"THE EVOLVING JOURNEY OF GREEN HYDROGEN IN INDIA'S PROGRESS TOWARDS NET-ZERO CARBON EMISSIONS"

Research Paper

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"Abstract"

"Green Hydrogen" (GH2) is becoming one of the main pillars of the Government's goal of becoming Energy independent by 2047 and achieving Net-Zero Carbon Emissions in India by 2070. Towards this in 2023, "National Green Hydrogen Mission" (NGHM) was initiated with the target of producing 5 million metric tonnes a year by 2030. This initiative is supported by substantial Government funding to help reduce the reliance on hard-to-abate industries (such as steel, cement, and transport) and fossil fuels. As noted in this work, despite the strategic guidance presented by Policy frameworks and incentives, what is limiting faster progress are implementation gaps, regulatory ambiguity, and infrastructure limitations. Central to industry preparedness is technological innovation, financial stability, and trained manpower. With effective financial instruments like Green bonds, the risks of investment can be mitigated. Challenges include the high cost of capital, land acquisition, physical disintegration, insufficient R&D, enforced Policy implementation, increased financial infrastructure, employee training, scalable storage, and a high level of safety, among others.

Keywords: Green Hydrogen, Energy Transition, Net-Zero Emissions, Infrastructure Development, Policy Implementation.

1 Introduction

The rapid economic development and massive population growth in India have created unprecedented demands on the energy sector, heightening the urgency of the problems surrounding the long-term viability of the energy industry and the maintenance of a consistent and trustworthy electricity grid. Fossil fuels such as coal, oil, and natural gas account for the vast majority of the world's energy consumption and are a major contributor to the escalating "greenhouse gas" (GHG) levels (Von Zabeltitz, 1994). opines that ambitious economic growth plans by the Government are quickly expanding the Country's energy use, and thus a well built and cleaner power structure is pivotal to supporting improvement in the living standard. The Ministry of Power has a road map of how energy can be delivered efficiently and cost-effectively across the country through the National Energy Plan (NEP). India is now the third-largest producer of energy-related CO_2 emissions, at 6.99% of the global total, ranking it (alongside China, 32.88%, and the USA% with 12.6 %) as one of the key players in the global climate action. "Climate change" (CC) not only starts to manifest itself as something that can upset the ecological balance of the planet, but it also gives rise to such multi-billion investments and Policy commitments as the Paris Agreement and the UN Framework Convention on Climate Change (UNFCCC) to ensure that the increase in the temperature will not exceed 2degrees C (Aggarwal, 2017). The need of finding new ways to generate electricity is highlighted by the World Energy Council's prediction that the world's energy sources would be exhausted by 2030.

As a result of its low coal reserves, which make the fuel expensive and vulnerable to energy price surges, India depends heavily on coal imports. According to the International Energy Agency, 80.9%

of the world's energy comes from fossil fuels, and in fiscal year 24 (FY24), India imported 268.24 million metric tonnes of coal (The Economic Times, 2024). Sustainable development and the avoidance of catastrophic climate change are thus seen as dependent on the adoption of "Renewable Energy" (RE) technology. "Renewable energy sources" (RES) such as solar, wind, biomass, waste, and hydropower are crucial in meeting both the electrical demand and the goal of reducing emissions. The Indian Government as well as investors are pushing for ambitious RE goals, with 500 GW of total capacity, 280 GW of solar, 140 GW of wind, 50 GW of biomass, and 70 GW of hydropower projected for the Country. By 2047, solar and wind power are expected to have significantly increased in capacity (Sholapurkar and Mahajan, 2015). The 175 GW renewables target alone would create approximately 330,000 jobs, and Policy development to promote technology uptake via rule-making, incentives, research and development as well as industry-specific interventions (Harrison and Kostka, 2014; Khare, Nema and Baredar, 2013; Schmid, 2012; Shukla, Sudhakar and Baredar, 2017).

