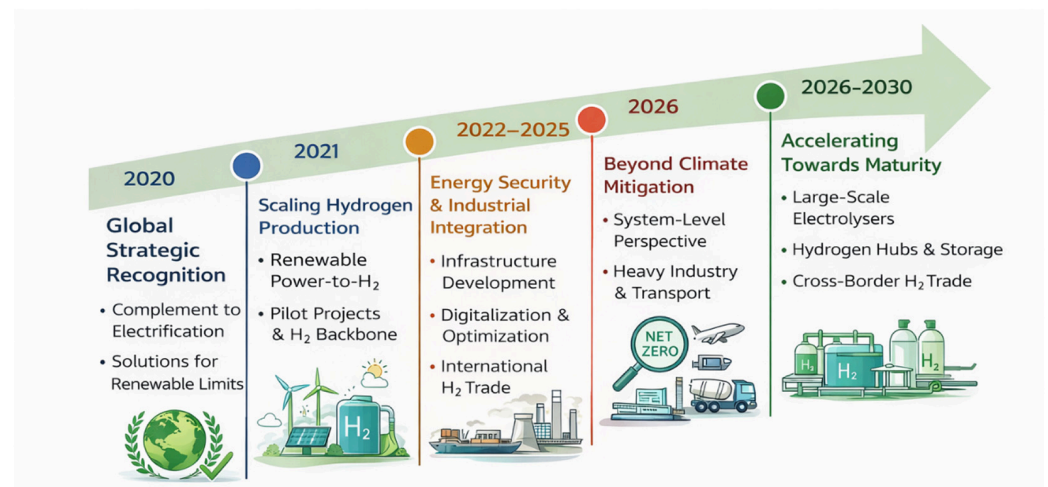


Figure 1. Hydrogen's evolving role in decarbonization from 2020 to 2030.

2. Review Methodology

This review was conducted through a structured search of peer-reviewed articles, reports, and policy documents published primarily between 2020 and early 2026. The year 2020 was chosen as the starting point as it coincides with the publication of the EU Hydrogen Strategy and a significant acceleration of national hydrogen roadmaps and policy frameworks globally following the Paris Agreement implementation cycle. The primary databases searched included Web of Science, Scopus, and Google Scholar, supplemented with grey literature from reputable institutional sources including the International Energy Agency (IEA), the European Commission, the International Renewable Energy Agency (IRENA), and the World Nuclear Association (WNA). Market data and industry reports from well-known analysts (e.g., Fortune Business Insights, IMARC Group, Custom Market Insights) were also consulted to provide quantitative estimates of production volumes and market size and are clearly identified as commercial forecasts throughout the review.

The search strategy employed combinations of keywords and Boolean operators across the five thematic domains of the review. For production pathways, the terms hydrogen production combined with green, blue, grey, turquoise, or nuclear were used. Storage and infrastructure searches combined hydrogen storage with underground, metal hydride, or liquid, and hydrogen infrastructure with a pipeline. End-use applications were searched using hydrogen end-use combined with industry, transport, or electricity. Digital optimization literature was retrieved using machine learning combined with hydrogen, and policy-related sources were identified through hydrogen policy combined with EU, IEA, or decarbonization. All database searches were conducted in English, while no language restrictions were applied to institutional and policy documents.

Studies were included if they: (i) addressed at least one of the five thematic domains covered by this review—production pathways, storage and transport infrastructure, end-use applications, policy and economics, or digital optimization; (ii) provided quantitative data, techno-economic analysis, or policy-level assessment; and (iii) were published in peer-reviewed journals, edited books, or recognized institutional outlets. Studies were excluded if they: (i) focused exclusively on laboratory-scale material characterization without broader system relevance; (ii) lacked sufficient methodological transparency to allow assessment of data quality; or (iii) were available only as preprints without subsequent peer review.

Approximately 110 references were retained after screening and are cited throughout this review.

The analysis followed a narrative synthesis approach, which is appropriate for system-level technology reviews spanning heterogeneous evidence types, including empirical studies, modelling outputs, policy documents, and market analyses. Within each thematic domain, selected studies were synthesized to identify key trends, performance metrics, deployment gaps, and research frontiers. A multi-criteria comparative framework was applied to the assessment of hydrogen production pathways, evaluating each route against five dimensions: carbon intensity, technological maturity expressed through Technology Readiness Level (TRL), process efficiency, scalability, and infrastructure compatibility. This framework enabled structured cross-pathway comparison and informed the system-level conclusions presented in the review.

3. Hydrogen Production Pathways

The hydrogen's main role is that of an energy carrier. Thus, its environmental impact is largely determined by the production pathway and the energy source used to drive the production process [54]. Hydrogen can be produced from a variety of feedstocks, including fossil fuels, water, biomass, and nuclear energy, using processes such as SMR, ATR, electrolysis, gasification, and other novel thermochemical or photochemical pathways [55]. These pathways vary significantly in terms of carbon intensity, process efficiency, cost, scalability and technological maturity [56]. A colour classification system has been widely used in academic and policy discussions to differentiate hydrogen production pathways by feedstock and emissions profile [57,58]. However, the analytical value of this classification is limited if it is used only to describe market forecasts pathway by pathway. In this review, the colour taxonomy is therefore used strictly as a shorthand for the five-criteria framework presented in Table 1—carbon intensity, TRL, efficiency, scalability, and infrastructure compatibility—rather than as a structure for sequential market reporting. Market size figures reported in the subsections below are retained for context but are clearly identified by source type; readers should refer to Table 1 for the analytical comparison. Therefore, the colour label is an indicative descriptor that indicates three key elements, i.e., (i) the source of the feedstock, (ii) the conversion technology used and (iii) the resulting carbon footprint [59,60]. In this regard, Figure 2 schematically summarizes the ten frequently referred to hydrogen colour categories, and the respective input resources and output streams for each production pathway are highlighted. This classification allows for more transparent comparison over production routes, emissions or by-products and provides a structured basis for assessment of their potential role in future net-zero energy systems.

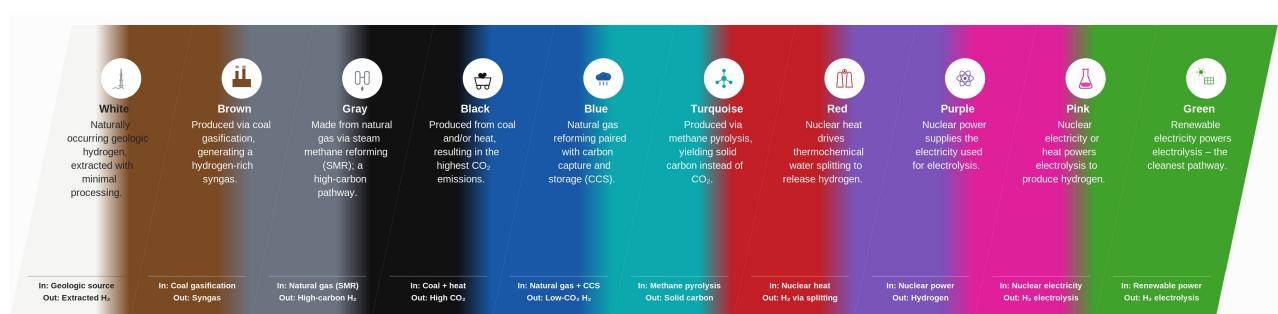


Figure 2. Schematic overview of the ten hydrogen colour pathways indicating energy sources.

