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Hydrogen as a strategic energy transition pathway: production technologies, cost dynamics, infrastructure, policy and India's statistical roadmap to 2030 and 2050

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The transition toward green hydrogen is increasingly recognized as a key strategy for achieving deep decarbonization and long-term energy sustainability, particularly in developing and rapidly industrializing economies. This study presents a comprehensive review of hydrogen production technologies, techno-economic performance, sectoral applications, and policy frameworks associated with the emerging hydrogen economy. The analysis compares major hydrogen production pathways, including alkaline electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC), with respect to efficiency, operational flexibility, technological maturity, and economic feasibility.

The study further evaluates the levelized cost of hydrogen (LCOH) under different renewable energy integration scenarios and identifies the major factors influencing hydrogen production costs, such as electricity price, electrolyzer capital cost, system efficiency, and infrastructure availability. Current green hydrogen production costs remain higher than conventional fossil-fuel-based hydrogen pathways; however, significant cost reductions are expected due to advancements in renewable energy technologies, economies of scale, and improvements in electrolyzer performance.

Sectoral demand assessment indicates substantial future growth in hydrogen utilization across fertilizers, petroleum refining, steel manufacturing, chemical industries, power generation, and heavy transportation sectors. In addition, the review highlights major challenges related to hydrogen storage, transportation, infrastructure development, financing, and regulatory frameworks. The study also discusses the role of national policies, industrial investments, and research initiatives in accelerating hydrogen adoption. Overall, this work provides a generalized and integrated perspective on the technological, economic, and policy dimensions of the hydrogen transition and outlines key pathways for enabling large-scale deployment of sustainable hydrogen systems.

Keywords: Green hydrogen; Energy transition; Decarbonization; Levelized cost of hydrogen (LCOH); Electrolysis; Renewable energy integration; National green hydrogen mission (NGHM); Hydrogen economy; India; Carbon neutrality; Sectoral demand; Electrolyzer deployment

INTRODUCTION

The global energy system is undergoing one of the most profound structural transformations in recorded history. Escalating climate risks, geopolitical energy dependencies, and legally binding net-zero commitments are driving unprecedented investment in clean energy technologies. Within this landscape, hydrogen has emerged as a uniquely versatile energy carrier capable of decarbonizing sectors where direct electrification remains technically or economically constrained—including steel production, long-haul transport, fertilizer synthesis, and high-temperature industrial processes [2, 20, 60].

India occupies a particularly significant position in this global transition. As the world's most populous nation and fifth-largest economy, with energy demand projected to outpace all other major regions by 2040, India's energy choices carry global consequence. Currently, India annually consumes approximately 6–7 million tons *per annum* (MTPA) of hydrogen, almost entirely produced through grey pathways—steam methane reforming (SMR) and coal gasification—contributing an estimate of 57–65 million tons of CO_2 annually from hydrogen production alone [65, 67, 134].

The national green hydrogen mission (NGHM), launched on January 4. 2023 with an outlay of INR 19,744 crore (approximately USD 2.4 billion), is the most ambitious clean energy policy initiative in India's history. It targets 5 MTPA of green hydrogen production by 2030—with an ambition to reach 10 MTPA including exports—positioning India for approximately 10% of the projected global green hydrogen demand of 100+ MTPA by 2030 [86, 135, 155].

Despite rapid policy momentum, the academic literature lacks a unified, statistically grounded review that consolidates multi-dimensional data from government documents, international agency forecasts, and peer- reviewed research into

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structured analytical framework. This review addresses that gap comprehensively—synthesising data across ten chart-illustrated quantitative dimensions and five creative process diagrams. This review integrates these dimensions within a unified analytical framework, constituting the most complete review of India's hydrogen transition available to date [31, 67, 109].

The hydrogen transition is structured across two strategic phases: Phase I (2023–2030) focuses on technology demonstration, policy activation, cost reduction, and initial industrial decarbonization; Phase II (2030–2050) targets large-scale commercial deployment, export leadership, and deep economy-wide decarbonization consistent with India's net-zero commitment for 2070 [67, 91, 135].

Despite the rapidly expanding body of literature on hydrogen energy systems, a critical gap persists in the integrated, India-specific assessment of hydrogen transition pathways, particularly in the context of long-term techno-economic feasibility, sectoral demand evolution, and policy-driven deployment frameworks. Existing reviews predominantly focus on global hydrogen trends, electrolyzer technologies, or isolated techno-economic aspects, often lacking a holistic, data-driven synthesis tailored to India's unique energy landscape [67, 109].

Several recent studies by international agencies such as IEA, IRENA, and NITI Aayog provide valuable projections; however, these analyses are typically fragmented across domains—technology performance, cost projections, infrastructure readiness, or policy frameworks—without offering a unified multi-dimensional evaluation. Furthermore, prior literature rarely integrates quantitative projections (2030–2050) with sector-wise hydrogen demand, infrastructure readiness, and investment trajectories in a single coherent framework. This creates a disconnect between strategic policy vision and implementable techno-economic pathways, particularly for emerging economies like India [106].

Another key limitation in existing reviews is the lack of comparative multi-criteria assessment of hydrogen production technologies (AWE, PEM, SOEC) under India-specific operating conditions, including renewable intermittency, cost sensitivity, scalability constraints, and infrastructure limitations. Additionally, limited attention has been given to the dynamic transition from grey to green hydrogen, especially in terms of cost convergence timelines, carbon reduction potential, and sectoral adoption thresholds [69].

Methodology of this review

This study employs a hybrid methodology combining systematic literature review (following PRISMA guidelines), bibliometric analysis, thematic synthesis, and statistical data consolidation [7, 8]. This PRISMA flow diagram, as shown in Figure 1, details the systematic literature selection process, starting with the initial identification of 731 records from comprehensive databases and alternative sources. After eliminating 96 duplicates, 635 unique records underwent a preliminary title and abstract screening, resulting in the exclusion of 339 irrelevant studies. The remaining 296 full-text articles were rigorously assessed for eligibility, where another 115 papers were excluded based on specific constraints such as lacking an India-focused scope or sufficient quantitative data. Ultimately, a refined cohort of 180 studies met all predefined criteria and was successfully synthesized. These final 180 papers were utilized across both the qualitative synthesis and quantitative statistical analyses for the study.

- *Literature search and data sources.* Databases searched include Scopus, Web of Science, ScienceDirect, and Google Scholar covering 2015–2025. Primary statistical data was sourced from: MNRE, NITI Aayog, NGHM mission documents, IEA global hydrogen review (2023), IRENA cost reports, IEEFA demand analyses, Bloomberg NEF hydrogen outlook, McKinsey global energy perspective, CEEW financing analyses, ORF America background papers, and Markntel Advisors market reports. Search terms included 'green hydrogen India statistics 2030-2050', 'NGHM targets', 'hydrogen demand forecast India', 'electrolyzer capacity India', and 'LCOH India' [7, 61, 67, 90, 135].
- *Statistical data consolidation.* Each quantitative data point presented in ten charts is cross-validated from at least two independent institutional sources. Where projections varied across sources, conservative central estimates are presented with source ranges noted. Data for charts 1–10 spans the period 2022–2050, covering demand, cost, capacity, investment, market size, CO_2 abatement, electrolyzer growth, renewable energy,

production mix, and CAPEX-LCOH correlation [61, 67, 109].

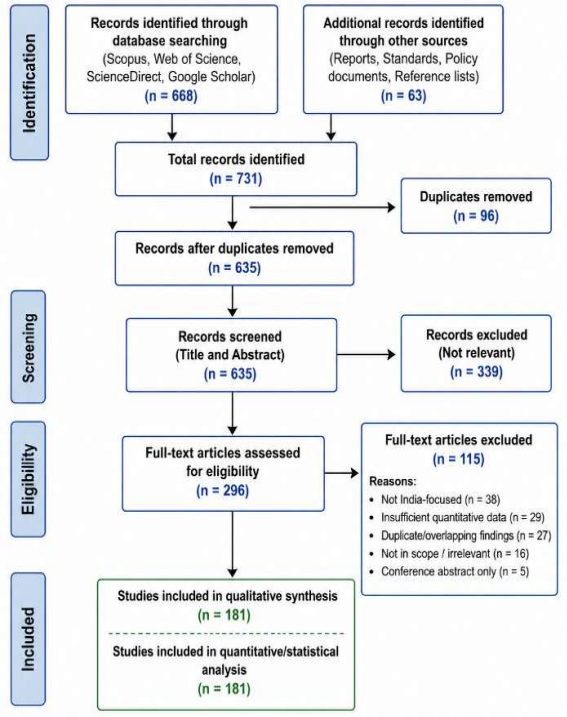


Figure 1. Methodology PRISMA framework of the review

Hydrogen energy fundamentals

Hydrogen (H_2) is the lightest and most abundant element in the universe yet does not occur freely in nature in significant quantities—it must be produced from compound forms such as water, natural gas, coal, or biomass. Its gravimetric energy content of 119.9–141.9 MJ/kg is 2–3 times higher compared to conventional hydrocarbon fuels, making it highly attractive for weight-sensitive applications such as aviation, shipping, and heavy-duty transport. However, its volumetric energy density at atmospheric pressure (10.7 MJ/m³) is lower by orders of magnitude than that of liquid fuels, necessitating compression to 350–700 bar or cryogenic liquefaction at −253°C for practical storage and transport [2, 9, 19]. Table 1 presents key thermodynamic and physical properties of hydrogen in comparison with conventional fuels.

Hydrogen functions as an energy carrier—not a primary source—analogous to electricity. When produced from renewable electricity *via* electrolysis, it enables seasonal and long-duration storage of intermittent solar and wind energy, and facilitates sector coupling across power, transport, and heavy industry. India's renewable energy capacity has grown from 35,850 MW (March 2014) to over 223,273 MW (March 2026)—a 6.2× increase in 12 years—providing an increasingly strong foundation for green hydrogen production [2, 9].

Table 1. Physical and thermodynamic properties of hydrogen *vs*. conventional fuels [2, 9, 19]

Property	Hydrogen	Methane	Gasoline	Diesel
Molecular weight (g/mol)	2.016	16.013	~110	~170
Boiling point (K)	20.3	111	298–488	453–633
Carbon content (mass%)	0	75	84	86
Higher heating value (MJ/kg)	141.9	55.5	47.3	44.8
Lower heating value (MJ/kg)	119.9	50.0	44.5	42.5
Auto-ignition temperature (K)	853	813	~623	~523
Volumetric energy (MJ/m³ STP)	10.7	33	33×10^3	35×10^3
Adiabatic flame temperature (K)	2,480	2,214	2,580	~2,300
Density (kg/m³ at 1 bar, 273 K)	0.089	0.720	730–780	830
Stoichiometric air/fuel ratio	34.4	17.2	14.7	14.5

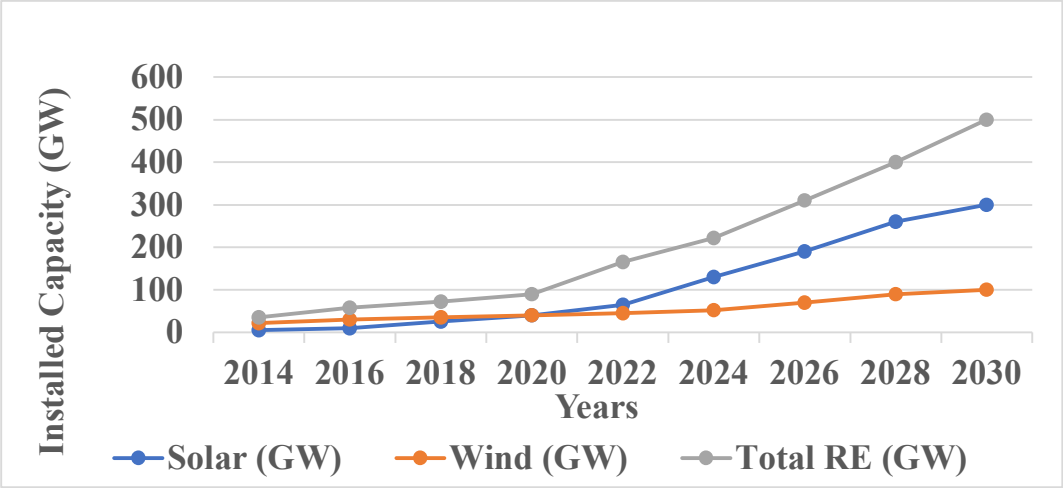


Figure 2. India's renewable energy installed capacity (GW) — historical & projected to 2030 [9, 105, 135, 153]

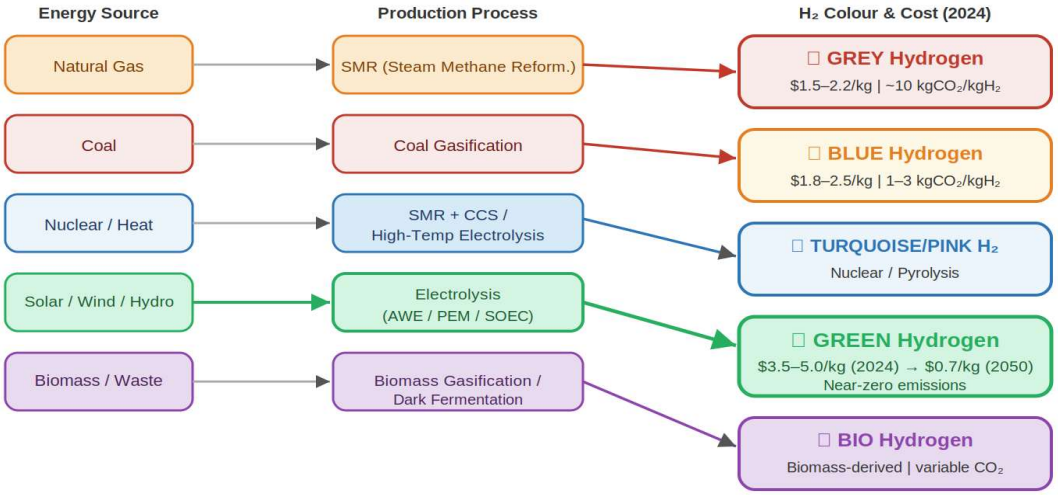


Figure 3. Hydrogen production pathways — color classification, processes & carbon intensity [11, 61, 109, 135]

The line graph in Figure 2, illustrates the growth and projected trajectory of renewable energy installed capacity in gigawatts (GW) from 2014 to 2030, categorized by solar, wind, and total renewable energy (RE) [105]. In the initial period between 2014 and 2020, both solar and wind capacities experienced steady but modest growth, with total RE capacity remaining under 100 GW. Post-2020, the trajectory accelerates sharply, driven primarily by a massive surge in solar capacity which overtakes wind power to become the dominant contributor [135]. By 2026, total RE capacity is shown tracking past 300 GW, with solar contributing roughly 190 GW and wind accounting for approximately 70 GW [153]. Looking forward to 2030, the aggressive upward trend is projected to continue, with total RE capacity targeting 500 GW, comprised of 300 GW from solar and 100 GW from wind [9].

Figure 3 provides a visual classification of all major hydrogen production pathways, their source materials, processes, environmental impact, and 2024 cost benchmarks. This figure replaces several paragraphs of descriptive text with a single-glance reference framework [11, 61, 109].

Hydrogen production technologies — technical assessment

Hydrogen production technologies broadly divide into conventional fossil-based routes and emerging renewable-based pathways. Technology selection determines carbon intensity, levelized cost of hydrogen (LCOH), scalability, and long-term strategic viability [109, 133].