Due to these shifts, Hydrogen and more specifically, GH2 produced by RE is rising to the ranks of the most crucial components of decarbonisation and sustainable energy. In countries that aim to attain net-zero emissions by 2050, Hydrogen is considered as a crucial component for industries like chemicals, heating, transportation, and steel that aren't well-suited to directly use electricity (King, 2021). At its current rate of use, Hydrogen accounts for less than 1% of all energy, but experts predict that this will increase rapidly to 10% by 2050 (Dong et al., 2022; Ishaq, Dincer and Crawford, 2022). But production and decarbonisation efficiency must rise if hydrogen is to join the net-zero transition. Nearly 80% of the world's 90 million tonnes of hydrogen production comes from fossil fuels. This results in 900 million tonnes of CO_2 equivalent, which is comparable to the combined output of the UK and Indonesia (Pollitt and Kong Chyong, 2022; Slorach and Stamford, 2021). It is imperative that India, an energy-hungry nation with ambitious hydrogen plans, considers the carbon intensity of hydrogen generation to ensure the sustainability of its expansion. Electrolysis and carbon capture, utilisation, and storage (CCUS) will play a larger role in the Global hydrogen supply under net-zero conditions; low-carbon systems will account for 70% of hydrogen generation by 2030 and nearly all of it by 2050 (Yan et al., 2020). With the possibility of reaching 3,600 GW by 2050, electrolysis has the ability to reduce CO2 emissions by as much as 60 gigatonnes (Ampah, Jin, Liu, et al., 2024; Fuhrman et al., 2023).

This increased political agreement, led by the Paris Accord, acknowledges the urgency to take action on climate the energy sector, which emits three-quarters of all GHGs, is at the heart of the shift (Rajamani and Werksman, 2018; Sokołowski, 2022). A net-zero emissions goal by 2050 requires an energy production and consumption behaviour seismic change, exploiting hydrogen, renewables, energy efficiency, and CCUS. The commitment of countries to be carbon neutral by 2040-2070 demonstrates the gravity of the task (Ampah, Jin, Liu, et al., 2024; Fuhrman et al., 2023). As a renewably powered electrolysis product, GH2 has the potential to revolutionize the journey of India to Net-Zero. The projected hydrogen demand will be more than 500 percent higher than 2020 by 2050 and will necessitate large-scale expansion of renewable-driven hydrogen facilities (Ampah, Jin, Afrane, et al., 2024). Leveraging falling wind and solar power prices, new paradigms of decarbonization are taking shape; however, economic feasibility, technological maturity, policy frameworks, and safety guarantees remain obstacles to scaling up to massive levels (Jamasb, 2017; Mitchell, 2016). The rate of increase in energy demand in India is exceeding any other major economy, where coal remains the primary and renewables as the secondary one. India is projected to leave behind all other countries in the energy consumption growth, as the energy requirement in RE is expected to rise not only by the current 17 Mtoe of RE in 2016, but also by the rate of 12 percent every year (Kumar and Majid, 2020). As the growth of power consumption in residential, commercial, agricultural, and manufacturing sectors during urbanization and industrialization increases the gap between the supply and demand, there is a continuing challenge to bridge the gap (Arto et al., 2016; IRENA, 2017).

NGHM is the flagship project of the Indian Government, with the aim of spurring local production of electrolysers, ramping up renewable hydrogen production, and encouraging its use in industries. With an initial investment of INR19,744 crore, the mission has a vision of attaining the goals of 2030 of producing 5 million metric tonnes (MMT) GH per year, generating an economic output of more than 8 lakh crores, creating 600,000 new jobs, decreasing fossil fuel imports by more than 1 lakh crore, and cutting the amount of annual GHG emissions by approximately 50 MMT. The NGHM strategy is gradual and initially includes demand stimulation, domestic production of electrolysers, pilot programs in steel, mobility, and shipping, as well as the establishment of regulatory prerequisites. The second level is associated with cost competitiveness, commercial project scaling, and augmented R&D activity. It will require a coordinated response at the Ministries, agencies, the public and the private sectors, all supported by incentive systems, supply interventions and infrastructure building (Pandey and Kumari, 2023).

Despite its transformative promise, GH2 faces significant challenges. Production is energy-intensive, necessitating ramped-up renewable capacity (an additional 125 GW by 2030) to meet projected targets, while the pace of capacity growth needs acceleration (Koshy, 2023). Electrolysers, if powered by the traditional coal-heavy grid during intermittent RE supply, risk undermining environmental benefits (Harichandan, Kar and Rai, 2023). Economic viability depends on technological advances, scale economies, and supportive policies, as production costs must fall to compete with fossil fuels (Madheswaran et al., 2024). Safety risks stemming from hydrogen's volatility, demand robust handling protocols, infrastructure investments, and industry readiness.