Table 1. Cross-pathway quantitative comparison matrix for major hydrogen production routes (five criteria, explicit numerical ranges).

Production Pathway	TRL	Carbon Intensity (kg CO ₂ /kg H ₂)	Process Efficiency (% LHV)	Scalability	Infra. Compat.	Near-Term Role
Grey hydrogen (SMR, unabated)	9	9–12 Unabated fossil	70–85%	High	High	Dominant today; must decline
Blue hydrogen (SMR + CCS)	8–9	1–3 If CH ₄ leakage < 1%, capture > 90%	60–75%	Med-high	High	Near-term bridge; conditional
Green hydrogen (PEM) (Renewable electrolysis)	7–8	0.5–2 Depends on the grid factor	65–80%	High	Low-med	Priority long-term pathway
Green hydrogen (ALK) (Alkaline electrolysis)	9	0.5–2 Depends on the grid factor	62–77%	High	Low-med	Lower dynamic response vs. PEM
Pink/Purple hydrogen (Nuclear-derived)	4–7	0.3–1 Lifecycle basis	25–45% (thermo) 65–80% (electric)	Medium	Medium	Baseload potential; pre-commercial
Turquoise hydrogen (Methane pyrolysis)	3–5	≈0 Solid carbon by-product	55–68%	Low-med	Medium	Emerging; carbon market dependent
White hydrogen (Natural/geological)	2–4	≈0 At the point of extraction	-	Unknown	Low	Speculative; resource mapping needed

To provide a systematic basis for cross-pathway comparison, Table 1 presents a consolidated cross-pathway matrix applying five criteria with explicit numerical ranges to all major production routes. The five criteria are: (i) carbon intensity (kg CO₂/kg H₂, based on lifecycle assessment literature); (ii) Technology Readiness Level (TRL, 1–9 scale, IEA/IRENA definitions); (iii) process efficiency (% on lower heating value, LHV, basis); (iv) scalability potential (scored low/medium/high based on current project pipeline and resource availability); and (v) compatibility with existing natural gas or industrial infrastructure (low/medium/high). These criteria are applied identically and simultaneously across all pathways, enabling direct cross-pathway trade-off assessment. The quantitative results are summarized in Table 1 and described as follows. Grey hydrogen (SMR, unabated) scores TRL 9, carbon intensity 9–12 kg CO₂/kg H₂, efficiency 70–85% LHV, scalability high, and infrastructure compatibility high—the highest maturity but the worst environmental performance of any pathway. Blue hydrogen (SMR + CCS) scores TRL 8–9, carbon intensity 1–3 kg CO₂/kg H₂ (contingent on methane leakage below 1% and capture rate above 90%), efficiency 60–75% LHV, scalability medium-high, and infrastructure compatibility high—a pragmatic near-term bridge with significant performance conditionality. Green hydrogen via PEM electrolysis scores TRL 7–8 at large scale, carbon intensity 0.5–2 kg CO₂/kg H₂ (dependent on grid emissions factor), efficiency 65–80% LHV, scalability high, and infrastructure compatibility low-medium—the lowest carbon intensity pathway with the highest long-term potential but requiring dedicated renewable electricity infrastructure. Alkaline electrolysis scores similarly (TRL 9, efficiency 62–77% LHV) but with lower dynamic response capability. Nuclear-derived (pink/purple) hydrogen scores TRL 4–7, carbon intensity 0.3–1.0 kg CO₂/kg H₂ on a lifecycle basis, efficiency 25–45% (thermochemical routes) or 65–80% (nuclear-electric electrolysis), scalability medium, and infrastructure compatibility medium. Turquoise hydrogen (methane pyrolysis) scores TRL 3–5, near-zero carbon intensity due to solid carbon by-product, efficiency 55–68% LHV, scalability low-medium, and infrastructure compatibility medium. White (natural geological) hydrogen scores TRL 2–4, effectively zero carbon intensity at the point of extraction, with scalability currently unknown and infrastructure compatibility low.

This systematic matrix reveals a clear frontier trade-off: pathways with the highest TRL and infrastructure compatibility (grey, blue) carry the highest or conditional carbon burdens, while pathways with the lowest carbon intensity (green, pink, turquoise, white) are at lower TRL with higher infrastructure requirements—a finding that directly informs the prioritization of technology support and infrastructure investment discussed in subsequent sections. Having said that, Figure 3 shows the key hydrogen production pathways plotted by levelized production cost and lifecycle carbon intensity, highlighting the trade-offs between economic and environmental performance.

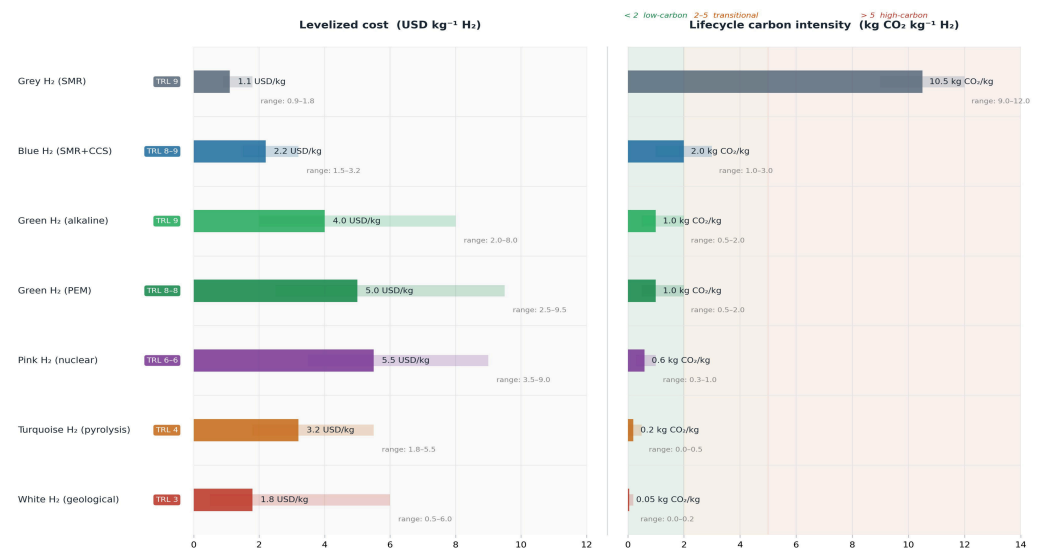


Figure 3. Comparison of major hydrogen production pathways by levelized cost (left panel) and lifecycle carbon intensity (right panel).