Conventional methods

- *Steam methane reforming (SMR).* SMR accounts for approximately 48% of the global hydrogen production and is the dominant method in India, supplying hydrogen to fertilizer plants and petroleum refineries. Figure 4 illustrates the industrial process of producing high-purity hydrogen (H_2) *via* steam methane reforming (SMR), beginning with the endothermic reaction of natural gas and steam in a catalyst-filled reformer furnace (700-1000^0 C). The resulting synthesis gas (syngas) undergoes heat recovery and is fed into a two-stage water-gas shift (WGS) reactor to exothermically convert carbon monoxide and water into additional hydrogen and carbon dioxide. Following this shift, a purification system, such as pressure swing adsorption (PSA), separates the final high-purity hydrogen product from off-gas byproducts that are recycled back into furnace fuel. Economically, the process is highly advantageous due to its low production costs and well-established, globally dominant infrastructure. However, it carries a heavy environmental burden, generating significant carbon dioxide (CO_2) emissions that make it environmentally unsustainable without carbon capture and storage (CCS). SMR emits approximately 9–12 kg CO_2 per kg H_2 without CCS—making it the largest source of industrial CO_2 in the hydrogen sector. In India, SMR currently supplies ~40% of hydrogen demand in refining alone, producing ~47 Mt of CO_2 by 2050 under a business-as-usual scenario. [56, 133, 134].
- *Coal gasification.* Coal gasification partially oxidizes coal at 1,200–1,500°C (efficiency 55–65%) to produce synthesis gas, emitting 18–20 kg CO_2/kg H_2—the highest carbon intensity of any pathway. Figure:5 gives the details of the process of coal gasification, where a coal feed reacts with oxygen and steam via partial oxidation to generate syngas (H_2, CO, CO_2). The syngas undergoes pollutant removal and is fed into a water-gas shift (WGS) reactor before being purified (e.g., via PSA) to yield clean hydrogen (H_2). While the method economically leverages domestic coal and enhances energy security, it carries an optional integration for CCS to prevent high carbon emissions from bypassing geological storage. Without CCS, the process outputs create severe environmental liabilities, notably high CO_2 emissions that hinder a low-carbon transition. Furthermore, the overall process incurs a substantial environmental footprint through heavy air pollution (SO_2, NO_x, and particulates) alongside high water consumption. India's large domestic coal reserves make this a transitional option with CCS integration, though CCS at scale remains technically and economically challenging [24, 53].

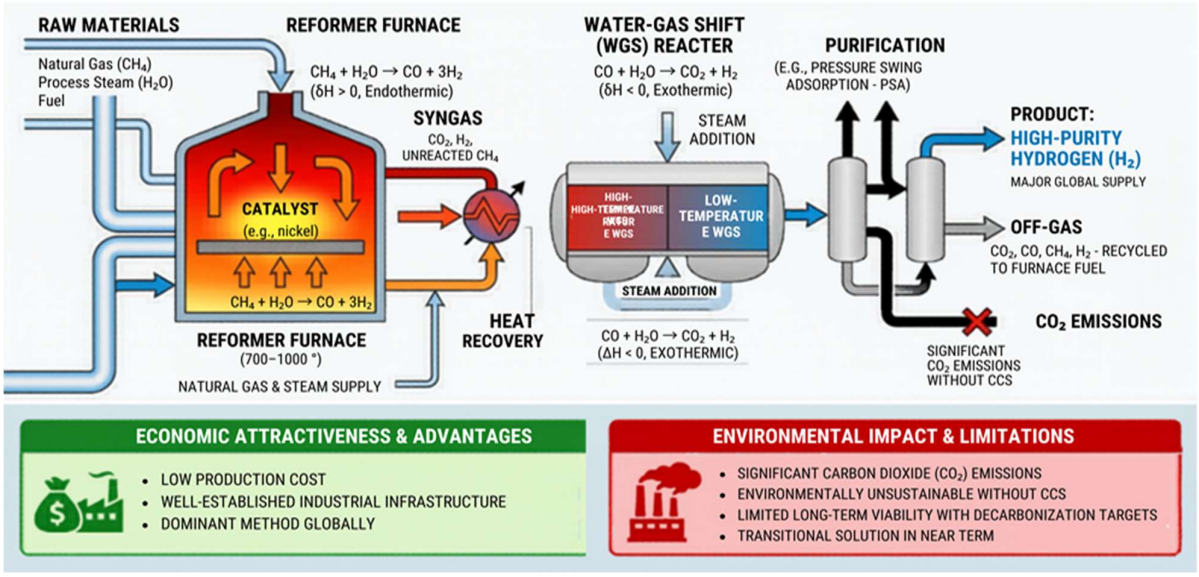


Figure 4. Steam methane reforming (SMR) process for hydrogen production

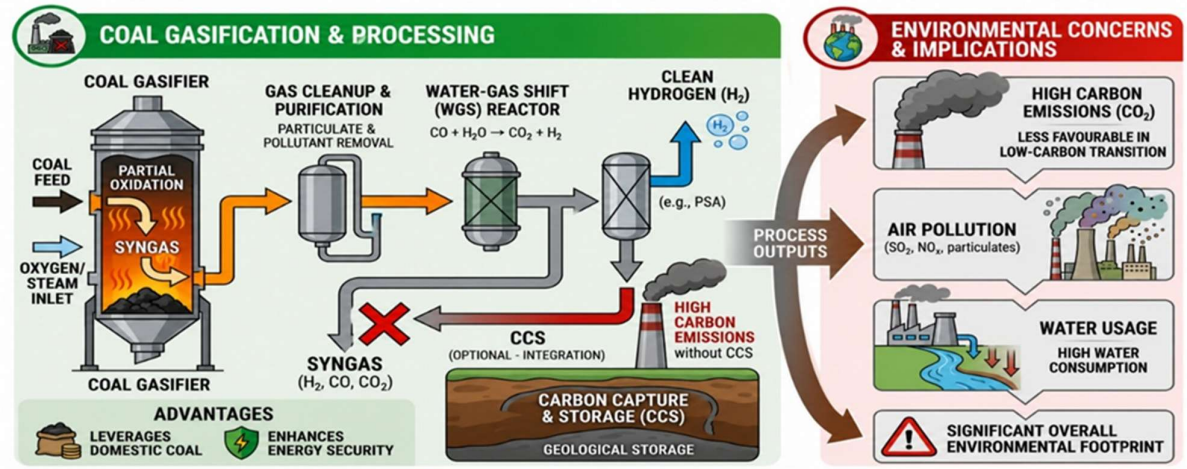


Figure 5. Coal gasification process for hydrogen production & environmental impact

Renewable-based methods

- *Alkaline water electrolysis (AWE).* AWE is the most commercially mature electrolysis technology with a global installed base exceeding 5 GW. Figure 6 presents an overview of alkaline water electrolysis (AWE) for hydrogen production, featuring its process schematic, industrial characteristics, and strategic application in India. The scheme depicts a DC power-driven cell operating at 60-90^0 C, where water (H_2O) splits to release hydrogen (H_2) at the cathode and oxygen (O_2) at the anode *via* hydroxyl (OH^-) ion transport across a porous separator. Industrially, AWE is highly advantageous due to being a mature, commercially established technology boasting long operational lifetimes and a relatively low capital cost. However, its primary operational limitation is a rigid design that offers limited flexibility for fluctuating power inputs and struggles with intermittent renewable sources. Strategically, its ideal deployment in India targets large-scale hydrogen production paired with stable, continuous renewable energy grids like utility-scale solar installations to ensure steady operation. The CAPEX of USD 500–1,100/kW (2024)—the lowest of any electrolysis option. Its primary restriction is limited dynamic response (<1% load change per sec), making it better suited to stable baseload renewable supply. In India, GAIL's 10 MW PEM plant at Vijapur and Indian Oil's solar-powered AWE station demonstrate both technologies at commercial scale [16, 41, 61, 150].
- *Proton exchange membrane (PEM) electrolysis*. PEM electrolyzers typically exhibit efficiencies of 70–90% based on the higher heating value (HHV) of hydrogen under optimized operating conditions. The upper end of this range generally represents stack-level performance achieved under controlled conditions. In practical industrial applications, overall system efficiency is often lower due to auxiliary power requirements, water purification systems, thermal management, gas compression, and balance-of-plant losses. Nevertheless, PEM technology remains highly attractive because of its rapid response, high current density, and compatibility with variable renewable energy sources [157]. Figure 7 depicts the details of the PEM electrolysis process, showcasing its operational mechanism, performance benefits, and future outlook. The simplified process schematic illustrates water (H_2O) split at the anode to produce oxygen (O_2), while protons (H^+) travel across a solid polymer electrolyte to the cathode to yield hydrogen (H_2). Performance advantages include higher efficiency and a rapid response to dynamic load conditions, making it ideal for seamless integration with variable renewable energy sources like wind and solar. On the downside, the technology faces key challenges, namely high capital costs and a critical dependence on scarce, expensive noble metal catalysts like platinum (Pt) and iridium (Ir). Despite these limitations, ongoing research in catalyst development and system optimization is expected to lower costs and enhance scalability, rendering PEM electrolysis a highly promising option for future clean hydrogen production in India. However, PEM requires platinum-group metal catalysts (iridium: 0.3–0.5 mg/cm²; platinum), driving CAPEX to USD 1,000–1,800/kW in 2024, declining to USD 300–700/kW by 2030. L&T's indigenously manufactured 1 MW ML-400 system at Hazira (March 2025) and GreenH's 100 MW Phase-1 facility at Jhajjar, Haryana (H2B2 partnership) are India's key PEM milestones [12, 61, 84, 179].

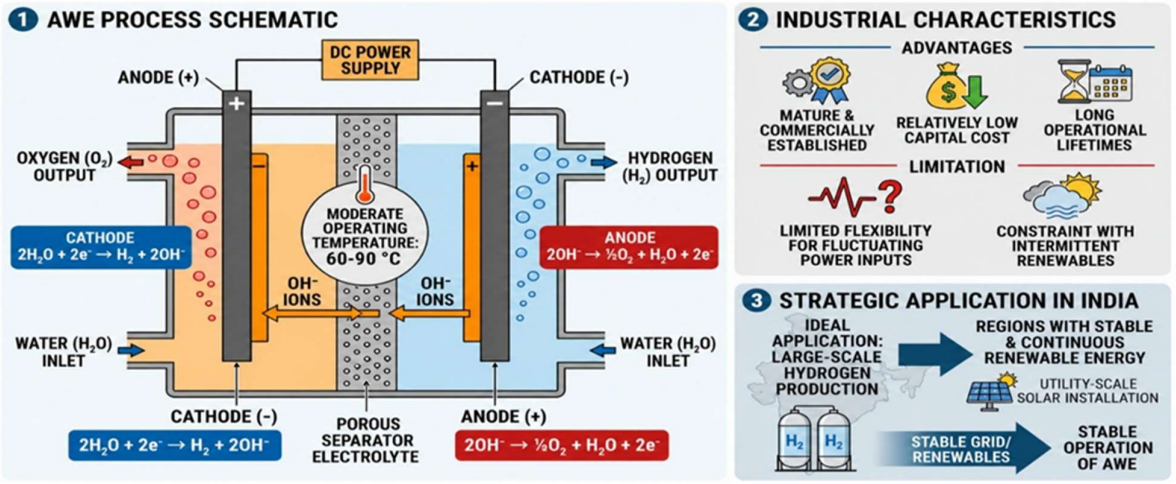


Figure 6. Alkaline water electrolysis

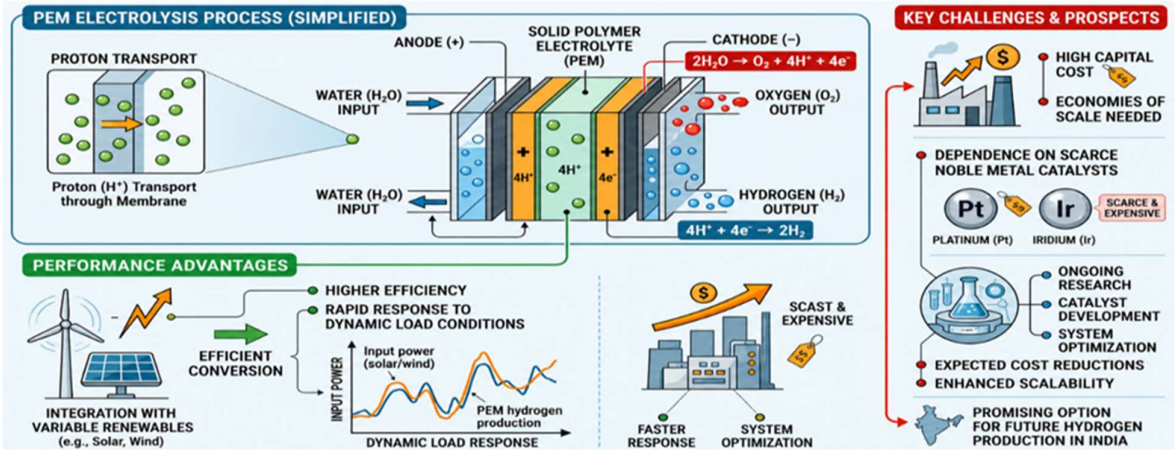


Figure 7. PEM electrolysis: technology, advantage and challenges

- *Solid oxide electrolysis cells (SOEC).* Figure 8 shows the SOEC technology which offers the highest efficiency among currently available electrolysis technologies, typically achieving electrical efficiencies of 85–95% under optimized operating conditions (600–1,000°C), incorporating waste heat from industrial processes. It also offers co-electrolysis of CO_2 and H_2O to produce syngas—a unique advantage. However, material degradation at elevated temperatures, slow start-up (>1 hour), and CAPEX of USD 2,000–3,000/kW (declining to USD 800–1,200/kW by 2030) limit near-term adoption. BARC's R&D program in Mumbai is actively developing SOEC membrane electrode assemblies for Indian industrial applications [32, 35, 61].
- *Biomass-based hydrogen production and their emerging routes.*

(i) Biomass-based hydrogen production. As shown in Figure 9, biomass-derived hydrogen offers a renewable pathway for hydrogen production while simultaneously utilizing agricultural residues, forestry waste, municipal solid waste, and other organic feedstocks [166, 169]. The most common production routes include biomass gasification, pyrolysis, and biological conversion processes. During gasification, biomass reacts with steam and oxygen at elevated temperatures (700–1000°C) to produce syngas, which can subsequently be processed through water–gas shift reactions to increase hydrogen yield [151]. India possesses substantial biomass resources from agriculture and agro-industrial sectors, making biomass-based hydrogen particularly attractive for decentralized and rural energy systems. However, feedstock variability, logistics, tar formation, and gas-cleaning requirements remain important challenges for large-scale deployment [151, 166, 169]. India generates approximately 500–700 million tons of agricultural residues annually, supporting biomass gasification

(efficiency 35–50%) for decentralized hydrogen production.

(ii) Biomass-based hydrogen production emerging routes. Microbial electrolysis cells (MECs) utilize electrochemically active microorganisms to generate hydrogen from organic substrates and wastewater. These systems offer simultaneous waste treatment and hydrogen production but currently face scalability and economic challenges [146, 151]. Photoelectrochemical (PEC) systems directly convert solar energy into hydrogen using semiconductor photoelectrodes. Recent advances in perovskite absorbers and nanostructured materials have improved solar-to-hydrogen conversion efficiencies, although stability and scalability remain key challenges [160]. Advanced cycles such as sulfur–iodine (S–I) and copper–chlorine (Cu–Cl) use high-temperature heat from nuclear or concentrated solar sources to split water into hydrogen and oxygen. Similarly, solar thermochemical processes employ metal oxide redox reactions to directly convert solar heat into chemical energy. Although these technologies exhibit high theoretical efficiencies, they remain at the demonstration stage [160]. Photocatalytic processes employ semiconductor catalysts such as TiO_2 and g-C_3N_4 to split water under solar irradiation. Despite significant progress in catalyst development, commercial-scale deployment remains limited by low conversion efficiencies [180]. Ongoing R&D at IIT Kharagpur, KPIT-Ankur (Vadodara), and TERI advances this route for agro-industrial clusters. PEC water splitting and dark fermentation remain at TRL 3–5 globally but hold promise for India's biomass-rich rural regions [1, 40, 62, 72, 117].