Figure 3 shows that while fossil-based routes are usually cheaper to produce, they are also much more carbon-intensive. Renewable-based electrolysis has the lowest lifecycle emissions, but at the cost of higher prices. The inclusion of TRL indicators further illustrates the different maturity of the various technologies and indicates that some low-carbon pathways are still at earlier stages of commercial deployment. Solid bars show mid-range values; lighter bars show full reported literature ranges. TRL badges indicate Technology Readiness Level on a scale of 1–9. Carbon intensity zones: green < 2 kg CO₂/kg H₂ (low-carbon), amber 2–5 kg CO₂/kg H₂ (transitional), red > 5 kg CO₂/kg H₂ (high-carbon). Pathways are ordered by decreasing carbon intensity. This figure provides the analytical comparison referenced in Section 3 (Table 1) in visual form, enabling direct cross-pathway trade-off assessment between cost and carbon performance.

3.1. Global Market Size of White Hydrogen

Currently, the extraction of white (natural) hydrogen combines conventional geological exploration and drilling techniques with specialized gas capture and purification technologies [61]. However, commercial production is limited, and the industry is still in an early stage of development [62]. The natural hydrogen industry is nascent but is increasingly gaining traction and holds significant potential for growth over the next decade. The global natural hydrogen market was valued at an estimated USD 4 billion in 2024 and is projected to grow to USD 10.5 billion by 2033 [63]. This is a commercial market forecast and carries substantial uncertainty, as white hydrogen production remains pre-commercial. Some analysts expect it to rise further to USD 15.1 billion by 2034, while more conservative estimates put it at around USD 8.95 billion. The compound annual growth rate (CAGR) for 2025–2034 is projected to be between 9% and 11% [64]. From the geological point of

view, global white hydrogen resources are estimated to be about 46 million tonnes, and the potential production capacity is expected to reach 115 million tonnes by 2033 [63,65]. The expected growth is due to the increase in exploration activities, technological advancements in low-energy extraction methods and the rising global interest in hydrogen as a sustainable energy carrier [64].

3.2. Global Production Trends of Grey Hydrogen

Grey hydrogen today remains the dominant type of hydrogen production worldwide, accounting for most volumes consumed in industrial processes and refining applications [66]. The world hydrogen production in 2022–2023 was about 95–97 million tonnes per year, of which more than 84% originated from unabated fossil fuel routes [67]. As shown in Table 2, grey hydrogen is projected to continue as the dominant in global supply through 2030, comprising more than 95% of total production. Production is expected to increase from approximately 97 million tonnes (Mt) in 2023 to around 105–110 Mt by 2030. In contrast, low-carbon hydrogen is currently a very small part of the market (less than 1 Mt in 2023). However, low-carbon production could increase substantially by 2030, depending on project maturity: operational and FID-stage projects point to ≈ 4.2 Mt/year, while full realization of all announced projects could yield up to 37–49 Mt/year. These ranges reflect fundamentally different evidence bases (operational capacity vs. announced plans) and should not be compared without qualification.

Table 2. Global hydrogen production (2023–2030) by total, grey, and low-emissions shares, with projected trends through 2030 [67–69].

Country/Region	2023 (Mt)	2024 (Mt)	2025 (Mt)	2026–2030 Forecast (Mt)
Global total hydrogen	97 * Mt produced worldwide	100 * Mt total estimated	102 * Mt (projected)	105–110 * Mt total projection (with continued fossil dominance)
Grey/fossil-based share	93–95 * Mt (96–98% of total)	97–99 * Mt (≈ 97 –99%)	100–101 * Mt (96–98%)	102–108 * Mt (95–98%)
Low-emissions (blue plus green)	<1 Mt (<1% of total)	Some growth in electrolyzer capacity but still <2 Mt	Increasing projects could add several Mt	Could reach 30–49 * Mt low-emissions under announced plans (but many delayed/cancelled)

* Estimated based on each region's share of total hydrogen production. These data combine fossil-based hydrogen outputs (primarily grey from natural gas SMR and fossil by-products) and account for variations in industrial hydrogen use by country; specific data may vary among data providers.

These projections show the continued dominance of grey hydrogen in the near term, even as low-carbon production pathways begin to scale in response to decarbonization policies and technological development [67–69]. Table 2 combines three distinct evidence categories that should not be read as equally reliable. The 2023–2024 figures are IEA verified operational data (high confidence). The 2025 estimate is an IEA near-term projection (medium confidence). The 2026–2030 forecast range is an IEA announced-projects scenario (low confidence), where the upper bound of 30–49 Mt assumes full realization of all announced projects with no delays or cancellations. The same source-type distinction applies to Tables 3–7 throughout Section 3.

3.3. Global Production Trends of Black Hydrogen

Black hydrogen (from coal, through gasification but without CCS) is still an important source of global hydrogen supply, particularly in coal-rich regions. The global hydrogen production in 2024 was nearly 100 Mt. Coal-based hydrogen accounted for approximately 20% of the total production (≈ 20 Mt) [69]. As shown in Table 3, production is very geographically concentrated. China is the main player in this sector, producing around 18–19 Mt per year; nearly 90% of the world’s hydrogen is produced from coal. Other countries are far less contributing, such as India (1.0–1.2 Mt, $\approx 5\%$), Russia (0.3–0.5 Mt, $\approx 2\%$), and Indonesia (≈ 0.2 Mt, $<1\%$). Production in other regions is negligible (approx. 0.2–0.3 Mt) [69]. Currently small, the share of black hydrogen is expected to decline as production of low-emission hydrogen, such as via water electrolysis and fossil-based hydrogen with CCS, increases. Current estimates indicate that low-carbon hydrogen will account for around 4% of global production in 2030 [IEA projection based on announced policies scenario; not a confirmed deployment figure].

Table 3. Estimated black hydrogen (coal-based) production by country (2025) [69].

Country	Black Hydrogen Production (Mt/Year)	Share of Global Black Hydrogen (%)
China	$\approx 18\text{--}19$	$\approx 90\text{--}95\%$
India	$\approx 1.0\text{--}1.2$	$\approx 5\%$
Russia	$\approx 0.3\text{--}0.5$	$\approx 2\%$
Indonesia	≈ 0.2	$\approx <1\%$
Other countries	$\approx 0.2\text{--}0.3$	$\approx <1\%$
Global Total	≈ 20 Mt/year	100%

Coal-based hydrogen is still economically competitive, mainly due to the well-developed infrastructure and relatively low production costs. Decarbonization policies, carbon pricing mechanisms and increasing investment in clean hydrogen technologies are expected to gradually transform the market in the coming decade [69].

3.4. Global Production Trends of Blue Hydrogen

Blue hydrogen, produced from fossil fuels, mainly natural gas, with CCUS, currently represents a very small share of global hydrogen production, less than 1% of the almost 100 Mt produced in 2024 [69,70]. Nevertheless, low-emission hydrogen, including blue hydrogen, is expected to expand significantly over the coming decade. Operational projects, projects under construction, and projects at the final investment decision (FID) stage are forecasted to reach around 4.2 Mt/year by 2030 [IEA confirmed-pipeline estimate, high confidence]. If all announced low-emissions hydrogen projects are successfully implemented, global production could potentially reach around 37 Mt/year [IEA announced-projects scenario, low confidence contingent on full project realization with no delays or cancellations]. However, these projections may be moderated by project delays, cancellations, and cost uncertainties [69]. This expected growth is backed by the increasing deployment of CCUS technologies, the establishment of natural gas reforming plants with carbon capture and the implementation of enabling policy frameworks across several regions. As seen in Table 4, global low-emissions hydrogen production is still very limited today (under 1 Mt per year in 2023–2024), which corresponds to less than 1% of total hydrogen supply. However, planned projects suggest high growth potential by 2030, showing the growing importance of blue hydrogen in the evolving global hydrogen economy [69].

Table 4. IEA-based estimated global low-emissions hydrogen production [69].

Year	Estimated Production (Low-Carbon Hydrogen, Mt/Year)	Notes (Blue Hydrogen Dominated)
2023	≈0.8 Mt	Total low-emissions hydrogen production (≈<1% of ≈100 Mt total)
2024	≈0.8–1.0 Mt	Low-emissions hydrogen production increased ≈10% in 2024
2025 (est.)	≈1.0 Mt	Forecast based on IEA expected output
2030 (operational + FID)	≈4.2 Mt	Production from projects operational, under construction or with FID (approx.)
2030 (announced projects)	≈37 Mt	Potential if all announced projects are realized

However, planned projects indicate significant growth potential by 2030, highlighting the role in its earliest stage of blue hydrogen in the changing global hydrogen economy [69].

3.5. Global Production Trends of Turquoise Hydrogen

Today, most hydrogen production is at pilot or small-scale industrial facilities, and commercial deployment is just now beginning to appear. For instance, in 2020, Monolith Inc. built plasma methane pyrolysis plants in Nebraska (USA), producing altogether about 2500 t of hydrogen and about 14,000 t of solid carbon, thus showing the early industrial feasibility of this technology [71]. Industrial deployment is expected to grow as demonstration and early commercial plants come on stream. Hycamite TCD Technologies is constructing a plant in Finland with a projected capacity of approximately 2000 t of turquoise hydrogen annually, which would be one of the largest of its type in Europe [72]. Yet for all this progress, turquoise hydrogen is still a small part of the world's hydrogen production. Market analysts estimate that in 2024, it contributed around 0.1% to low-carbon hydrogen production, and it is likely to remain a minor contributor compared with green and blue hydrogen until 2030. But the market forecasts suggest a lot of growth potential in the long run. The global turquoise hydrogen market was valued at nearly USD 80 million in 2024 and is expected to see rapid growth in the 2030s due to the scale-up of methane pyrolysis technologies and increasing commercial value of solid carbon by-products [73]. This is a speculative market forecast extrapolated from early-stage pilot data, and turquoise hydrogen has no significant commercial-scale deployment as of 2025. Table 5 shows estimated and projected annual production of turquoise hydrogen for selected regions and plants, 2020–2025, and more general projections for 2026–2030 [72,73].

Table 5. Turquoise hydrogen production (2020–2030)—Estimated and projected trends [72,73].

Region/Project	2020 (H ₂ /t)	2021 (H ₂ /t)	2022 (H ₂ /t)	2023 (H ₂ /t)	2024 (H ₂ /t)	2025 (H ₂ /t)	2026–2030 Forecast (H ₂ /t)
Monolith (USA)	≈2500 *	≈2500 *	≈2500 *	≈2500 *	≈2800 *	≈3000 *	≈5000–10,000 *
Hycamite (Europe)	0 *	0 *	≈500 *	≈1000 *	≈1500 *	≈2000 *	≈3000–8000 *
Other Pilot Projects	≈100 *	≈150 *	≈200 *	≈300 *	≈400 *	≈500 *	≈1000–3000 *
Global Total	≈2600 *	≈2650 *	≈2700 *	≈3000 *	≈4700 *	≈5500 *	≈9000–21,000 *

* Estimate based on available industrial project reports and market forecasts. Specific annual production figures prior to 2025 are indicative because official global statistics for turquoise hydrogen are not yet broadly published.

3.6. Global Production Trends of Red Hydrogen

Red hydrogen, produced via high-temperature nuclear thermochemical processes, is still in the very early stage of technology development. Today, only a few pilot facilities and national research programmes are operational, but several countries have announced

targets and reactor-linked demonstration projects with the promise of future deployment and integration into low-carbon energy systems [74]. As summarized in Table 6, Japan is currently at the forefront of development efforts with the high temperature engineering test reactor (HTTR) demonstration project planned for 2028–2030, using a 30 MWt high-temperature gas-cooled reactor to support hydrogen production experiments. Current designs for very-high-temperature reactors (VHTRs) for deployment in 2030 could, in the longer term, be scaled to produce on the order of 30,000 t of hydrogen a year per reactor, illustrating the longer-term scaling potential of nuclear-based hydrogen production. Despite these, red hydrogen is only a small part of the world’s supply of hydrogen. Low-emission hydrogen (nuclear-based, electrolytic, and CCUS-based production) is expected to increase to around 37 Mt/year by 2030 [IEA announced-projects scenario, low confidence—this upper-bound figure assumes full realization of all announced projects], compared to around 100 Mt of total hydrogen production in 2024, where less than 1% is currently low-emission [IEA verified operational data] [69].

Table 6. Selected red hydrogen production trends and plans [69,75,76].

Country/Project	Status/Timeline	Indicative Capacity/Target
Japan-HTTR Hydrogen Project [75]	Demo planned, hydrogen production aspired by ≈ 2028 –2030	HTTR thermal output ≈ 30 MW (test basis for red H_2 production); scaled future VHTRs ≈ 300 MWt $\rightarrow \approx 30,000$ t H_2 /yr
Japan-Future VHTR Demonstrator [76]	Planned commercial demonstration in 2030	Estimated 300 MWt units producing $\approx 30,000$ t H_2 /yr
Global Low-Emission Hydrogen (incl. nuclear potential) [69]	By 2030 based on announced projects	≈ 37 Mt H_2 /yr (mostly non-nuclear now)
Global Total Hydrogen Production [69]	2024 actual	≈ 100 Mt H_2 /yr ($\leq 1\%$ low-emission)

They underline the nascent stage of red hydrogen technologies and their potential contribution to the future growth of the portfolio of low-carbon hydrogen production pathways.

3.7. Purple Hydrogen (Hybrid Nuclear Thermochemical-Electrolytic Processes)

Purple hydrogen is produced via hybrid thermochemical-electrolytic cycles, with the most notable being the hybrid sulphur (HyS) process, which utilizes both high-temperature nuclear heat and nuclear-produced electricity. The decomposition of sulphuric acid at temperatures above 800°C into sulphur dioxide, water and oxygen is the first step in the process. The hydrogen and sulphuric acid are then manufactured by SO_2 -depolarized electrolysis of the sulphur dioxide generated. This closes the chemical cycle in effect and reduces electricity consumption dramatically compared to conventional water electrolysis. Optimized HyS systems can reach overall thermal efficiencies of about 40–47% (lower heating value, LHV). Low-carbon nuclear energy provides both heat and electricity, so direct CO_2 emissions remain very low, typically in the range of 0.5–3 kg CO_2 per kg of hydrogen. Most indirect emissions are linked to the nuclear fuel cycle. Lifecycle assessments generally indicate that the carbon footprint of purple hydrogen is among the lowest of the low-carbon hydrogen production pathways, indicating the potential of purple hydrogen as an attractive pathway for large-scale decarbonized hydrogen production [77,78].