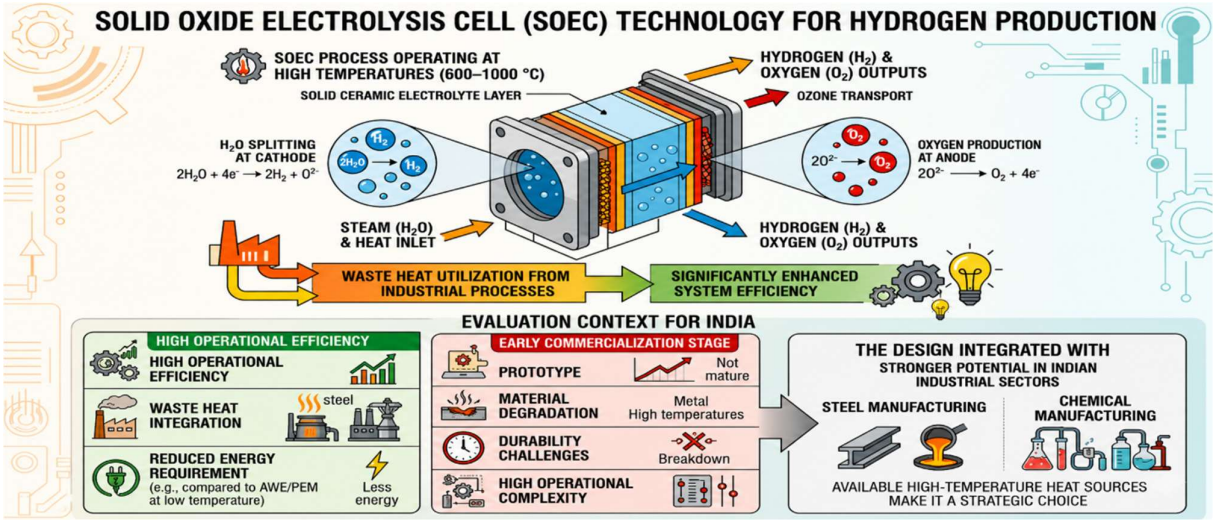


Figure 8. Hydrogen production by solid oxide electrolysis cell (SOEC) technology

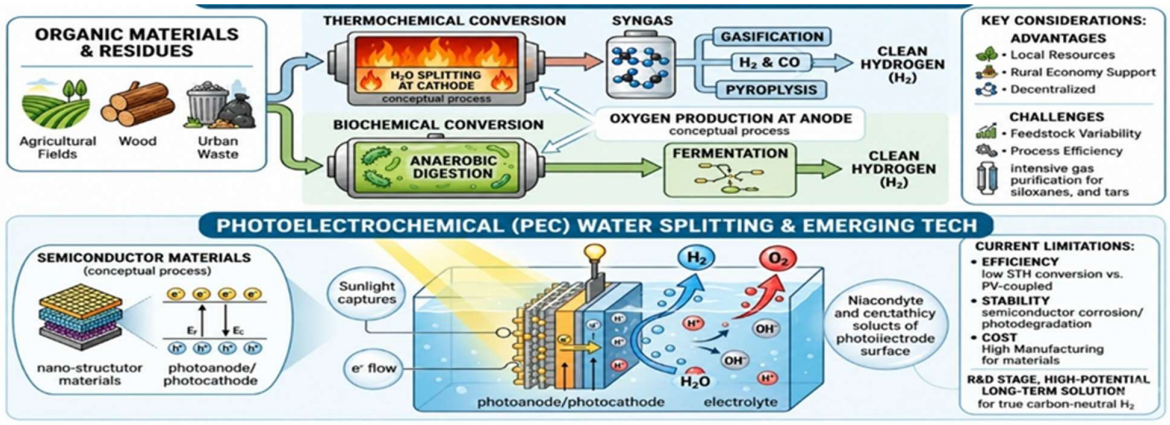


Figure 9. hydrogen production technologies (a) by conversion from biomass (b) by water splitting of photo-electro chemical (PEC)

Comparative electrolyzer analysis

Table 2. Comparative technical parameters of hydrogen production *via* electrolysis technologies [12, 16, 32, 61, 109]

Parameter	AWE	PEM	SOEC
Operating temperature (°C)	60–95	50–80	600–1,000
Current density (A·cm^{-2})	0.15–0.65	1.00–2.00	0.20–1.00
Electrolysis efficiency (%)	60–75	70–90	85–100
System efficiency (%)	51–60	46–60	76–81
Electrolyzer energy (kWh/Nm^3)	4.20–4.80	3.80–5.00	2.60–3.60
System energy (kWh/Nm^3)	5.00–5.90	5.20–5.90	3.70–3.90
Load flexibility (%)	20–100	0–120	−100 to +100
Cold start time	1–2 h	5–10 min	>1 h
Warm start time	1–5 min	<5 s	15 min
Industrial pressure (MPa)	0.1–3	0.1–5	0.1–1.5
CAPEX 2024 (USD/kW)	500–1,100	1,000–1,800	2,000–3,000
CAPEX 2030 target (USD/kW)	300–600	300–700	800–1,200
Commercial status	Mature / low CAPEX	Scaling / High CAPEX	Experimental

Table 2 presents a comparative assessment of the major electrolyzer technologies currently employed for hydrogen production. Alkaline water electrolysis (AWE) remains the most commercially mature and cost-effective technology, making it suitable for large-scale deployment [16]. Proton exchange membrane (PEM) electrolyzers offer higher hydrogen purity, rapid response characteristics, and better compatibility with intermittent renewable energy sources, albeit at higher capital costs [12]. Solid oxide electrolysis cells (SOECs) exhibit the highest theoretical efficiency due to their utilization of high-temperature heat; however, challenges related to material durability and commercial maturity continue to limit widespread deployment [32]. The comparison highlights the trade-offs between efficiency, cost, operational flexibility, and technological readiness among the different electrolyzer technologies [61].

Figure 10 illustrates the relative performance of AWE, PEM, and SOEC technologies with respect to efficiency, capital cost, operating temperature, and technology readiness level. The figure demonstrates that AWE currently dominates commercial installations because of its low cost and proven reliability, whereas PEM technology is increasingly preferred for renewable-energy-integrated hydrogen production due to its operational flexibility [24, 61, 133].

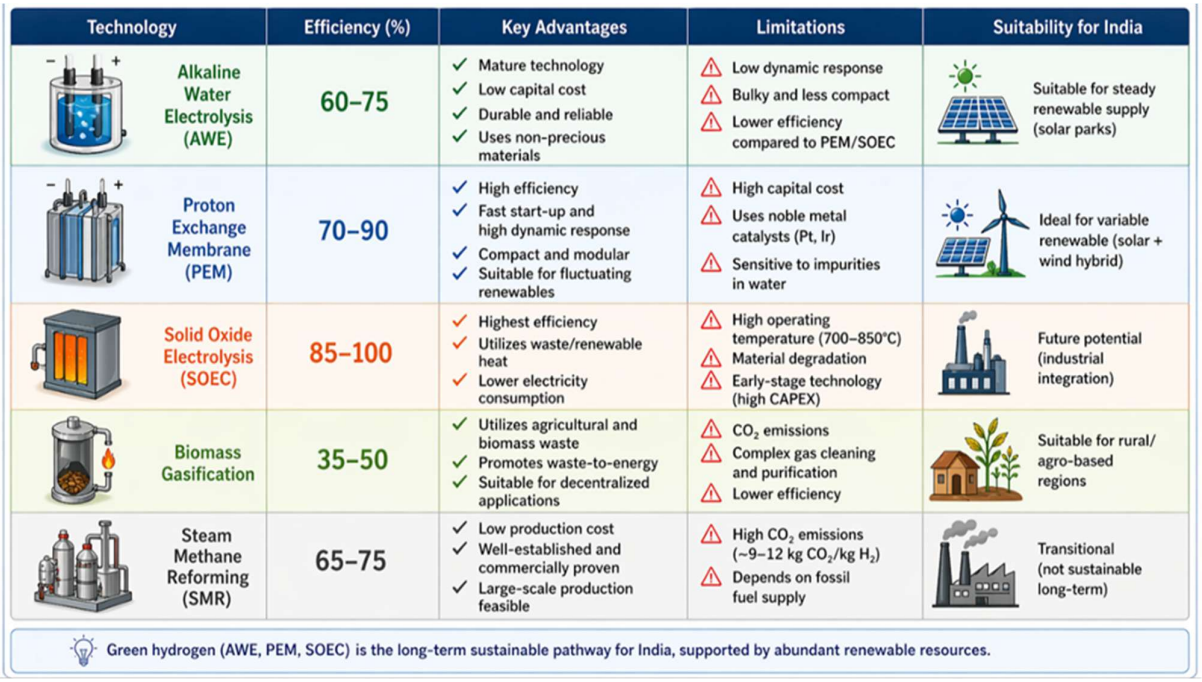


Figure 10. Comparison of different types of hydrogen production technologies

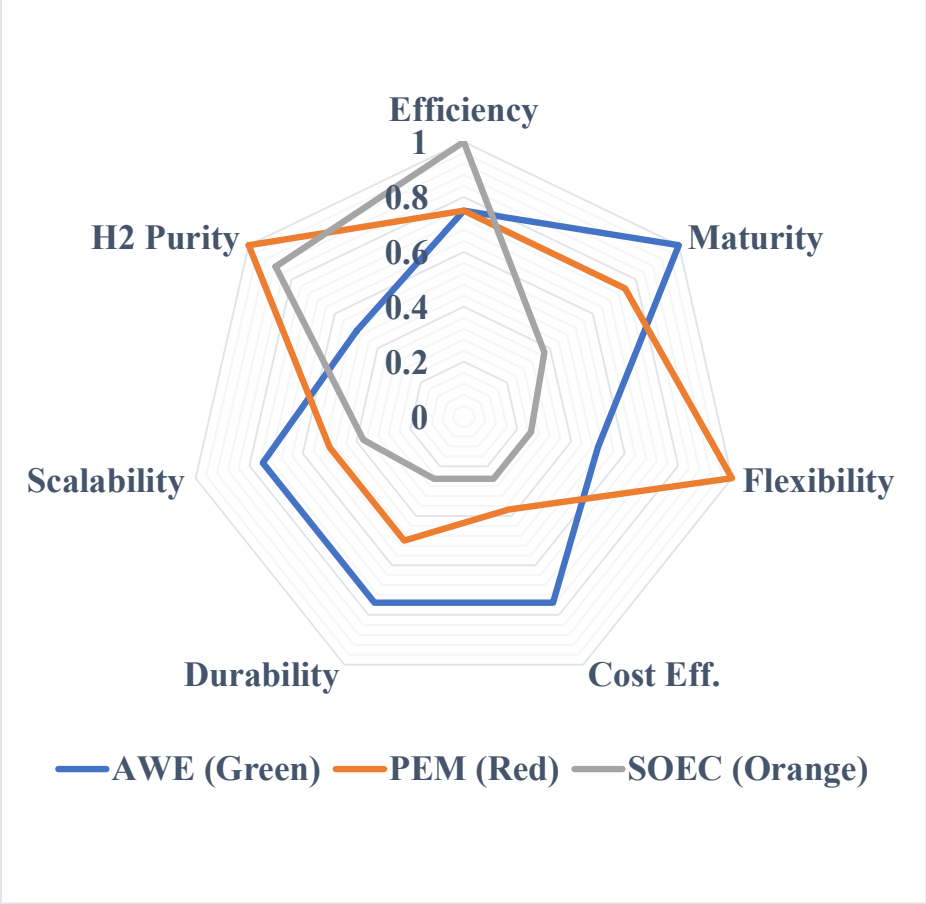


Figure 11. Electrolysis technology comparison — multi-criteria radar chart (normalized 0-1 scale) [12, 16, 32, 109].

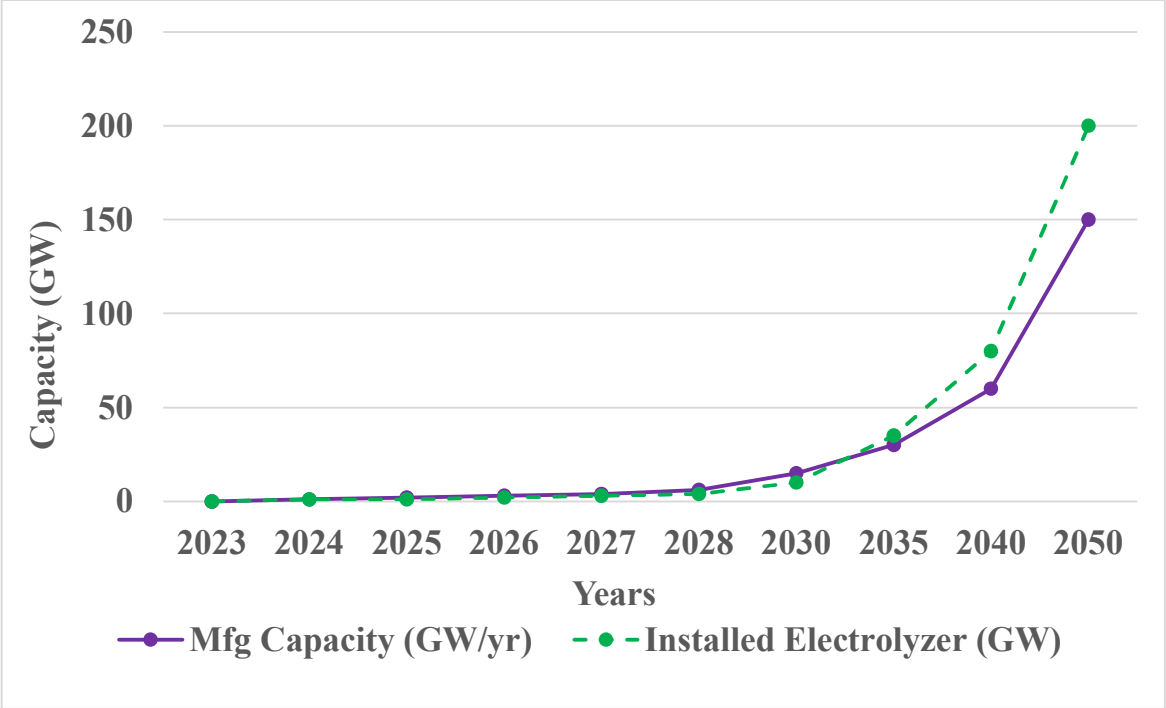


Figure 12. India's electrolyzer manufacturing & installed capacity forecast (GW) — 2023 to 2050 [106, 135, 156, 159]

Table 3. Hydrogen classification and cost analysis — India context [11, 39, 61, 135, 170].

Type	Production	CO_2 Emissions	Cost 2024 ($/kg)	Cost 2030 ($/kg)	Key Insight
Grey H_2	SMR / Coal Gasification	~10 $kgCO_2/kgH_2$	1.5–2.2	1.4–2.1	Cheapest; not net-zero compatible
Blue H_2	SMR + CCS	1–3 $kgCO_2/kgH_2$	1.8–2.5	1.6–2.3	Transitional bridge pathway
Green H_2	Electrolysis (RE)	<0.5 $kgCO_2/kgH_2$	3.5–5.0	2.0–3.5	Future dominant; cost falling fast

Although SOEC technology offers superior efficiency potential, further technological advancements and cost reductions are required before large-scale commercialization can be achieved [1, 16, 144]. The radar diagram in Figure 11 provides a visual multi-criteria comparison of AWE, PEM, and SOEC technologies across seven performance dimensions—efficiency, maturity, flexibility, cost-effectiveness, durability, scalability, and hydrogen purity—offering a single-glance strategic selection guide [12, 16, 32, 109].

The line graph as shown in Figure 12, projects the expansion of electrolyzer infrastructure from 2023 to 2050, tracking manufacturing capacity (GW/year) alongside cumulative installed electrolyzer capacity (GW). Between 2023 and 2030, both metrics remain exceptionally low, indicating a slow initial market ramp-up before accelerating significantly after 2035. By 2050, the sector experiences exponential growth, with manufacturing capacity surging to 150 GW/year and installed electrolyzer deployment climbing to a peak of 200 GW [106,135,156, 159].

Hydrogen cost dynamics and classification

The color-coded classification of hydrogen by production pathway and carbon intensity is the foundational framework for evaluating its role in decarbonization, market development, and policy design [11, 39, 61].

Figure 13 illustrates the projected decline in green hydrogen production costs as electrolyzer manufacturing scales up and renewable electricity prices continue to decrease. The most substantial cost reductions are expected after 2030, driven by economies of scale, technological learning, improved system efficiencies, and supportive policy interventions. This trend supports the growing competitiveness of green hydrogen relative to conventional fossil-fuel-based hydrogen production pathways.