3.8. Global Market Size of Pink Hydrogen

The following market figures are drawn from a commercial industry report represent speculative long-range projections. They should be interpreted as indicative of growth direction, not as verified production data. Over the past years, a global pink hydrogen

market has emerged, driven by an increasing interest in nuclear-powered hydrogen production and its potential for industrial decarbonization. The market was valued at USD 36.86 billion in 2025. It is estimated to be valued at USD 45.13 billion in 2026. Market estimates indicate substantial growth, with the potential to reach USD 219.37 billion by 2034, demonstrating a compound annual growth rate (CAGR) of around 21.85% during the forecast period [79]. Europe is the current largest market, and countries such as the United Kingdom, Russia and Sweden are key players in nuclear-based hydrogen initiatives. The United States leads North America, which is another significant contributor, and the regional market is expected to reach around USD 54.81 billion by 2032. Meanwhile, the Asia-Pacific region is emerging as a fast-growing market, particularly in China, Japan and South Korea, where nuclear-assisted production pathways are increasingly being included in hydrogen strategies. Other regions, including Latin America, the Middle East and Africa, are slowly joining the pink hydrogen industry thanks to nuclear energy projects. In the United Arab Emirates, for example, projects are considering nuclear-powered hydrogen production as part of broader clean energy plans. Current market trends and regional developments are summarized in Table 7.

Table 7. Estimated pink hydrogen market size across major regions and countries from 2025 to 2034, highlighting the historical, current, and projected market values in USD billion [79].

Region/Country	2025	2026	2030 (Projection)	2034 (Projection)
Europe	≈21.53	≈26.61	≈65	≈120
UK	-	≈16.47	≈40	≈70
Russia	-	-	≈5–6	≈10
Sweden	-	-	≈3–4	≈7
North America	-	≈12.52	≈35	≈65
USA	-	-	-	≈54.81
Canada	-	-	≈5	≈10
Asia Pacific	-	≈5.52	≈15	≈30
China	-	≈3.96	≈10	≈20
Japan	-	≈1.56	≈4	≈7
South Korea	-	-	≈3	≈5
Rest of World (LATAM, MEA)	-	-	≈8	≈15

Market growth is being driven by the growing demand for low-carbon hydrogen in the transport, refining, steel production, and ammonia synthesis sectors, along with government policies for a zero-emission energy system and long-term decarbonization strategies [79].

3.9. Green Hydrogen (RES-Powered Electrolysis)

The choice of energy source dictates the efficiency, reliability and scalability of the system for producing green hydrogen (water electrolysis using RES electricity). Solar and wind are both relatively low-cost and highly scalable forms of renewables. Hydropower gives a stable baseload electricity supply with a high conversion efficiency, and geothermal energy can supply continuously with hydrogen, but is geographically limited to areas with geothermal resources [80]. Table 8 compares four main types of RES for green hydrogen production: solar photovoltaic (PV)/concentrated solar power (CSP), wind (onshore and offshore), hydropower and geothermal energy.

Table 8. Key parameters of RES types for green hydrogen production [81,82].

Parameter	Solar PV/CSP	Wind (Onshore/Offshore)	Hydropower	Geothermal
Capacity factor	15–30%	25–55%	30–60%	70–90%
Conversion efficiency	15–30%	35–50%	85–95%	10–20%
Intermittency	High	High	Low	Very Low
Capital cost	Moderate	Moderate-High	High	High
Operational cost	Low	Low	Low	Low
Scalability	High	High	Medium	Medium
Environmental impact	Low–Moderate	Low–Moderate	Moderate-High	Low–Moderate
Suitability for continuous H ₂ production	Moderate	Moderate	High	Very High

The comparison is based on key parameters relevant for hydrogen production: scalability, capacity factor, intermittency, efficiency and economics. Solar and wind energy are very scalable and inexpensive to run. But they are highly intermittent, and capacity factors are moderate, meaning that without energy storage systems or hybrid renewable configurations, hydrogen production would not be continuous. On the other hand, hydropower has high efficiency, low intermittency and reliable base load power. However, it typically has a very high capital investment and potential environmental constraints associated with large-scale water infrastructure. Geothermal energy is very stable and is only seldom interrupted, so it can be used for continuous hydrogen production, although it is geographically limited in its availability and has high initial development costs. Overall, the optimal type of RES for green hydrogen production depends on regional resource availability, economic conditions, and the required continuity of hydrogen supply [81,82].

3.10. EU Green Hydrogen Strategy: Targets vs. Reality

Through the EU Hydrogen Strategy and the REPowerEU plan that aims at improving energy security, accelerating the net-zero transition and scaling up low-carbon hydrogen technologies, the EU has integrated the development of hydrogen into its decarbonization strategy. One of the main goals is to produce renewable hydrogen, in particular green hydrogen produced via water electrolysis using RES electricity, a key component of the future EU energy system [83]. The EU is targeting 10 Mt of domestic renewable hydrogen production and 10 Mt of imports by 2030 with at least 40 GW of electrolyzer capacity [EU policy targets under REPowerEU, not deployment commitments; actual realization depends on project pipeline conversion]. Interim targets of 6 GW and 1 Mt of production by 2024 were significantly missed, with only ~0.3 GW installed [84,85], underscoring the gap between policy ambition and verified deployment [83,86]. However, deployment has been slower than anticipated, noting that this paper was finalized in early 2026. Today, Europe has an operational electrolyzer capacity of approximately 5 GW (including projects that are in and/or ready for implementation). Despite the project pipeline having grown rapidly, a large proportion of projects are still in the early development or pre-final investment decision stages, indicating a large gap between policy ambitions and actual implementation, with many projects still in conceptual, pilot or feasibility stages (Table 9), rather than becoming fully commercialized [84,85,87].

Combined, these results show that the current installed capacity is a small fraction of both the short- and long-term hydrogen targets for the EU, highlighting the large gap between strategic planning and the real-world deployment of green hydrogen infrastructure.

Table 9. Comparison of EU green hydrogen targets and actual deployment (2024/2025) [84–87].