Grey hydrogen: current dominance, declining future

Grey hydrogen produced *via* SMR dominates India's current production mix with an estimated 88% share in 2024 and production costs of USD 1.5–2.2/kg—the lowest of any pathway—supported by mature infrastructure. However, associated carbon emissions of 9–12 kg CO_2/kg H_2 are fundamentally incompatible with India's net-zero 2070 commitment. Under NITI Aayog projections, grey hydrogen's share is expected to decline from 88% (2024) to approximately 20% (2030) and near-zero by 2050 [67, 103, 134].

The pie chart of figure:14 illustrates the market share distribution of different hydrogen production methods. It clearly demonstrates that fossil-fuel-based grey hydrogen (Grey H_2) overwhelmingly dominates the global market, accounting for 88% of the total share. Low-emission alternatives remain comparatively marginal, with blue hydrogen (Blue H_2) and green hydrogen (Green H_2) capturing just 5% each, while alternative methods categorized under Other make up the remaining 2%

Green hydrogen: cost trajectory to competitiveness

As shown in Figure 15, Green H_2's production cost in India currently ranges from USD 3.5–5.0/kg (2024), driven primarily by electricity costs (60–70% of LCOH) and electrolyzer CAPEX. The pathway to cost competitiveness is multi-factorial: solar PV LCOE below USD 0.025/kWh at prime Indian sites; electrolyzer CAPEX declining from USD 1,100/kW (2020) to USD 380/kW (2030) to USD 120/kW (2050); improved capacity utilization through wind-solar hybrids (>50%); and WACC reduction from 9–11% to 5–7% through institutional finance mechanisms [61, 98, 144, 170]. NITI Aayog's optimistic scenario projects LCOH falling to approximately USD 1.60/kg by 2030 and USD 0.70/kg by 2050. The NGHM's own 2030 target is USD 2.0–3.5/kg. IRENA's global modelling suggests USD 0.7–1.6/kg by 2050 under a 1.5°C scenario [67, 61, 135, 159].

As shown in Figure16, the dual-axis line graph illustrates the projected cost reduction trajectories for green hydrogen infrastructure and production in India from 2020 to 2050.

Electrolyzer CAPEX (left axis): The capital expenditure for electrolyzers shows a steep decline from 1100 USD/kW in 2020 down to roughly 600

USD/kW in 2026, and is projected to hit a minimum of 130 USD/kW by 2050.

Levelized cost of hydrogen (LCOH, right axis): Mirroring the CAPEX trend, the LCOH (scaled by 100) drops consistently from an initial 700 units (7.00 USD/kg) in 2020 down to an estimated 70 units (0.70 USD/kg) by 2050.

Overall, the graph highlights a direct correlation where continuous technology maturity and scaling drastically lower both manufacturing capital costs and the final levelized price of hydrogen over the 30-year period.

INDIA'S TWO-PHASE HYDROGEN STATISTICAL ROADMAP: 2030 AND 2050

Based on consolidated data from the NGHM, NITI Aayog, IEA, IRENA, IEEFA, CEEW, ORF America, Markntel Advisors, and McKinsey, India's hydrogen transition is characterized across two strategic phases with distinct quantitative milestones [61, 67, 86, 97, 103, 135, 159]. Figure 17 presents a comprehensive timeline visual of these two phases, integrating all key milestones, capacity targets, investment flows, and impact metrics into a single navigable reference figure [135, 155].

PHASE I (2023–2030): FOUNDATION, SCALE-UP AND COST REDUCTION

The 2030 horizon is anchored by the NGHM's binding targets. Table 4 consolidates key 2030 objectives validated across multiple independent institutions [135, 155].

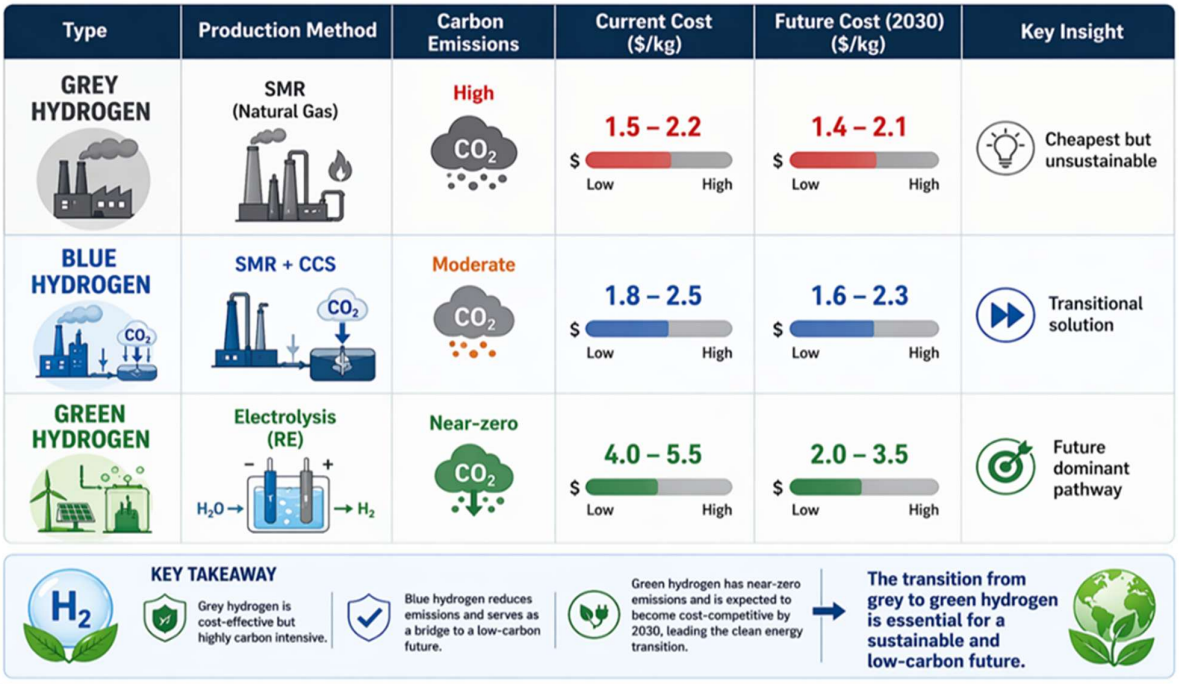


Figure 13. Comparison of different types of hydrogen: cost, emission and future outlook

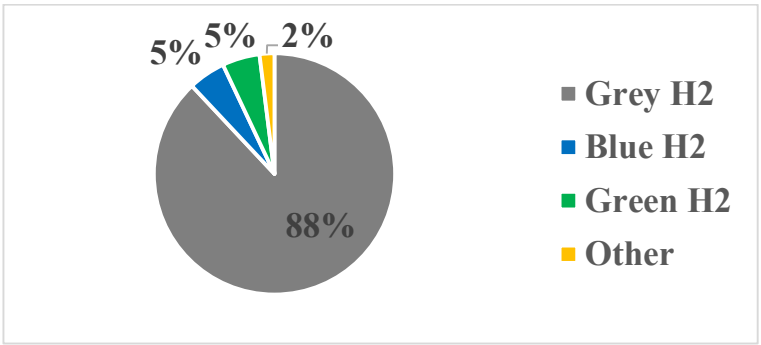


Figure 14. India's hydrogen production mix 2024 (% by source) — grey dominance *vs*. green target [MNRE 2023; IEEFA 2024; IEA 2024]

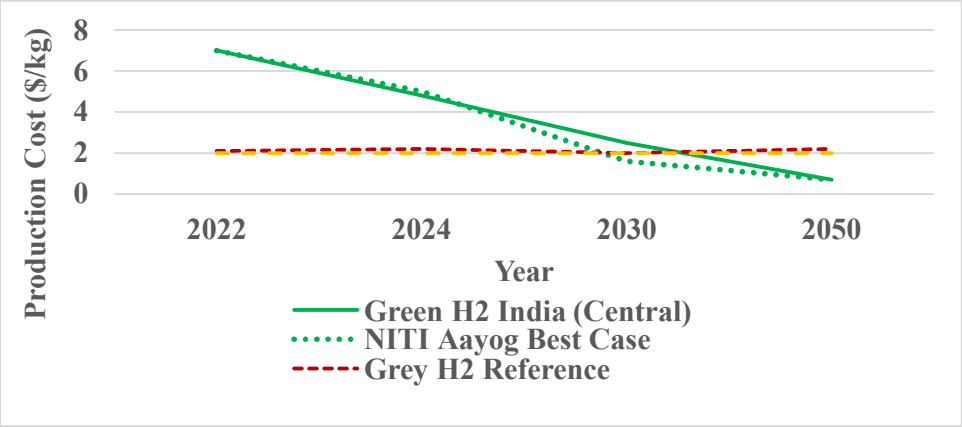


Figure 15. Green hydrogen production cost trajectory in India (USD/kg) — 2022 to 2050 [61, 67, 98, 144, 170]

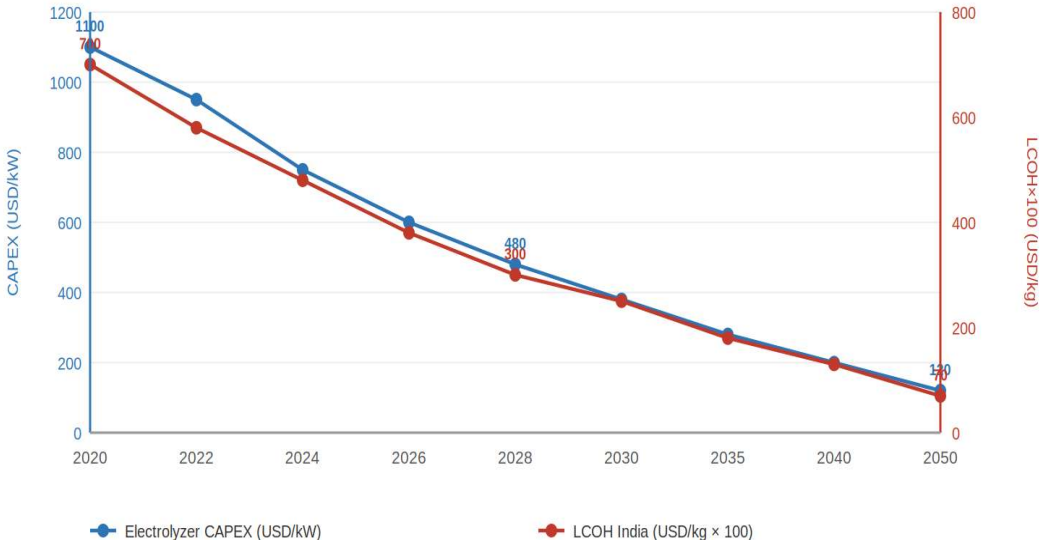


Figure 16. Electrolyzer CAPEX decline (USD/kW) & impact on LCOH (USD/kg×100) — 2020 to 2050 [44, 61, 98, 141]

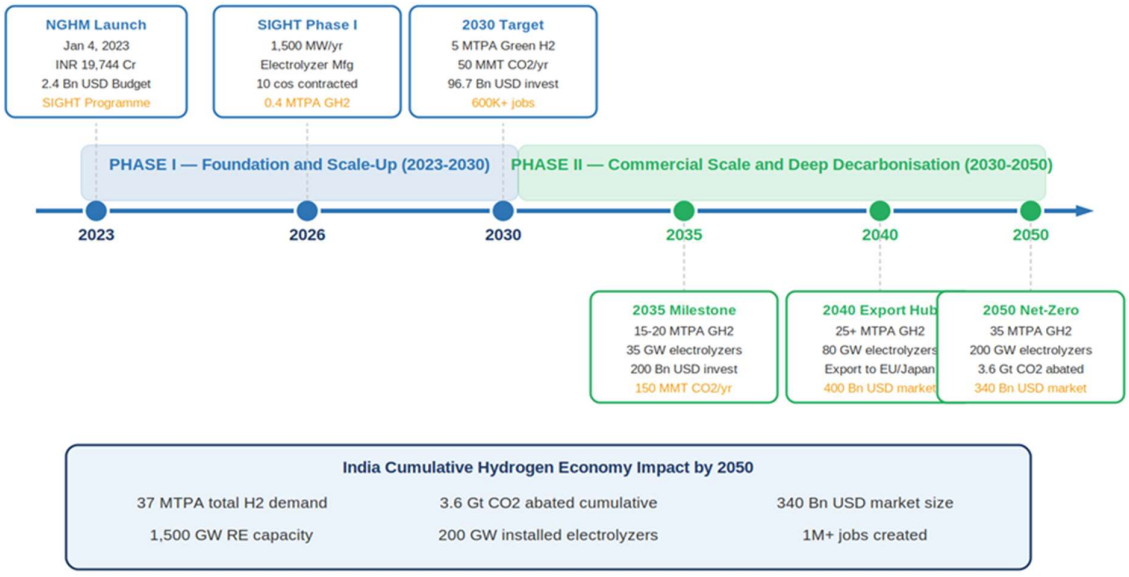


Figure 17. India's two-phase green hydrogen roadmap — key milestones 2023 to 2050 [67, 68, 86, 135, 155, 159]

As shown in Figure 18, key Phase I highlights: green hydrogen's share of total demand rises from ~5% (2024) to 25–33% (2030), corresponding to 3.5–5 MTPA of green production. The SIGHT program's electrolyzer manufacturing incentives (average USD 39.5/kW subsidy; USD 560 million total) will build 1,500 MW/yr capacity by 2026, scaling to 15 GW/yr by 2030. Annual CO_2 abatement reaches 50 MMTPA—equivalent to taking 10 million petrol cars off the road. Fossil fuel import savings of INR 1 lakh crore (USD ~12 billion) will reduce India's current account deficit [134, 144, 153, 154].