Indicator	Target	Actual/Realized (2024/2025)	Notes/Source
Electrolysis capacity	40 GW by 2030	≈0.385 GW operational (Sep 2024)	Installed capacity is <1% of 2030 target [84]
Interim electrolysis goal	6 GW by 2024	≈0.3 GW installed	≈5% of interim target realized [85]
Domestic hydrogen production	10 Mt by 2030	Minimal/pilot-scale	Most projects are in concept or feasibility stage [87]
Imported hydrogen	10 Mt by 2030	Planning stage	Supply chains and certification under development [86]
Project maturity	–	≈98% at concept/pilot/feasibility stage	Slow operational progress relative to timelines [87]

4. Hydrogen Storage, Transport, and Infrastructure

Globally, metal hydride storage is primarily considered a research-stage hydrogen storage technology. Current systems demonstrate reversible gravimetric capacities of approximately 1.30–1.85 wt% and volumetric densities up to about 90 g L^{−1}. Despite these promising material properties, most applications remain limited to laboratory research, pilot projects, and material development programmes in regions such as Europe, the United States, Japan, and China. To date, large-scale industrial deployment has not been achieved, meaning that metal hydride storage has not yet been implemented at the national energy-system level and remains largely confined to experimental and niche applications rather than grid-scale energy storage [88]. In contrast, underground hydrogen storage, particularly in salt caverns, represents one of the most mature options for large-scale hydrogen storage. Several operational or historical projects have demonstrated their feasibility in different countries. For example, the Teesside project in the United Kingdom involved three salt caverns with a combined storage capacity of approximately 210,000 m³ of hydrogen, with purity levels around 95%. In the United States, storage sites such as Clemens Dome, Moss Bluff, and Spindletop have historically stored hydrogen volumes ranging from 566,000 to 906,000 m³. These examples indicate that salt cavern storage has already been implemented in industrial contexts in countries including the United States, the United Kingdom, and Germany, with storage capacities ranging from several hundred thousand to nearly one million cubic metres [89]. Hydrogen transport infrastructure is also expanding globally, as given in Table 10.

Table 10. Global hydrogen infrastructure: pipelines and transport overview [69,90].

Country/Region	Active Pipelines (km)	Pipelines Under Development (km)	Total Target Network by 2040 (km)
Germany	≈2000	9000–9154	9000–9154
Spain	≈2000	6020	6020
Bulgaria	–	4476	4476
China	400–737	Under construction	TBD
Europe (total)	≈5000	–	≈40,000
World	≈5000	–	37,000+

Germany is developing one of the largest hydrogen pipeline networks in Europe. Within the scope of the European hydrogen backbone initiative, some 9000–9154 km of pipelines are planned. Spain is also developing important infrastructure, with 6020 km of pipelines planned, and in Bulgaria, with approximately 4476 km in development. In total, Europe’s hydrogen pipeline network is expected to reach some 40,000 km by 2040. China

has 400–737 km of hydrogen pipelines in operation in Asia and plans for further expansion. Today, the global active hydrogen pipeline network is estimated at around 5000 km, most of which is in North America and Europe. There are many other means of transport besides pipelines. Tube trailers (usually filled with some 1 tonne of hydrogen) and hydrogen refuelling stations (HRS) are commonly used for regional distribution. For long-distance transport of larger amounts of hydrogen, cryogenic tanks are used to transport liquid hydrogen at a temperature of about 20 K. The development of storage technologies and transport infrastructure will be key to enabling a scalable hydrogen economy. However, several system-level constraints currently limit progress beyond the technology-specific advances described above. First, repurposing existing natural gas pipelines for hydrogen is technically feasible for lower-grade steel but requires material qualification, compressor upgrades, and valve replacement for high-pressure transmission lines, with retrofit costs estimated at 10–30% of new-build costs depending on pipeline age and steel grade. Second, the energy penalties of compression and liquefaction are substantial: compression to 700 bar for onboard vehicle storage requires approximately 15% of hydrogen's energy content, while liquefaction to 20 K consumes 30–36% of its LHV. Ammonia and liquid organic hydrogen carriers (LOHCs) offer higher volumetric density for shipping but introduce reconversion losses of 20–35%. Third, purity requirements differ sharply by end-use: PEM fuel cells require $\geq 99.97\%$ H_2 (ISO 14687 Grade D) [91], while industrial processes tolerate lower grades, creating segregation challenges in shared infrastructure. Fourth, underground hydrogen storage in salt caverns is the most mature large-scale option, but geological availability is geographically limited—the EU has significant resources in the North Sea region and Germany, but southern and eastern EU member states have limited access. Fifth, safety and permitting frameworks for hydrogen infrastructure remain fragmented across jurisdictions; harmonized codes are still being developed under frameworks such as the EU Hydrogen Safety Panel and ISO/TC 197 [92] and their absence is a material barrier to project financing. These constraints collectively define the infrastructure bottleneck that limits deployment regardless of progress on production-side costs.

Assessed against the five-criterion framework applied throughout this review, the infrastructure constraints analyzed in this section affect all five dimensions. Scalability is constrained by limited salt cavern availability, pipeline capital intensity, and the absence of permitting frameworks. Infrastructure compatibility is challenged by hydrogen embrittlement in high-strength steel and compressor replacement requirements. Process efficiency is reduced by compression ($\approx 15\%$ LHV), liquefaction (30–36% LHV), and carrier reconversion (20–35% for LOHC and ammonia), which increases the effective carbon intensity of green hydrogen pathways evaluated in Section 3. TRL varies sharply: salt cavern storage is TRL 9, while large-scale LOHC reconversion and aquifer storage remain at TRL 4–6. Carbon intensity implications of infrastructure choice are therefore not separable from production pathway choice—a system-level finding that single-technology reviews cannot capture.

5. End-Use Applications of Hydrogen

The role of hydrogen as an integrating vector for decarbonization across sectors is increasingly recognized, linking industrial production, transport and power generation within an integrated energy system. Hydrogen has traditionally been used in the oil refining and ammonia production industries, but its application has expanded significantly to hard-to-abate sectors such as steel production, high temperature industrial heat, heavy-duty transport, maritime shipping, aviation fuels and grid balancing between 2020 and 2025. In 2023–2024, global demand for hydrogen was about 95–100 Mt, with fossil fuels still accounting for over 95%. But low-carbon hydrogen production is expanding steadily, based on policy frameworks and investment in major economies including the

EU, China, the United States and Japan [67,69]. The main objectives of the expansion of hydrogen applications are: (i) deep industrial decarbonization in the steel, chemicals, and refining sectors [93], (ii) complementing electrification where battery-based solutions are limited [94], and (iii) enhanced flexibility of energy systems via hydrogen storage, blending and dispatchable generation in power and heat networks [95]. Global hydrogen demand grew from around 90 Mt in 2020 to around 100 Mt in 2024 [IEA verified historical data] and is projected to grow to 130–150 Mt by 2030 [IEA demand scenario estimate includes both announced-policy and announced-project assumptions; actual demand is highly sensitive to policy implementation pace] (Figure 4). Industry is the dominant consumer of hydrogen today, with oil refineries consuming some 40–42 Mt and ammonia production 30–33 Mt, or some 30–35% of total demand. The AREH project and others like it demonstrate the potential for low-carbon hydrogen for ammonia synthesis to reduce CO₂ emissions by as much as 90%. And today, methanol production is about 12–15 Mt, and hydrogen-based steel production is about 5–6 Mt, with 85–95% CO₂ emissions reductions per tonne of steel. The use of hydrogen in the transport sector is still limited. Current estimated use is less than 0.2 Mt for road transport, less than 0.1 Mt for maritime shipping and less than 0.05 Mt for rail and aviation applications. However, demand in these sectors could grow to 3–8 Mt by 2030 [IEA announced-projects scenario, low confidence—contingent on FCEV rollout, bunkering infrastructure, and maritime regulation timelines] with ammonia as a preferred hydrogen carrier for long-distance maritime transport. Hydrogen is also likely to have a role in power and heat applications such as supporting turbine-based power generation, combined heat and power (CHP) systems, grid back-up, and blending with natural gas networks (potentially consuming 5–10 Mt by 2030 [IEA scenario estimate, speculative blending mandates and retrofit economics remain unresolved in most jurisdictions]).