Table 4. Phase I (2030): India's green hydrogen mission — consolidated statistical targets [61, 671, 135, 144, 155, 156, 164, 170]

NGHM target (2030)	Projected value	Source
Green H_2 production	5 MTPA (up to 10 MTPA incl. exports)	MNRE NGHM 2023
Total investment mobilized	INR 8 lakh crore (~USD 96.7 Bn)	MNRE NGHM 2023
RE capacity addition (for H_2)	~125 GW additional	MNRE NGHM 2023
Annual CO_2 abatement	50 MMT per year	MNRE NGHM 2023
Fossil fuel import savings	INR 1 lakh crore (~USD 12 Bn)	MNRE NGHM 2023
Jobs created (direct + indirect)	>6 lakh (600,000+)	MNRE NGHM 2023
Electrolyzer manufacturing	≥1,500 MW/yr (Phase I) → 15 GW/yr (2030)	MNRE SIGHT 2023
LCOH target	USD 2.0–3.5/kg by 2030	IRENA 2023; CEEW 2024
Market value	USD 8 billion by 2030	Markntel Advisors 2024
Global market share target	~10% of global GH_2 market	NITI Aayog 2022

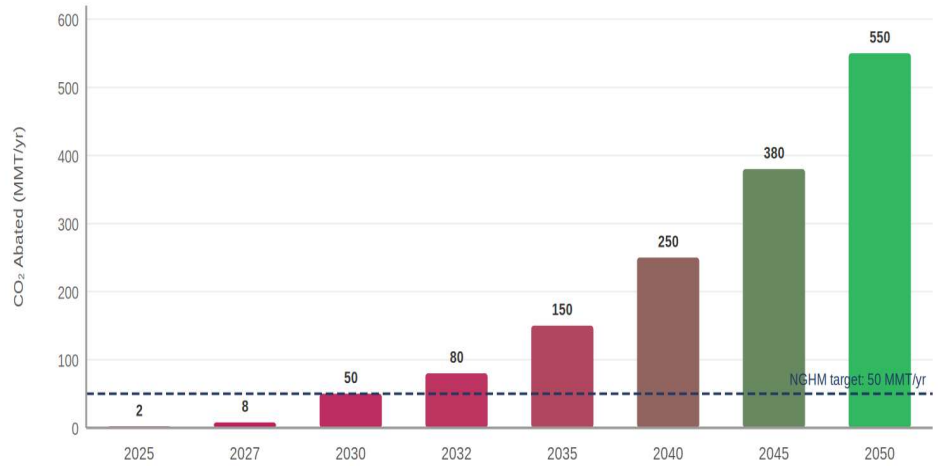


Figure 18. Annual CO_2 emissions abated *via* green hydrogen in India (MMTPA) — 2025 to 2050 [67, 134, 135]

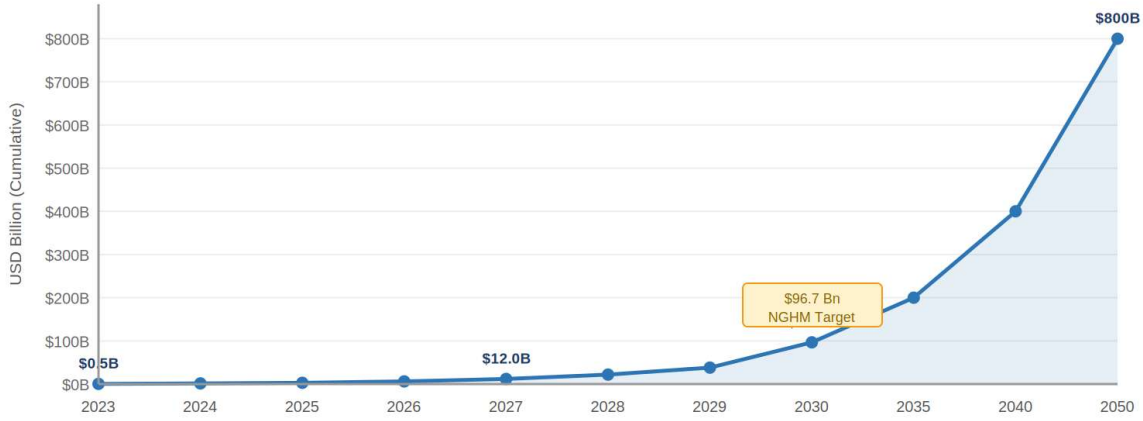


Figure 19. Cumulative investment in India's green hydrogen ecosystem (USD billion) — 2023 to 2050 [135, 143, 156, 164]

Table 5. Phase II (2050): India's green hydrogen long-term statistical projections [9, 67, 68, 69, 112, 134, 159, 164]

Indicator (2050 Horizon)	Projected value	Source
Total H_2 demand (India)	28–37 MTPA (4× vs 2024)	NITI Aayog 2022; IEEFA 2024
Green H_2 share	≥80% of total (22–30 MTPA)	NGHM 2023; IEA NZE Scenario
Green H_2 LCOH India	USD 0.70–1.60/kg (best case)	NITI Aayog 2022
Installed electrolyzer capacity	192–224 GW	FSR/EUI 2023; IRENA 2023
Total RE installed capacity	1,000–1,500 GW	IEA 2024; IRENA 2023
Cumulative CO_2 abated (2020–50)	3.6 Giga-tons	NITI Aayog 2022
Green H_2 market value (India)	USD 340 billion	Markntel Advisors 2024
Cumulative investment (2023–50)	USD 800 billion+	NITI Aayog; Bloomberg NEF 2023
Employment (H_2 sector)	Multi-million (direct + indirect)	NITI Aayog 2022
India net-zero target year	2070	GoI NDC 2022

The line graph in Figure19) charts a projected exponential growth curve for cumulative financial investments, measured in billions of US Dollars (USD Billion Cumulative) from 2023 to 2050. The timeline begins in 2023 with a modest baseline of $0.5B, rising slowly over the first few years to reach a cumulative total of $12.0B by 2027. An highlighted yellow callout box emphasizes the "NGHM Target" milestone of $96.7 Billion, which is projected to be achieved around the year 2030. Beyond 2030, the investment curve steepens dramatically, rapidly climbing from $200B in 2035 to approximately $400B by 2040. By the end of the projection period in 2050, the cumulative investment experiences a massive surge to reach an ultimate peak of $800B.

PHASE II (2030–2050): COMMERCIAL SCALE, EXPORT AND DEEP DECARBONIZATION

The 2050 horizon involves transformational change in India's energy system architecture, with hydrogen becoming a mainstream carrier across all hard-to-abate sectors [67, 68, 91].

Critical 2050 milestones

*A*s shown in Figure 20, total hydrogen demand reaches 28–37 MTPA (a fourfold increase *vs*. 2024), with green hydrogen comprising ≥80% of supply at 22–30 MTPA. IRENA's 1.5°C scenario requires global green hydrogen of 523 MTPA—India targeting 35 MTPA (10% share) requires 192–224 GW of installed electrolyzers, a 1,600-fold increase from 2024 levels. Cumulative CO_2 abatement reaches 3.6 Gt (2020–2050), equivalent to India's current five years of total energy sector emissions. The green hydrogen market in India alone reaches USD 340 billion—exceeding current total renewable energy investment [67, 71, 73, 112, 143].

As shown in Figure 21, this bar chart illustrates the projected exponential growth of a market size measured in billions of US dollars (USD Billion) from 2023 through 2050. According to Markntel Advisors (2024), the market is projected to expand at a robust compound annual growth rate (CAGR) of approximately 25.2% between the years 2026 and 2032. The market starts at a modest baseline of $0.3 B in 2023, climbing slowly through the decade to reach $8.0 B in 2030 and $14.0 B by 2032. Growth accelerates significantly after 2035 ($35.0 B), with the market size more than doubling by 2040 ($90.0 B) and doubling again by 2045 ($180.0 B). By the final year of 2050, the market experiences its most dramatic surge, peaking at an ultimate value of $340.0 B [156, 164, 170, 174].

SECTORAL HYDROGEN DEMAND — DETAILED STATISTICAL ANALYSIS

India's hydrogen demand is projected to grow from approximately 6.3 MTPA (2024) to 15 MTPA (2030) and 37 MTPA (2050), driven by both conventional demand growth and the emergence of entirely new hydrogen-consuming sectors [65, 67, 134, 154].

As shown in Figure 22, the projected demand trajectory indicates a substantial increase in hydrogen consumption between 2030 and 2050, primarily driven by the fertilizer, refining, steel, transportation, and power sectors. The results highlight the critical role of hydrogen in achieving long-term decarbonization objectives and underline the need for significant investments in production capacity, storage infrastructure, and transmission networks.

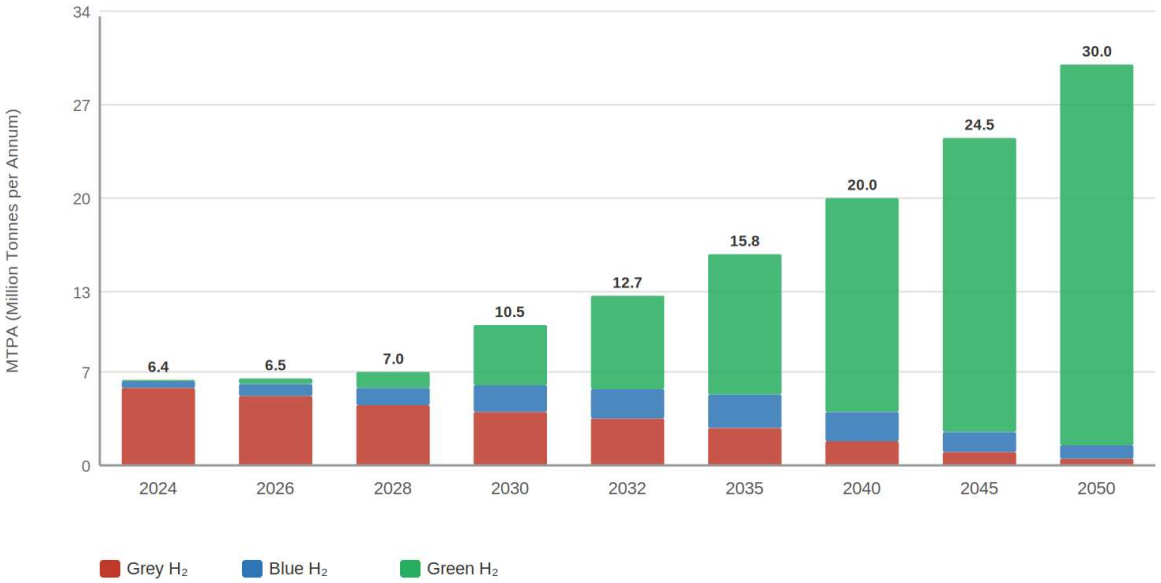


Figure 20. India's total hydrogen demand by type (MTPA) — 2024 to 2050, Stacked forecast [67, 103, 134, 135, 154]

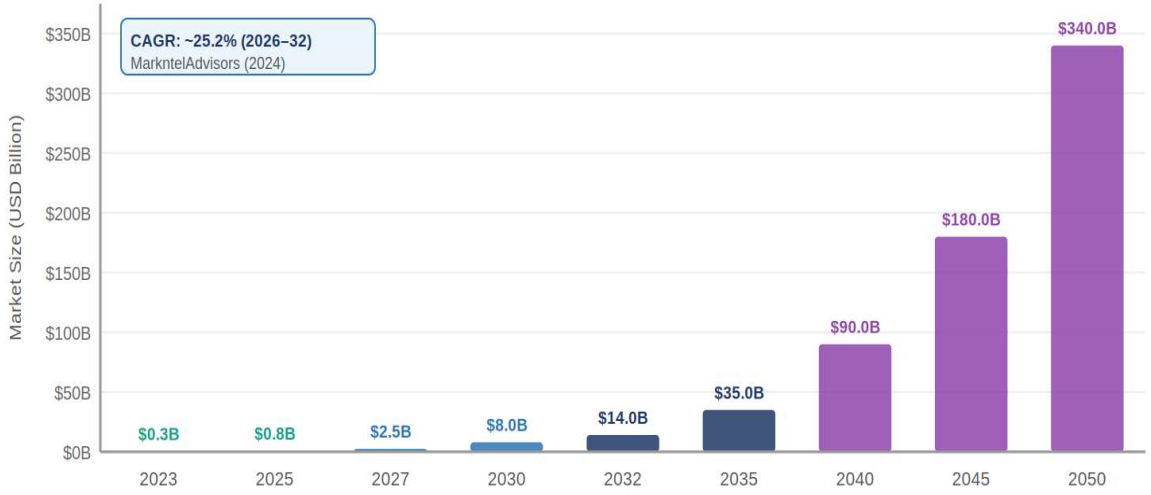


Figure 21. India's green hydrogen market size (USD billion) — 2023 to 2050 [156, 164, 170, 174]

Table 6. India's hydrogen sectoral demand and growth forecast — 2024, 2030 and 2050 [52, 54, 65, 67, 70, 74, 96, 134, 154]

Sector	2024 (MTPA)	2030 (MTPA)	2050 (MTPA)	Breakeven ($/kg)	Key driver
Fertilizer	3.0	6.1	8.0	1.7–2.1	Largest existing H_2 user; NH_3 synth.
Refining	2.5	4.5	6.0	1.7–2.1	Hydrocracking and desulfurization
Steel	0.3	1.0	8.0	<1.0	DRI green steel; biggest 2050 mkt
Mobility (road)	0.05	0.8	5.0	1.2–2.0	Trucks, buses, FCEVs
Shipping	0.05	0.6	3.0	1.7–2.0	Green NH_3/H_2 bunkering
Power & storage	0.1	0.5	3.0	—	Seasonal storage; grid balancing
Chemicals	0.4	1.5	4.0	—	Methanol, ammonia derivatives
TOTAL	~6.3	~15.0	~37.0	—	NGHM/NITI Aayog/IEA/IEEFA

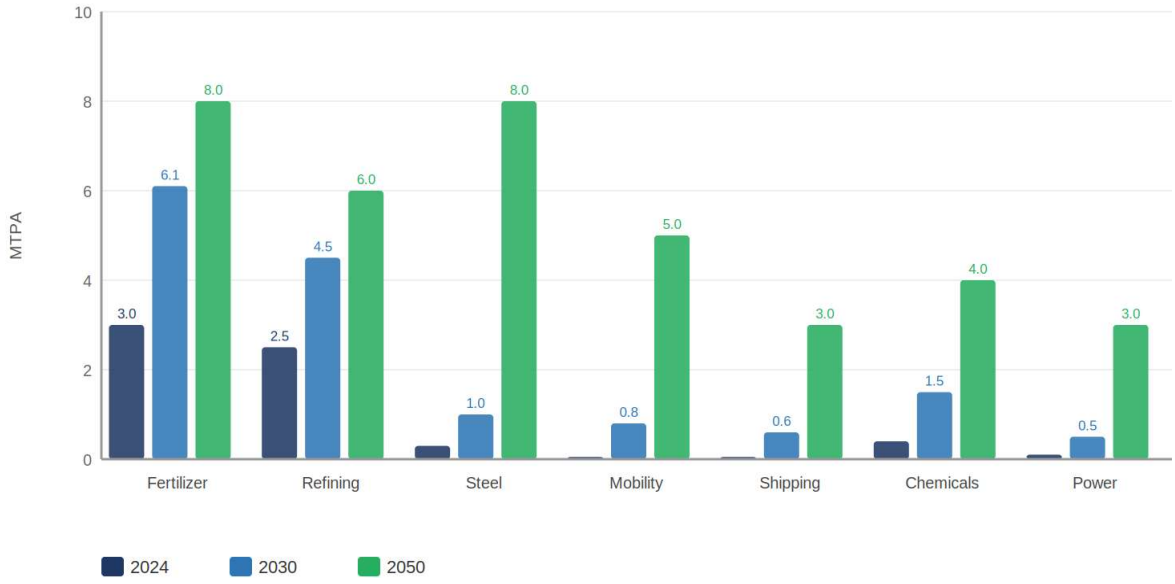


Figure 22. India's sectoral hydrogen demand by phase (MTPA) — 2024, 2030 and 2050 [52, 54, 67, 70, 74, 96, 134]

Fertilizer sector — early mover and largest consumer

India's fertilizer sector is the single largest hydrogen consumer with approximately 3.0 MTPA in 2024, projected to grow to 6.1 MTPA by 2030 and 8.0 MTPA by 2050, driven by rising food security demands. NITI Aayog projects green hydrogen uptake in fertilizers at 24% of sector demand by 2030 and near 100% by 2050, enabled by conversion of existing SMR-based ammonia plants and new green ammonia facilities. Cumulative CO_2 savings in this sector alone could reach 820 million tons between 2020 and 2050. The breakeven cost for green hydrogen adoption in fertilizers is USD 1.7–2.1/kg—achievable by 2030 under optimistic RE scenarios. [52, 67, 80, 134]

Refining — existing infrastructure advantage

India's refining capacity of ~250 Mt/year crude processing is the fourth-largest globally, with hydrogen demand of ~2.5 MTPA (2024), rising to 4.5 MTPA by 2030 and 6.0 MTPA by 2050. On-site SMR plants currently produce ~27 Mt of CO_2/year in this sector alone, rising to 47 Mt by 2050 without intervention. Green hydrogen uptake is projected at 24% of sector demand by 2030 and 100% by 2050 under NITI Aayog's efficient scenario, with a breakeven of USD 1.7–2.1/kg [54, 133].

Steel — largest long-term opportunity

India is the world's second-largest steel producer with current CO_2 emissions of 269 Mt/year (11% of India's total), projected to rise to 951 Mt/year by 2050 without decarbonization. Hydrogen-based DRI (direct reduced iron) can eliminate virtually all process emissions. India's DRI capacity of ~35 Mt/year (world's largest) provides an immediate retrofit opportunity. Tata Steel and JSW Steel have announced green steel roadmaps targeting 5 Mt/year of H_2-based production by 2030. NITI Aayog and RMI project steel and heavy-duty trucking together will drive 52% of India's hydrogen demand growth by 2050, reaching 8.0 MTPA—the largest sectoral demand by 2050 [69, 74, 99, 126, 132].