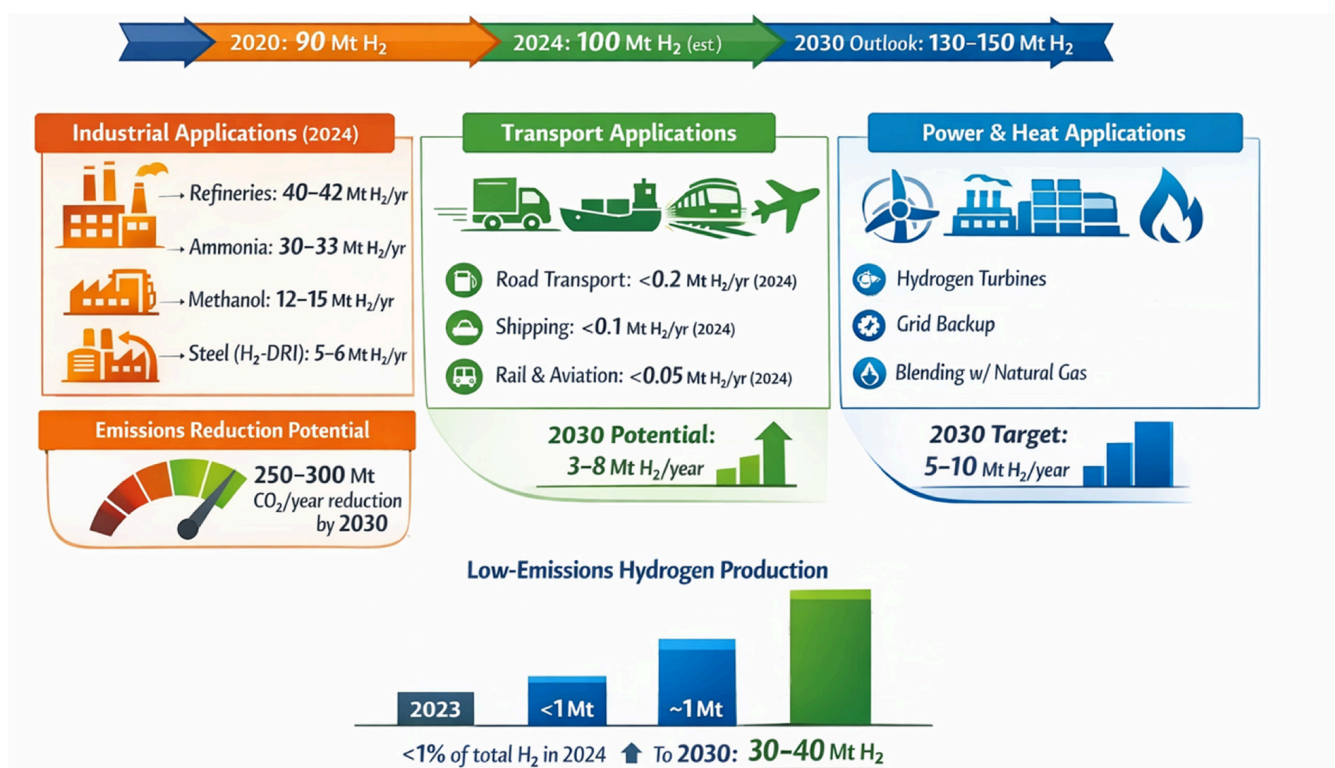


Figure 4. Schematic overview of hydrogen end-use applications in industry, transport, and power and heat sectors, highlighting key deployment pathways and decarbonization roles toward 2030.

In 2024, more than 95% of hydrogen was still produced from fossil sources [IEA verified operational data, 2024]. Policy measures in the EU, China, the United States, and

Japan are expected to drive growth in low-carbon hydrogen supply to around 30–40 Mt by 2030 [IEA announced-projects scenario, low-to-medium confidence this range reflects the span between the operational + FID trajectory (≈ 4.2 Mt) and the full announced-projects upper bound (≈ 37 Mt), with the 30–40 Mt figure representing a policy-supported midpoint contingent on significant acceleration of project execution]. This transition could lead to reductions in global CO₂ emissions of roughly 250–300 Mt/year, especially in hard-to-abate industrial sectors [67,69,96–98]. A structured competitiveness assessment across the primary hard-to-abate sectors clarifies where hydrogen deployment is genuinely justified versus where alternative pathways are more efficient. In steel production, hydrogen-based direct reduced iron (H-DRI) can reduce emissions from the current 1.8–2.1 tCO₂/tonne steel to below 0.1 tCO₂/tonne using green hydrogen, whereas BF-BOF with CCS achieves only 50–80% capture at USD 60–100/tCO₂ avoided; direct electrification is not viable for primary steelmaking from iron ore, making H-DRI the dominant decarbonization route for integrated steel plants. In chemicals, ammonia synthesis is inherently hydrogen-dependent and cannot be electrified; the cost-competitiveness threshold for green ammonia is green hydrogen below approximately USD 1.8/kg, projected to be achievable in high-resource regions by 2030. For methanol, green methanol currently costs USD 800–1200/tonne versus USD 400–600/tonne for conventional methanol, with cost convergence requiring carbon pricing above USD 80/tCO₂. In heavy transport, BEVs achieve well-to-wheel efficiency of approximately 73–77% versus 25–35% for FCEVs, giving BEVs a fundamental energy cost advantage for regional distribution (<300 km); however, FCEVs retain competitiveness for long-haul (>500 km, >40 tonne payload) where battery weight penalties are prohibitive. In contrast, hydrogen deployment in building heating and light-duty vehicles is not justified on current techno-economic grounds: heat pumps achieve $\approx 300\%$ COP versus $\approx 90\%$ for hydrogen boilers, and BEVs dominate light-duty transport on both efficiency and cost metrics. The clearest long-term hydrogen demand sectors are therefore ammonia synthesis, primary steel production, refinery hydroprocessing, long-haul maritime and aviation fuels, and long-duration seasonal storage—applications where electrification is technically impractical or economically inferior.

Assessed against the five-criteria framework, the end-use analysis reveals a clear hierarchy. Hard-to-abate industrial sectors—ammonia synthesis, primary steel production via H-DRI, and refinery hydroprocessing—score highest on the scalability and infrastructure compatibility dimensions because hydrogen is either the only viable decarbonization route or already integrated into existing industrial infrastructure, requiring process adaptation rather than new infrastructure build-out. Long-haul maritime and aviation score high on infrastructure compatibility (existing fuel handling) but medium on scalability due to the requirement for new bunkering and airport infrastructure. In contrast, building heating and light-duty vehicles score low on both scalability and cost-competitiveness relative to alternatives: heat pumps ($\approx 300\%$ COP vs. $\approx 90\%$ for hydrogen boilers) and battery electric vehicles (73–77% well-to-wheel vs. 25–35% for FCEVs) are demonstrably more efficient and are already scaling rapidly without requiring new fuel infrastructure.