Mobility and transport

India's fuel cell vehicle (FCEV) market is growing rapidly. Key milestones include: IOCL's 15 green H_2 FCEV bus trials across Delhi, Haryana, and UP (September 2023); Indian Railways' Hydrogen for Heritage DEMU program—900 kW output from 8× Ballard FCmove-HD+ fuel cells with dynamic trials from 2025; and Amara Raja's 80 kg/day refuelling station in Leh, Ladakh (November 2024)—India's first H_2 refuelling station operating at 3,500 m altitude and temperatures from −20°C to +30°C. Mobility demand is projected to grow from negligible (2024) to 0.8 MTPA (2030) and 5.0 MTPA (2050). [70, 78, 123, 139, 157, 158, 172, 173].

Shipping, export and port hubs

India's strategic coastal geography positions it uniquely for green ammonia and hydrogen export. Priority maritime export hubs include Odisha (Paradeep, Gopalpur), Gujarat (Deendayal/Kandla, Hazira), Tamil Nadu (Tuticorin), and Maharashtra (JNPT). India targets 10% of the projected 100+ MTPA global green hydrogen market by 2030.

Shipping sector breakeven at USD 1.7–2.0/kg is relatively favorable due to existing high bunker fuel taxes [88, 96, 112, 131, 135, 147].

STATE-OF-THE-ART HYDROGEN INFRASTRUCTURE IN INDIA

Hydrogen infrastructure development is a prerequisite for realizing the NGHM's ambitious targets. Figure 23 maps the complete green hydrogen value chain from renewable energy source to end-use application, showing cost components, Indian milestones, and technology options at each stage [65, 135].

- *Renewable energy source (RE source):* Large-scale solar and wind power (~223 GW) provide low-cost renewable electricity, which serves as the primary energy input for green hydrogen production through AWE, PEM, or SOEC electrolyzers.
- *Electrolysis*: Water is split into hydrogen and oxygen using electricity, with hydrogen production costs estimated at approximately $3.5–5.0 per kg in 2024.
- *Purification*: The produced hydrogen is purified to 99.99% purity using technologies such as PSA, VPSA, or membrane separation, adding approximately $0.5–1.0 per kg to the cost.
- *Storage*: Hydrogen is stored either as compressed gas (around 350 bar) or in carriers such as LOHC and ammonia, with storage costs ranging from $1–2 per kg.
- *Transport*: Hydrogen is transported through pipelines, trucks, or ships, with additional logistics costs of approximately $0.5–1.5 per kg depending on distance and delivery method.
- *End use:* The delivered hydrogen is utilized in sectors such as fertilizers, steel manufacturing, mobility, and power generation, resulting in a total delivered cost of about $5–8 per kg in 2024, with projected reductions to $2–3 per kg by 2030 and $0.7–1.5 per kg by 2050.

Current production infrastructure

India's 6–7 MTPA hydrogen demand is currently served almost entirely by on-site SMR plants in the fertilizer (52% of consumption) and refining (46%) sectors. The western region accounts for 52.1% of total hydrogen demand due to the concentration of refining and petrochemical capacity in Gujarat and Maharashtra [32, 65, 67].

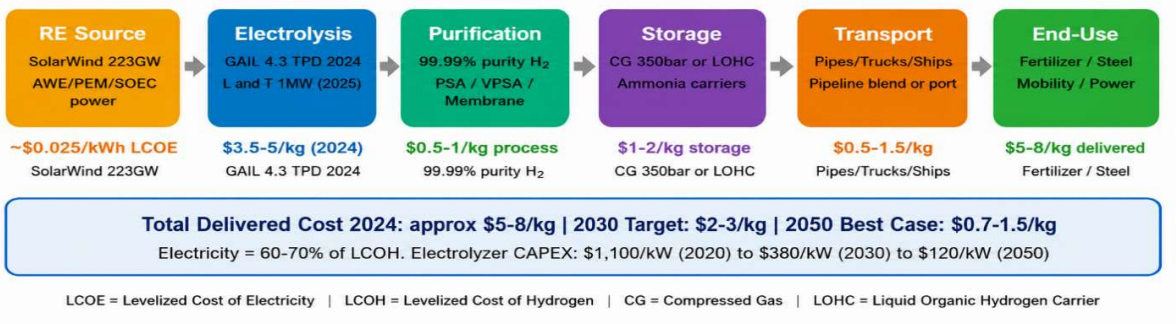


Figure 23. Green hydrogen value chain — stages, costs and Indian milestones [65, 110, 123, 135, 150, 179]

Regulatory framework

Table 7. Key regulatory agencies for hydrogen energy in India

Regulatory Agency	Role and Responsibilities
MNRE (Ministry of new and renewable energy)	Nodal agency; NGHM policy formulation; SIGHT programme [105]
PESO (Petroleum and explosives safety organization)	Regulation of H_2 storage, handling, and transport safety [115]
CEA (Central electricity authority)	National electricity planning; RE-H_2 grid integration [49]
BIS (Bureau of Indian standards)	H_2 safety standards, product certification frameworks [47]
PNGRB (Petroleum and natural gas regulation board)	Blending approval: 5% → 20% vol. H_2 in PNG networks [110]
Ministry of ports, shipping and waterways	Green shipping corridors; hydrogen bunkering regulation [96]

Green hydrogen pilot projects — statistical overview

GAIL's Vijapur plant (May 2024): 10 MW PEM; 4.3 TPD; 99.99% purity; powered by 20 MW co-located solar. L&T Hazira (March 2025): 1 MW indigenous ML-400 PEM; 200 Nm^3/hr; 300 MW/yr PLI allocation. NTPC Kawas (January 2023): 1 MW floating solar electrolysis; 5% vol./vol. PNG blending; PNGRB approved. Amara Raja Leh (November 2024): 80 kg/day; supports 5 NTPC fuel cell buses; India's first H_2 refuelling station [110, 139, 150, 152, 179].

Storage, transport and hydrogen hubs

India currently lacks a dedicated hydrogen pipeline network. The NGHM envisions utilizing India's 40,000 km natural gas pipeline network for hydrogen blending (approved at 5% vol./vol., roadmap to 20%) and eventual pure hydrogen transport. Underground geological storage feasibility is under assessment. The NGHM plans at least two green hydrogen hubs by 2026, with Odisha, Gujarat, Tamil Nadu, and Maharashtra identified as priority coastal hub locations. Co-locating production with consumption reduces delivered costs by 15–25% [27, 107, 112, 116, 131, 135, 147].

BARRIERS TO LARGE-SCALE DEPLOYMENT

Despite significant policy momentum, green hydrogen's large-scale deployment faces a complex web of technical, economic, infrastructural, and regulatory barriers—particularly acute in India's emerging market context [61, 144, 154].

Economic and cost competitiveness

Green hydrogen currently costs USD 3.5–5.0/kg versus grey hydrogen at USD 1.5–2.2/kg—a cost premium of USD 2–3/kg that must close to USD 0/kg by 2030 for competitiveness without subsidy. India's WACC for green hydrogen projects is 9–11% *vs.* 4–6% in Europe—adding approximately USD 1.0–1.5/kg to LCOH. Current NGHM production subsidies (USD 0.66/kg declining to USD 0.40/kg) cover only 10–20% of the cost gap, significantly below the US IRA's USD 3/kg production tax credit. An estimated USD 80–120 billion of new infrastructure investment is required by 2030, of which the government's INR 19,744 crore covers less than 5%. [48, 61, 135, 143, 144].

POLICY, GOVERNANCE AND R&D LANDSCAPE

NGHM governance architecture

Figure 24 provides a complete visual map of the NGHM's governance architecture, funding flows, and implementing agencies—from Union Cabinet to field-level executing organizations [135].

SIGHT program and financial incentives

The SIGHT program (INR 17,490 crore) provides: production-linked incentives of USD 0.66/kg (year 1) tapering to USD 0.40/kg (year 3); electrolyzer manufacturing support of average USD 39.5/kW (USD 560 million total); and a 25-year waiver on interstate transmission system (ISTS) charges for green hydrogen projects commissioned before 31 December 2030. By May 2024, eight companies secured contracts for 1,500 MW/yr electrolyzer manufacturing and ten companies contracted to produce 0.4 MTPA green hydrogen under Phase I [135, 156, 177].

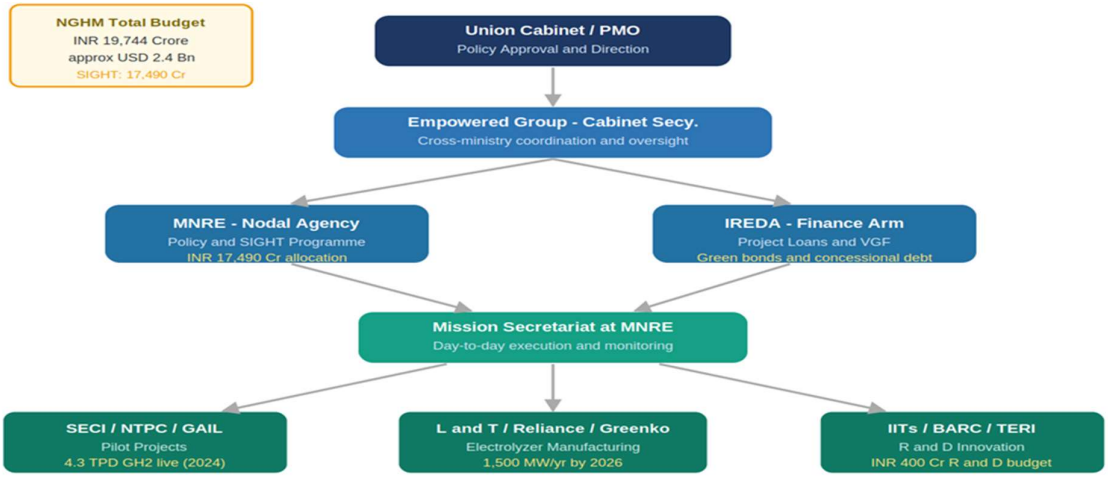


Figure 24. NGHM governance, funding and execution architecture [135, 156, 178]

Table 8. NGHM risk management framework [135]

Risk type	Risk category	Mitigation strategy
Strategic	Supply chain disruptions	Diversify supply chains; build domestic manufacturing
Technological	Technology disruptions	Technology-agnostic R&D funding; multiple parallel threads
Operational	Water availability constraints	Co-locate RE plants and H_2 production near water sources
Operational	Land availability constraints	State-level land banks for RE and H_2 deployment
Operational	Safety incidents	Rigorous standards enforcement; PESO oversight
Financial	Sustainable demand uncertainty	Demand creation through HPOs and blending mandates
Financial	Affordable RE access	Integrated planning of RE capacity addition
Financial	Electrolyzer availability	PLI incentives for domestic electrolyzer ecosystem
Financial	CAPEX overruns	Scale-up to achieve economies of scale
Financial	Credit access	Risk-sharing frameworks; FDI facilitation; bond markets

Table 9. NGHM governance bodies [135]

No.	Governing body	Primary function
1	MNRE (nodal agency)	Mission directives and policy oversight
2	IREDA (finance)	Financial assistance and project funding support
3	Empowered group (Cabinet secy.)	Cross-ministry implementation monitoring
4	Mission secretariat (MNRE)	Day-to-day execution and coordination

International collaborations

Table 10. India–EU collaborations in green hydrogen [55, 84, 113, 119, 145]

Sr.	Indian company	EU partner	Collaboration details
1	Reliance New Energy Ltd.	Stiesdal A/S (Denmark)	Low-cost HydroGen electrolyzer manufacturing in India [119]
2	GR Promoter / GreenH	H2B2 GreenH (Spain)	1,000 MW PEM plant; Phase-1 100 MW operational at Jhajjar, Haryana [84]
3	Greenko Group	John Cockerill (Belgium)	2 GW electrolyzer factory; USD 500 million investment [55]

Table 11. India–US hydrogen collaborations [59, 66, 102, 130]

Collaboration	Focus area	Year	Details
US-India hydrogen task force	H_2 R&D	2021	MNRE–US DOE partnership for technology development
SCEP (strategic clean energy partnership)	Safety and hubs	2024	Clean hydrogen cost reduction and safety priorities
Ohmium collaborations	Electrolyzer Mfg.	2024	US-based OEM building projects in South India
Hydrogen carriers (LOHCs and NH_3)	Transport tech.	2024	Joint LOHC and ammonia carrier development
H_2 transport infrastructure	Mobility	2024	Distribution network viability across Indian regions

State-level hydrogen policies

Six Indian states—Maharashtra, Uttar Pradesh, Andhra Pradesh, Rajasthan, Odisha, and West Bengal—have released dedicated green hydrogen policies with investment incentives, land allocation, and electricity tariff concessions. Andhra Pradesh targets 12,000 jobs per MTPA of green hydrogen production; Gujarat projects 1.8 lakh jobs from electrolyzer manufacturing; Uttar Pradesh has attracted INR 1.15 trillion in green hydrogen investments. [46, 121, 142]

Research and development landscape

India's R&D ecosystem for hydrogen is anchored by IITs, CSIR laboratories, BARC, ONGC Energy Centre, and TERI. MNRE's R&D roadmap (October 2023) allocated INR 400 crore under the NGHM with DST, DBT, and DRDO providing complementary funding [35, 106].

INDUSTRIAL APPLICATIONS AND KEY PILOT PROJECTS

GAIL India — Vijapur green hydrogen plant

Commissioned: 24 May 2024. Capacity: 4.3 TPD (1,569.5 t/yr). Technology: 10 MW PEM electrolyzer. Purity: 99.99%. Power source: 20 MW co-located solar plant. Significance: India's first commercial-scale dedicated green hydrogen plant, directly demonstrating NGHM Phase I objectives.

The plant provides real-world data on continuous PEM performance under Indian solar irradiance profiles [150, 156].

Larsen & Toubro — Hazira electrolyzer

Commissioned: 1 March 2025. Capacity: 1 MW; 200 Nm^3/hr. Technology: Two-stack ML-400 PEM system—India's first indigenously manufactured electrolyzer stack. PLI allocation: 300 MW/yr under NGHM. Strategic significance: establishes India's domestic electrolyzer manufacturing capability, critical for import substitution and achieving the SIGHT program's 1,500 MW/yr target by 2026. [161, 178]

Indian railways — hydrogen for heritage demu

India's Hydrogen for Heritage program retrofits 1600 HP diesel DEMU trains with hydrogen fuel cells, delivering 900 kW total power output (800 kW from 8× Ballard Power Systems FCmove-HD+ PEM fuel cells at 100 kW each, plus 400 kW battery backup). Hydrogen is stored as compressed gas at 350 bar in removable cylinders refillable in 45 minutes at Jind, Haryana. Dynamic trials are planned from 2025 covering 50,000 km; project cost is approximately INR 111.83 crore. India's 900 kW output surpasses Germany, France, Sweden, and China's existing hydrogen train deployments [100, 177].

Table 12. Key R&D Institutions in India's green hydrogen ecosystem

Institution	Location	Research focus
BARC	Mumbai	PEM MEA; AWE electrocatalysts; photoelectrochemical splitting [136]
ONGC EC – ICT Mumbai	Mumbai	Cu-Cl thermochemical cycle; molten salt thermal storage [114]
ONGC EC – IIT Delhi	Delhi	IS thermochemical cycle; 15-bar closed-loop metallic system [94]
ONGC EC – CSIR IIP	Dehradun	Open-loop I-S cycle; H_2 from H_2S in refineries [94]
Indian Oil R&D – IISc	Faridabad	Oxy-steam biomass gasification; VPSA H_2 separation [41]
Indian Oil R&D Centre	Faridabad	Solar-powered AWE/PEM/SOEC; 5,000 bar storage [41]
KPIT – Agharkar RI	Pune	Microbial dark fermentation from biomass and methane [40]
KPIT – Ankur Scientific	Vadodara	Woody biomass gasification for pure H_2 [40]
IIT Delhi	Delhi	Bunsen reactor; nanostructured H_2 materials [94]
IIT Madras	Chennai	Solar seawater electrolysis; photocatalysis [95]
IIT Guwahati	Guwahati	Biohydrogen from lignocellulosic biomass [57]
IIT Kharagpur	Kharagpur	Biological H_2 production from organic waste [42]
IIT Kanpur	Kanpur	Photoelectrochemical wastewater splitting [58]
IIT Hyderabad	Hyderabad	H_2S decomposition; CO_2 to syngas via plasma catalysis [43]
IIT Indore	Indore	Catalytic H_2 from methanol [148]
IIT BHU Varanasi	Varanasi	Ultra-pure on-site H_2; photocatalytic water splitting [45]
CSIR NEERI	Nagpur	Liquid organic hydride H_2 supply systems [50]
TERI	Gurgaon	Bio-hydrogen in closed-loop bioreactor [72]
NMRL – DRDO	Mumbai	Autothermal reforming; AIP for naval submarines [101]
SPRERI	Anand, Gujarat	Dual-fuel biomass gasification for H_2 [71]

Steel and green hydrogen integration

Tata Steel and JSW Steel are leading India's green steel transition, with hydrogen-based DRI production at demonstration scale. The world's largest hydrogen-based DRI plant (HYBRIT, Sweden) at 1.5 MTPA provides the commercial blueprint. India's 35 MTPA DRI capacity—the world's largest—constitutes a ready retrofit base. NITI Aayog projects steel sector hydrogen demand reaching 8.0 MTPA by 2050, making it the largest sectoral driver of India's long-term hydrogen economy [17, 69, 74, 99, 126, 132].

CROSS-SECTIONAL ANALYSIS AND STRATEGIC INSIGHTS

Technology–cost–scalability trade-offs

Synthesis of the preceding analysis reveals clear technology trade-offs: AWE offers optimal maturity, cost, and scalability for India's near-term (2024–2030) requirements; PEM is preferred for variable renewable coupling and high-purity applications; SOEC is the long-term bet for industrial waste-heat integration (2035–2050); biomass routes are most appropriate for decentralized rural applications. The radar diagram (Figure 11) visually captures these trade-offs across seven dimensions [1, 12, 16, 32, 61, 109].

India in global comparative context

Globally, the EU leads hydrogen policy ambition with EUR 470 billion committed through REPowerEU and IPCEI. Japan targets 3 MTPA of clean hydrogen by 2030 with USD 107 billion strategic investment. The US offer USD 3/kg production tax credits under the IRA and have committed USD 8 billion for hydrogen hubs. India's public investment of USD 2.4 billion (NGHM) is modest in absolute terms, but its renewable energy cost advantage—solar LCOE below USD 0.025/kWh at best sites—provides a structural competitive advantage that no European country has replicated [81, 86, 91, 130, 135, 175].

IRENA's 1.5°C scenario requires global green hydrogen of 125 MTPA by 2030 and 523 MTPA by 2050. India, targeting 5 MTPA (2030) and 35 MTPA (2050), would represent 4% and 7% of global production, respectively — a realistic and strategically important contribution [97, 159].

RESEARCH GAPS, FUTURE PATHWAYS AND POLICY RECOMMENDATIONS

Critical research gaps

Despite the rapidly expanding body of literature on hydrogen energy systems, a critical gap persists in the integrated, India-specific assessment of hydrogen transition pathways, particularly in the context of long-term techno-economic feasibility, sectoral demand evolution, and policy-driven deployment frameworks. Existing reviews predominantly focus on global hydrogen trends, electrolyzer technologies, or isolated techno-economic aspects, often lacking a holistic, data-driven synthesis tailored to India's unique energy landscape [67, 109].

Several recent studies by international agencies such as IEA, IRENA, and NITI Aayog provide valuable projections; however, these analyses are typically fragmented across domains—technology performance, cost projections, infrastructure readiness, or policy frameworks—without offering a unified multi-dimensional evaluation. Furthermore, prior literature rarely integrates quantitative projections (2030–2050) with sector-wise hydrogen demand, infrastructure readiness, and investment trajectories in a single coherent framework. This creates a disconnect between strategic policy vision and implementable techno-economic pathways, particularly for emerging economies like India [106].

Another key limitation in existing reviews is the lack of comparative multi-criteria assessment of hydrogen production technologies (AWE, PEM, SOEC) under India-specific operating conditions, including renewable intermittency, cost sensitivity, scalability constraints, and infrastructure limitations. Additionally, limited attention has been given to the dynamic transition from grey to green hydrogen, especially in terms of cost convergence timelines, carbon reduction potential, and sectoral adoption thresholds [69].

Future technology priorities

Priority R&D targets: non-noble metal PEM catalysts achieving >90% efficiency at >100,000 hours durability; solid-state hydrogen storage exceeding 6 wt% H_2 capacity at near-ambient conditions; wind-solar hybrid electrolysis achieving >60% capacity utilization; AI-enabled predictive maintenance for electrolyzer stacks targeting >99% uptime; and advanced membrane electrode assemblies for high-current-density PEM operation exceeding 3 A/cm².

To address these gaps, the present study introduces a comprehensive and integrated review framework that combines:

- Techno-economic analysis of hydrogen production pathways, including cost trajectories, efficiency, and CAPEX trends [106];

- Comparative multi-criteria evaluation of electrolyzer technologies using performance, scalability, and deployment-readiness indicators [62];
- India-specific hydrogen demand modelling (2024–2050) across key sectors such as fertilizers, refining, steel, mobility, and power [10];
- Policy and infrastructure assessment, aligned with the National green hydrogen mission (NGHM) and global decarbonization targets [10];
- Two-phase strategic roadmap (2030 and 2050) integrating production targets, investment flows, and emission reduction potential [4].

Strategic policy recommendations

Based on the comprehensive analysis, the following recommendations are proposed: (i) increase production subsidies to USD 1.5–2.0/kg, comparable to US IRA levels; (ii) introduce mandatory hydrogen purchase obligations (HPOs) for refineries (5% by 2027, 20% by 2030) and fertilizer plants (5% by 2028); (iii) implement carbon pricing at USD 20–50/tCO_2; (iv) standardize 10–15 year offtake agreements between government entities and green hydrogen producers; (v) develop hydrogen corridors connecting Gujarat, Rajasthan, and Tamil Nadu hubs to industrial consumers; (vi) harmonize state-level intrastate wheeling charge waivers; and (vii) establish an India Hydrogen Safety Institute to build inspection and certification capacity [48, 67, 69, 135, 142, 143, 144].

DISCUSSION

This review synthesizes evidence from 175 sources into a unified multi-dimensional analytical framework— a comprehensive assessment of India's hydrogen transition pathway integrating technological, economic, policy, infrastructure, and market dimensions. Three overarching insights emerge with particular strategic significance [38, 67, 90, 135].

First, the cost-sustainability trade-off is real but narrowing faster than base-case projections assumed. Green hydrogen in India has fallen from USD 7/kg (2022) to USD 3.5–5/kg (2024)—a 30–50% reduction in two years. NITI Aayog's best-case of USD 1.60/kg by 2030 and USD 0.70/kg by 2050 is technically achievable given observed solar cost trajectories (now below USD 0.025/kWh at prime sites), electrolyzer scale-up dynamics, and India's demonstrated manufacturing capability (L&T's ML-400 PEM system) [67, 98, 150, 179].

Second, infrastructure remains the most critical bottleneck. India's renewable energy base is growing at the required pace (223 GW in 2024, on track for 500 GW by 2030). The technology has been demonstrated at pilot scale. What is missing is connective tissue: hydrogen pipelines, storage hubs, refuelling stations, and port export terminals. An estimated USD 80–120 billion of infrastructure investment is required by 2030—10–15× the government's current NGHM outlay—underscoring the critical importance of private sector mobilization and multilateral financing [48, 87, 128, 135, 143].

Third, India's competitive advantage is structural, not cyclical. Solar LCOE below USD 0.025/kWh, abundant coastal land for export hubs, a large existing industrial hydrogen base, and an emerging domestic electrolyzer manufacturing capability together constitute a durable competitive position. However, realizing this advantage requires closing the WACC gap—reducing financing costs from 9–11% to 5–7%—through IREDA lending, multilateral development bank (ADB, World Bank, IFC) co-financing, green bond issuance, and credible long-term offtake frameworks that reduce project revenue risk [93, 118, 128, 143, 144, 179].

The interdependence of barriers deserves special emphasis. High production costs limit demand; limited demand delays infrastructure investment; insufficient infrastructure raises delivered costs; policy uncertainty deters private capital; slower investment prevents cost reduction—a reinforcing negative feedback loop. Breaking this loop requires simultaneous coordinated intervention across cost, infrastructure, and market dimensions. The NGHM represents precisely this kind of integrated intervention, but its financial scale currently lags peer programs in the US and EU by a factor of 10–40× [48, 118, 142, 143, 144].

CONCLUSION

This comprehensive review delivers a statistically supported and analytically structured assessment of hydrogen as a strategic energy transition pathway for India. Drawing on 175 references across government mission documents, international agency projections, peer-reviewed science, and industry analyses, and presenting ten quantitative charts and five creative process diagrams, it characterizes India's hydrogen trajectory across ten dimensions simultaneously — demand, cost, production mix, electrolyzer capacity, sectoral adoption, CO_2 abatement, investment flows, market size, renewable energy growth, and global positioning.

Core findings are unambiguous:

(i) Green hydrogen is on a steep cost reduction curve that will bring it to near cost parity with grey

hydrogen in India by 2030–2035 under favorable policy conditions;

(ii) The 5 MTPA NGHM target is technically achievable but requires a 3–5× amplification of current financial incentives to close the infrastructure gap;

(iii) Fertilizer and refining sectors offer the fastest near-term decarbonization payoffs, while steel, mobility, and shipping define the long-term market;

(iv) India's structural renewable energy advantage—already demonstrated in solar LCOE below USD 0.025/kWh—positions it as a credible candidate for 10% of the global green hydrogen market by 2030.

The cumulative impact is staggering in scale: 3.6 Gt CO_2 abated (2020–2050); a market valued at USD 340 billion by 2050; 600,000+ jobs by 2030; INR 1 lakh crore in fossil fuel import savings by 2030; and a pathway consistent with India's legally committed net-zero target of 2070. Realizing this opportunity—for India and for global climate stability—requires the urgency, scale, and coordinated application of policy, investment, technology, and international partnership that this review has comprehensively mapped.

REFERENCES

1. D. Das, T.N. Veziroğlu, *Int. J. Hydrogen Energy*, **26** (5), 437 (2001).
2. A. Züttel, *Nature*, **414** (6861), 353 (2003).
3. G. W. Crabtree, et al., *Physics Today*, **57** (12), 39 (2004).
4. J. A. Turner, *Science*, **305** (5686), 972 (2004).
5. M. Z. Jacobson, et al., *Science*, **308** (5730), 1901 (2005).
6. R. Kothari, et al., *Renew. Sustain. Energy Rev.,* **12** (8), 1909 (2008).
7. D. Moher, et al., *PLOS Medicine*, **6** (7), e1000097 (2009).
8. N. J. van Eck, L. Waltman, *Scientometrics*, **84** (2), 523 (2010).
9. E. Cetinkaya, et al., *Int. J. Hydrogen Energy,* **37** (3), 2071 (2012).
10. A. Ursúa, et al., *Proc. IEEE*, **100** (2), 410 (2012).
11. J. O. M. Bockris, *Int. J. Hydrogen Energy*, **38**, 2579 (2013).
12. M. Carmo, D. L. Fritz, J. Mergel, D. Stolten, *Int. J. Hydrogen Energy*, **38**, 4901 (2013).
13. C. Acar, I. Dincer, "Comparative assessment of hydrogen production methods", *Int. J. Hydrogen Energy*, **39**, 1–12 (2014).
14. H. W. Langmi, J. Ren, B. North, M. Mathe, D. Bessarabov, *Electrochim. Acta*, **128**, 368 (2014).
15. I. Dincer, C. Acar, *Int. J. Hydrogen Energy*, **40**, 11094 (2015).
16. M. Schalenbach, G. Tjarks, M. Carmo, W. Lueke, M. Mueller, D. Stolten, *J. Electrochem. Soc.*, **163**, F3197 (2016).
17. Ministry of Steel, Government of India, *National Steel Policy 2017*, New Delhi, 2017.
18. N. Muradov, in *Compendium of Hydrogen Energy*, Vol. 1, R. Basile, A. Basile, T. N. Veziroglu (Eds.), Woodhead Publishing, Cambridge, pp. 45–76 (2017).
19. P. Nikolaidis, A. Poullikkas, *Renew. Sustain. Energy Rev.*, **67**, 597 (2017).
20. P. Preuster, C. Papp, P. Wasserscheid, *Acc. Chem. Res.*, **50**, 74 (2017).
21. E. S. Hanley, J. P. Deane, B. P. Ó Gallachóir, *Renew. Sustain. Energy Rev.*, **82**, 3027 (2018).
22. J. O. Abe, A. P. I. Popoola, E. Ajenifuja, O. M. Popoola, *Int. J. Hydrogen Energy*, **44**, 15072 (2019).
23. P. Capros, D. Van Regemorter, L. Paroussos, P. Karkatsoulis, C. Fragkiadakis, S. Tsani, I. Charalampidis, T. Revesz, *Energy Policy*, **134**, 110960 (2019).
24. S. S. Kumar, V. Himabindu, *Mater. Sci. Energy Technol.*, **2**, 442 (2019).
25. G. Maggio, G. Nicita, G. Squadrito, *Int. J. Hydrogen Energy*, **44**, 11371 (2019).
26. J. W. Makepeace, T. He, C. Weidenthaler, T. R. Jensen, F. Chang, M. Vegge, P. Ngene, Y. Kojima, P. E. de Jongh, P. Chen, W. I. F. David, *Int. J. Hydrogen Energy*, **44**, 7746 (2019).
27. R. Moradi, K. M. Groth, *Int. J. Hydrogen Energy*, **44**, 12254 (2019).
28. E. Rivard, M. Trudeau, K. Zaghib, *Materials*, **12**, 1973 (2019).
29. I. Staffell, D. Scamman, A. V. Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah, K. R. Ward, *Energy Environ. Sci.*, **12**, 463 (2019).
30. A. Boretti, *Int. J. Hydrogen Energy*, **46**, 2367 (2021)
31. F. Dawood, M. Anda, G. M. Shafiullah, *Int. J. Hydrogen Energy*, **45**, 3847 (2020).
32. A. Hauch, S. D. Ebbesen, S. H. Jensen, M. Mogensen, *Science*, **370**, eaba6118 (2020).
33. S. E. Hosseini, B. Butler, *Int. J. Green Energy*, **17**, 13 (2020).
34. S. Krishnan, S. S. Kumar, V. Himabindu, *Energy Sources A: Recovery Util. Environ. Eff.*, **42**, 1351 (2020).
35. A. Nadar, S. S. Kumar, V. Himabindu, *Int. J. Hydrogen Energy*, **45**, 12691 (2020)
36. A. Pareek, S. S. Kumar, V. Himabindu, *Mater. Sci. Energy Technol.*, **3**, 319 (2020).
37. A. M. Elberry, M. A. Eldean, A. A. Elsayed, *Int. J. Hydrogen Energy*, **46**, 15671 (2021).
38. Hydrogen Insights 2021*,* Hydrogen Council, Brussels, 2021.
39. Hydrogen for Net Zero, Hydrogen Council and McKinsey & Company, Brussels, 2021.
40. *The Indian Express*, "Pune Labs: Hydrogen from Agri-Residue", 2021.
41. Indian Oil R&D Centre, Indian Institute of Science, Oxy-Steam Biomass Gasification, BioEnergy International, 2021.
42. Indian Institute of Technology Kharagpur, Hydrogen by Biological Routes, IIT Kharagpur Repository, 2021.