6. Machine Learning Integration

ML and digital optimization are increasingly applied across the full hydrogen value chain, from production and storage to distribution and end-use. This section provides a structured, evidence-based analysis of ML contributions organized into four application domains: (i) electrolyzer efficiency and control; (ii) component degradation and predictive maintenance; (iii) infrastructure monitoring and safety; and (iv) system-level scheduling and energy management. For each domain, we characterize the algorithms used, the input

data required, the key performance indicators (KPIs) reported, illustrative case studies from the recent literature, and the principal technical limitations [99–101].

6.1. Electrolyzer Efficiency Optimization and Adaptive Control

In recent years, machine learning (ML) algorithms have become an effective tool for modelling, predicting, and optimizing the performance of hydrogen electrolyzers. Among the most widely used methods are MLP, LSTM, SVR, and GPR, which are used to predict key parameters such as current density, cell voltage, and hydrogen production rate. The results of the studies show that ANN models can achieve a mean absolute error (MAE) in the range of 0.038 to 0.040 for predicting current density, while SVR models achieve an RMSE of 0.008 after optimizing the hyperparameters. Also, LSTM models have shown very high performance in predicting cell potential under variable load conditions with $R^2 = 98.98\%$, RMSE = 0.022, and MAE = 0.015. Furthermore, the two-stage machine learning models achieved MAEs of 0.018 for flow prediction and 0.183 for hydrogen production rate, which indicate good accuracy under real operating conditions. However, the reduced generalizability to different stacks and catalysts remains one of the main limitations of these models. To overcome this challenge, physics-aware neural networks (PINNs) have been developed by combining operational data and physical laws and have been able to achieve RMSEs of less than 2% under different operating conditions using only 20% of the training data. These results indicate that PINNs are a promising avenue for developing generalizable machine learning models for hydrogen production systems [102,103].

6.2. Degradation Prediction and Predictive Maintenance

Degradation of electrolyzers and fuel cells is one of the primary drivers of operating cost and a key barrier to the bankability of hydrogen projects. In this context, machine learning algorithms, especially LSTM and transformer-based models, have been developed for the prediction of remaining usable life (RUL) and preventive maintenance planning. These models are able to extract degradation patterns using data such as cell voltage, electrochemical impedance spectroscopy (EIS), operating temperature, flow cycles, and membrane hydration status. The results show that CNN-LSTM models in PEM electrolyzers were able to predict voltage degradation up to 1000 h ahead with R^2 above 0.98 and absolute voltage error below 5 mV, validated on datasets of 1140 h (constant load) and 660 h (start-stop cycles). Also, in PEM fuel cells, CNN-based models using EIS data have achieved an accuracy of over 98.5% in detecting flooding and drying faults, while TCN-LSTM models reached $R^2 = 99.74\%$ and MAPE = 0.77% in voltage degradation prediction under dynamic load cycles. Despite these successes, the lack of long-term and real-time data remains a major challenge in developing these models. For this reason, transfer learning approaches that use a model pre-trained on one stack's historical data and fine-tuned on limited real-time data from a new stack have been proposed as a promising solution to improve generalizability and prediction accuracy [104–106].

6.3. Infrastructure Monitoring, Leak Detection, and Safety

Due to the high permeability of hydrogen and its wide flammability range (4–75% by volume in air), leak detection and integrity monitoring of transmission and storage infrastructures are among the most important machine learning applications in hydrogen systems. In this area, algorithms such as CNN, SVM, and recurrent neural networks (RNN) have been used to analyze pressure, flow rate, acoustic emission, and multi-gas sensor data. The results show that CNN models applied to transient-state pressure and flow data from hydrogen-blended pipelines have achieved classification accuracy above 80% for leak size and location identification, while CNN-ANFIS hybrid systems have demonstrated high predictive accuracy for leak detection using standard field instrumentation in hydrogen-

natural gas blended pipelines. Also, deep learning models applied to hydrogen refuelling stations have achieved leak localization with an average spatial error of 0.54 m using fused CFD-generated and sensor data, enabling rapid source identification that plays an important role in increasing operational safety. However, the lack of labelled data for rare events remains a major challenge in the development of these systems. For this reason, anomaly detection and semi-supervised learning approaches, especially those based on autoencoders trained on normal operating data without requiring leak samples, have been proposed as promising solutions for safety monitoring and early detection of leaks in hydrogen infrastructures [107–109].

System-Level Scheduling, Demand Forecasting, and Energy Management

At the level of integrated energy systems, ML optimizes hydrogen production, storage, and consumption under renewable uncertainty using RL for real-time scheduling and LSTM/transformer models for demand forecasting. Transfer multi-agent RL applied to distributed HRS scheduling has demonstrated revenue increases of up to 32.9% and a 34-fold reduction in computation time compared to basic RL. GAIL-based real-time energy management at grid-connected HRS achieved total profit improvements of up to 29% over rule-based baselines. At the microgrid level, DDPG-based scheduling incorporating demand response reduced contract load curtailment costs by 16% compared to operation without demand response, while an LSTM combined with nature-inspired optimization achieved demand forecasting MAPE of 4.8%, reduced average grid import by 35.6%, cut PV curtailment by 21.4%, and improved energy self-sufficiency from 71.5% to 89.7% [110–112].

7. Conclusions

The role of hydrogen in future net-zero energy systems will be important but strategically selective: strongest where direct electrification is technically impractical or economically inferior, and limited where alternatives such as heat pumps or battery electric vehicles are demonstrably more efficient. In 2024, global demand for hydrogen is close to 100 Mt. The challenge of decarbonization is reflected in the fact that more than 95% of hydrogen is still produced from fossil fuels. Green, blue, nuclear-derived and turquoise hydrogen are expanding but in early deployment stages in low-carbon pathways. Renewable electrolysis offers the largest potential for long-term decarbonization, while low-carbon hydrogen could facilitate near-term scale-up if methane emissions and carbon capture performance are tightly managed. Infrastructure development, particularly large-scale storage and transport networks, is still a big bottleneck. Hydrogen is best used in hard-to-abate sectors such as steel production, ammonia production, refining and heavy transport. Ultimately, hydrogen is to complement electrification and be deployed in a strategic manner where alternatives are limited, backed by integrated infrastructure and digital optimization tools such as machine learning.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
ATR	Autothermal Reforming
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO ₂	Carbon Dioxide
CSP	Concentrated solar power
EU	European Union
FID	Final Investment Decision
GHG	Greenhouse Gasses
H ₂	Hydrogen
HRS	Hydrogen Refuelling Station
ML	Machine Learning
PV	Photovoltaic
RES	Renewable Energy Sources
SMR	Steam Methane Reforming

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