43. Indian Institute of Technology Hyderabad, H_2S Decomposition; CO_2 to Syngas via Plasma, IIT Hyderabad Repository, 2021.
44. Making Green Hydrogen a Cost-Competitive Climate Solution, *International Renewable Energy Agency (IRENA), Abu Dhabi, 2021.*
45. *The Telegraph*, "IIT-BHU: India's First Ultra-Pure On-Site H_2 Device", 2021.
46. Government of Andhra Pradesh, Andhra Pradesh Green Hydrogen Policy 2022, Amaravati, 2022.
47. Bureau of Indian Standards (BIS), Standards for Hydrogen Energy Systems, New Delhi, 2022.
48. Council on Energy, Environment and Water (CEEW), Boosting Investments for Domestic Green Hydrogen, New Delhi, 2022.
49. Central Electricity Authority (CEA), National Electricity Plan 2022–2032, New Delhi, 2022.
50. CSIR-National Environmental Engineering Research Institute (NEERI), Liquid Organic Hydrides for H_2 Supply, Nagpur, 2022.
51. Energy Transitions Commission (ETC), Making the Hydrogen Economy Possible, London, 2022.
52. Fertiliser Association of India (FAI), Annual Statistics 2021–22, New Delhi, 2022.
53. Global CCS Institute, Global Status of CCS 2022, Melbourne, 2022.
54. Bharat Petroleum Corporation Limited (BPCL), Sustainability Report 2021–22, Mumbai, 2022.
55. Greenko Group, Greenko–John Cockerill 2 GW Electrolyzer Factory, LiveMint report, 2022.
56. International Energy Agency (IEA), Hydrogen in Industry: Challenges and Opportunities, Paris, 2022.
57. Indian Institute of Technology Guwahati, Biohydrogen from Lignocellulosic Biomass, Guwahati, 2022.
58. Indian Institute of Technology Kanpur, PEC Wastewater Splitting and Fuel Cells, Kanpur, 2022.
59. Indian Register of Shipping, Provisional Guidelines – Fuel Cell Vessels, Mumbai, 2022.
60. IPCC, Climate Change 2022: Mitigation of Climate Change (AR6 WG-III), Cambridge University Press, Cambridge, 2022.
61. International Renewable Energy Agency (IRENA), Green Hydrogen Cost Reduction: Scaling Up Electrolysers, Abu Dhabi, 2022.
62. M. Kumar, A. Sharma, R. Singh, NPG Asia Mater., 14, 88 (2022).
63. J. Mathur, S. Mungla, Renew. Sustain. Energy Rev., 156, 112014 (2022).
64. McKinsey & Company, Decarbonising Shipping: All Hands on Deck, McKinsey Sustainability, 2022.
65. Ministry of New and Renewable Energy (MNRE), Government of India, National Hydrogen Energy Roadmap, New Delhi, 2022.
66. Ministry of Road Transport and Highways (MoRTH), AIS-157: Safety Requirements for Compressed H_2 Fuel Cell Vehicles, New Delhi, 2022.
67. NITI Aayog, Harnessing Green Hydrogen: Opportunities for Deep Decarbonisation in India, New Delhi, 2022.
68. NITI Aayog, Rocky Mountain Institute (RMI), India's Energy Transition Pathways 2030/2050, New Delhi, 2022.
69. Rocky Mountain Institute (RMI), NITI Aayog, Green Hydrogen in India: Opportunity and Pathways, New Delhi, 2022.
70. Society of Indian Automobile Manufacturers (SIAM), Hydrogen Roadmap for Automotive Sector in India, New Delhi, 2022.
71. Sardar Patel Renewable Energy Research Institute (SPRERI), Annual Report 2021–22: Biomass Gasification, Vallabh Vidyanagar, 2022.
72. The Energy and Resources Institute (TERI), Bio-Resources for Low-Carbon Bio-Hydrogen, New Delhi, 2022.
73. World Economic Forum (WEF), Hydrogen for Net Zero: India's Pathway, Geneva, 2022.
74. World Steel Association, Steel's Contribution to a Low Carbon Future, Brussels, 2022.
75. World Bank, Green Hydrogen in Developing Countries, World Bank Group, Washington, DC, 2022.
76. Adani New Industries Ltd., Green Hydrogen and Renewable Energy Investment Plan, Ahmedabad, 2023.
77. ACME Group, Green Ammonia and Hydrogen Projects, Gurugram, 2023.
78. Ashok Leyland Ltd., *Project HEMA:* Hydrogen Commercial Vehicles, Chennai, 2023.
79. BloombergNEF, Hydrogen Economy Outlook 2023, London, 2023.
80. Department of Fertilisers, Ministry of Chemicals and Fertilizers, Government of India, Annual Report 2022–23, New Delhi, 2023.
81. European Commission, REPowerEU: Hydrogen Import Strategy, Brussels, 2023.
82. Florence School of Regulation, The Green Hydrogen Economy: Insights from India, European University Institute, Florence, 2023.
83. Gujarat State Electricity Corporation Ltd. (GSECL), Renewable Energy-Powered Green Hydrogen Hubs in Gujarat, Vadodara, 2023.
84. GreenH Technologies, 1000 MW PEM Electrolyzer Plant in India, Bengaluru, 2023.
85. Greenko Energy Holdings, Green Hydrogen Production Targets, Hyderabad, 2023.
86. Hydrogen Council, Hydrogen Insights *2023*, Brussels, 2023.
87. India H_2 Alliance (IH2A), Industry Coalition for Net-Zero Hydrogen, New Delhi, 2023.
88. Indian Ports Association, Green Hydrogen Bunkering Infrastructure, New Delhi, 2023.
89. International Register of Shipping (IRS), Hydrogen Safety Codes for Maritime Applications, London, 2023.
90. International Energy Agency (IEA), *Global Hydrogen Review 2023*, Paris, 2023.
91. International Energy Agency (IEA), Net Zero by 2050: A Roadmap for the Global Energy Sector, Paris, 2023.

92. International Energy Forum (IEF), India's Green Hydrogen Mission: Economic Analysis, Riyadh, 2023.
93. Asian Development Bank (ADB), Accelerating the Hydrogen Economy in South and Southeast Asia, Manila, 2023.
94. ONGC Energy Centre, Indian Institute of Technology Delhi, *IS Thermochemical Cycle*, *SPGIndia Proceedings*, 2023.
95. Indian Institute of Technology Madras, Hydrogen from Seawater Using Solar Energy, Chennai, 2023.
96. International Maritime Organization (IMO), IMO's Work to Cut GHG Emissions from Ships, London, 2023.
97. International Renewable Energy Agency (IRENA), Global Hydrogen Trade to Meet the 1.5°C Climate Goal, Abu Dhabi, 2023.
98. International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2022, Abu Dhabi, 2023.
99. JSW Steel Ltd., Sustainability Report 2022–23: Pathway to Green Steel, Mumbai, 2023.
100. Kochi Metro Rail Ltd. (KMRL), Hydrogen Train Feasibility Study, Kochi, 2023.
101. Larsen & Toubro, Defence Research and Development Organisation (DRDO), Air-Independent Propulsion for Indian Navy, Mumbai, 2023.
102. V. Jiman, *India*–US Green Hydrogen Collaboration Overview, LinkedIn article, 2023.
103. McKinsey & Company, Global Energy Perspective 2023: Hydrogen Outlook, New York, 2023.
104. McKinsey Global Institute, India's Turning Point: An Economic Agenda to Spur Growth and Jobs, New Delhi, 2023.
105. Ministry of New and Renewable Energy (MNRE), Government of India, National Green Hydrogen Mission Policy Document, New Delhi, 2023.
106. Ministry of New and Renewable Energy (MNRE), Government of India, R&D Roadmap for Green Hydrogen Ecosystem in India, New Delhi, 2023.
107. Ministry of Petroleum and Natural Gas (MoPNG), Government of India, Draft National Policy on Repurposing Gas Pipelines for Hydrogen, New Delhi, 2023.
108. Maharashtra State Electricity Distribution Co. Ltd. (MSEDCL), Green Hydrogen Integration with Grid: Maharashtra Roadmap, Mumbai, 2023.
109. R. Nagar, B. P. Vinayan, N. Rajalakshmi, S. Ramaprabhu, *Int. J. Hydrogen Energy*, **36**, 8822 (2011).
110. NTPC Ltd., India's First Green Hydrogen Blending in PNG, Press Release, 4 January 2023, New Delhi.
111. NTPC Renewable Energy Ltd., Green Hydrogen Strategy, New Delhi, 2023.
112. Odisha Renewable Energy Development Agency (OREDA), Green Hydrogen Hub Feasibility: Paradeep and Gopalpur, Bhubaneswar, 2023.
113. Observer Research Foundation (ORF), India–EU Green Hydrogen Partnership, New Delhi, 2023.
114. ONGC Energy Centre, Strides in Green Hydrogen Production, New Delhi, 2023.
115. Petroleum and Explosives Safety Organisation (PESO), Regulations for Storage and Handling of Hydrogen, Nagpur, 2023.
116. Petroleum and Natural Gas Regulatory Board (PNGRB), Technical Standards for Hydrogen–Natural Gas Blending, New Delhi, 2023.
117. S. A. Rawool, M. S. Akula, P. V. Korake, R. B. Mane, B. M. Thombare, S. B. Shrivastava, in: Handbook on Advanced Materials, A. K. Sharma, R. K. Mishra (eds.), Springer, 2023, p. 345.
118. Reserve Bank of India, Report on Currency and Finance 2022–23: Towards a Greener India, Mumbai, 2023.
119. Reliance Industries Ltd., New Energy – Stiesdal Partnership, Mumbai, 2023.
120. ReNew Power, *Green Hydrogen and Ammonia Projects Pipeline*, Gurugram, 2023.
121. Rajasthan Renewable Energy Corporation Ltd. (RRECL), Rajasthan Green Hydrogen Strategy and Incentive Policy, Jaipur, 2023.
122. Steel Authority of India Ltd. (SAIL), Sustainability Report 2022–23, New Delhi, 2023.
123. Indian Oil Corporation Ltd. (IOCL), First Green Hydrogen-Powered Bus in Delhi, Press Release, September 2023, New Delhi.
124. Shell International, Shell Hydrogen Study: Energy of the Future, The Hague, 2023.
125. Siemens Energy, Hydrogen Solutions for India, Erlangen, 2023.
126. P. Sun, Z. Yuan, Y. Zhang, J. Wu, *Energy Rep.*, **9**, 3612 (2023).
127. Ministry of Finance, Government of India, Union Budget 2023–24: Green Hydrogen and Clean Energy Allocations, New Delhi, 2023.
128. International Finance Corporation (IFC), World Bank Group, Financing Green Hydrogen in Emerging Markets, Washington, DC, 2023.
129. United Nations Development Programme (UNDP), Hydrogen Futures: Powering Sustainable Development in the Global South, New York, 2023.
130. U.S. Department of Energy, Technical Targets for PEM Fuel Cell Components, Washington, DC, 2023.
131. Tamil Nadu Energy Development Agency (TEDA), Green Hydrogen Hub: Tamil Nadu Coastal Policy, Chennai, 2023.
132. Tata Steel Ltd., Green Steel Roadmap: Hydrogen in DRI Production, Mumbai, 2023.
133. P. A. Thakar, V. Bhojak, Energy Fuels, **37**, 2896 (2023).
134. thyssenkrupp Uhde India Pvt. Ltd., Green Hydrogen: Benefits to Economy and Environment, Gurugram, 2023.
135. Government of India, Ministry of New and Renewable Energy, National Green Hydrogen Mission: Mission Document, New Delhi, 2023.
136. BP plc, BP Energy Outlook 2023: India Country Insights, London, 2023.

137. ABB Group, Electrification and Green Hydrogen: India Market Overview, Zürich, 2024.
138. ACME Solar Holdings Ltd., Annual Report 2023–24, Gurugram, 2024.
139. Amara Raja Energy & Mobility Ltd., India's First Hydrogen Refuelling Station – Leh, Ladakh, Press Release, November 2024.
140. Ballard Power Systems, FCmove-HD+ Technical Data Sheet, Burnaby, Canada, 2024.
141. BloombergNEF, Hydrogen Market Outlook 2024, London, 2024.
142. *Business Standard*, "UP Secures INR 1.15 Trillion Investment in Green Hydrogen", 2024.
143. CapstonesDC, India's Hydrogen Sector Primed for Foreign Investment, 2024.
144. Council on Energy, Environment and Water (CEEW), Boosting Investments for Domestic Green Hydrogen Financing, New Delhi, 2024.
145. CNBC TV18, India–EU Boost Ties with Extensive Green Hydrogen Roadmap, 2024.
146. F. Dawood, G. M. Shafiullah, M. Anda, *Energy Convers. Manage.*, **315**, 118856 (2024).
147. Deendayal Port Authority, Green Hydrogen Export Hub – Kandla, Gandhidham, 2024.
148. *The Economic Times*, "IIT Indore Catalyst for Hydrogen from Methanol", 2024.
149. Federation of Indian Petroleum Industry (FIPI), Hydrogen Market Report 2023, New Delhi, 2024.
150. GAIL (India) Ltd., Green Hydrogen Plant Commissioning, Press Release, 24 May 2024, New Delhi.
151. A. Ghimire, L. Frunzo, F. Pirozzi, E. Trably, R. Escudié, P. N. L. Lens, G. Esposito, *Bioresour. Technol.*, **399**, 130750 (2024).
152. GreenH Mobility, India's First Hydrogen Refuelling Station – Leh, Ladakh, Bengaluru, 2024.
153. Global Wind Energy Council (GWEC), India Wind Energy Market Outlook 2024–2028, Brussels, 2024.
154. Institute for Energy Economics and Financial Analysis (IEEFA), Enabling Sustainable Demand for Green Hydrogen in India, 2024.
155. National Green Hydrogen Mission (NGHM), Overview – Production Targets and Key Statistics, Ministry of New and Renewable Energy, New Delhi, 2024.
156. India Brand Equity Foundation (IBEF), Hydrogen Energy in India: National Green Hydrogen Mission Roadmap, New Delhi, 2024.
157. International Energy Agency (IEA), World Energy Investment 2024, Paris, 2024.
158. Indian Railways, Ministry of Railways, Hydrogen for Heritage: Hydrogen DEMU Specifications, New Delhi, 2024.
159. International Renewable Energy Agency (IRENA), Quality Infrastructure Roadmap for Green Hydrogen, Abu Dhabi, 2024.
160. K. Domen, Q. Wang, *Nat. Energy*, **9**, 112 (2024).
161. Larsen & Toubro Ltd., Annual Report 2023–24, Mumbai, 2024.
162. X. Li, J. Ogden, *Energy Policy*, **142**, 111498 (2020).
163. Mahindra Last Mile Mobility Ltd., Hydrogen Fuel Cell Commercial Vehicle Strategy, Mumbai, 2024.
164. MarkNtel Advisors, India Green Hydrogen Market 2026–2032, New Delhi, 2024.
165. National Renewable Energy Laboratory (NREL), Hydrogen and Fuel Cell Technologies Office Annual Progress Report 2024, Golden, CO, USA, 2024.
166. A. I. Osman, N. Mehta, A. M. Elgarahy, M. Hefny, A. Al-Hinai, A. H. Al-Muhtaseb, D. W. Rooney, *Environ. Chem. Lett.*, **22**, 1 (2024).
167. NTPC Ltd., Annual Report 2023–24, New Delhi, 2024.
168. Press Information Bureau (PIB), Government of India, India's Green Hydrogen Revolution: An Ambitious Approach, New Delhi, 2024.
169. Y. K. Salkuyeh, B. A. Saville, H. L. MacLean, *Renew. Sustain. Energy Rev.*, **193**, 114312 (2024).
170. R. Sawhney, Decoding India's Green Hydrogen Potential, ORF America Background Paper No. 20, Washington, DC, 2024.
171. Solar Energy Corporation of India (SECI), Tender for Green Hydrogen Production Units 2024, New Delhi, 2024.
172. Tata Motors Ltd., Hydrogen Fuel Cell Bus Programme, Pune, 2024.
173. The Hydrogen Energy, India's Hydrogen Train – Technical Details, 2024.
174. U.S. Commercial Service, India Green Hydrogen Market Intelligence, Washington, DC, 2024.
175. World Economic Forum (WEF), Green Hydrogen: Enabling Measures Roadmap for India, Geneva, 2024.
176. X. Wei, F. Song, J. Teng, J. Zheng, S. Zhu, K. Wang, X. Zhi, S. Bao, L. Qiu, *Int. J. Hydrogen Energy,* **109**, 67 (2025).
177. J.-H. Wang, Y.-F. Li, C.-M. Feng, *Renew. Energy,* **240**, 121982 (2025).
178. French Institute of International Relations (IFRI), India's Green Hydrogen Strategy in Action, Paris, 2025.
179. Larsen & Toubro Ltd., First Indigenously Manufactured Electrolyser at Hazira, Press Release, 1 March 2025.
180. Sustainable Future, Opportunities and Limits of India's Green Hydrogen Pursuit, *2025*.