The potential indirect greenhouse effect of hydrogen emissions, through their interaction with atmospheric chemistry, further underscores the need for comprehensive monitoring and mitigation. A successful GH2 transition requires technology advancement, strategic policymaking, financial sustainability, and vigilant environmental stewardship.

The study examines the potential of GH2 to help India achieve net-zero emissions by 2070, specifically focusing on the obstacles to commercialization and the strategic routes to adoption. Policy efficacy, industry preparedness, infrastructural sufficiency, financial models, scalability, and safety precautions are among the key questions investigated. The study's overarching goal is to help India meet its sustainability goals and become a leader in the clean energy industry by facilitating the greater use of GH2 in the Country's energy and industrial sectors through the integration of literature synthesis, policy analysis, and stakeholder perspectives.

2 Literature Review

2.1 Green hydrogen In the context of India's energy transition

GH2 has emerged as a pivotal component of India's decarbonization pathways, recognized for its role in transforming hard-to-abate sectors, including fertilizers, steel, and long-haul transportation (Tongia and Patel, 2024). articulate that GH's primary objective is the reduction of carbon emissions across these key sectors, and India aims to significantly scale up production to 5 million tonnes annually by 2030, an ambitious leap from today's almost negligible quantities. India's current hydrogen production, approximately 6 Mtpa, is generated through the steam reforming of natural gas, with most of it used in fertilizer manufacturing and oil refining, both of which are highly carbon-intensive when relying on fossil fuels. Although the cost trajectory for GH is downward, even optimistic projections suggest it will remain above $2/kg by 2030 well above the often-cited $1/kg global competitiveness target. The declining price hinges on reductions in renewable electricity (RE) supply costs, improved electrolyser efficiency, and government incentives (notably through NGHM. Strategic interventions, including capital incentives and policy-driven waivers—like those for RE transmission, can further reduce production costs, but broader challenges of infrastructure, water supply, and market readiness remain substantial.

Multiple scholars reinforce GH's status as a carbon-neutral fuel, emphasizing its pivotal role in cutting greenhouse gas (GHG) emissions and facilitating sustainable growth, especially for developing nations like India, where RE potential is vast yet industrialization and population growth fuel escalating energy demand. (Gupta, Kumar and Kumar, 2024) stress the multi-dimensional benefits of GH, ranging from social acceptance and technical viability to economic and policy considerations. Analytical approaches—such as AHP, fuzzy-AHP, and DEMATEL have identified social and Policy aspects as the most influential in determining GH's adoption, highlighting the need for robust regulatory and market frameworks. Despite Government intent and industrial interest, adoption faces substantial obstacles (Dixit et al., 2024). Use fuzzy Interpretive Structural Modelling (ISM) to explain that "Technological Immaturity," lack of regulatory clarity, and "Policy Inconsistencies" are fundamental barriers that must be systematically addressed. Overcoming these challenges requires coordinated effort from Policymakers, industry players, and financiers, alongside dedicated R&D for scalable, cost-effective solutions. (Ghosh and Roy, 2024) underscore the strategic scale of India's GH ambitions, which include a planned investment of INR 19,744 crores (about $2.3 billion) to achieve energy independence by 2047 and net-zero emissions by 2070, asserting the necessity of integrated, adaptive policy frameworks driven by both national vision and local action.

Regional efforts are thus emerging as critical. (Janardhanan, Zusman and Moinuddin, 2024) emphasize that while India's Central Government sets the overall Hydrogen agenda, State Governments are vital for on-the-ground implementation, including employment generation, infrastructure development, and fostering local innovation. They advocate a six-point cooperation plan, covering skills enhancement, infrastructure, demand incentives, investment facilitation, R&D, and co-innovation, reflecting the multi-stakeholder nature of a GH-led transition. At the macro scale, GH is increasingly embedded in India's decarbonization discourse, complementing electrification and renewables to mitigate carbon intensity and strengthen energy security. Its trajectory is inextricably linked to regulatory progress, technological maturation, finance mobilization, and integration across sectors.

2.2 Policy initiatives, incentives and public-private partnerships

India's policy push towards a GH2 economy is headlined by NGHM, which establishes a framework for production, consumption, and export. By 2047, the Nation aims for Energy independence, and by 2070, to attain Net-Zero Emissions, with GH anticipated as a linchpin for both goals. The NGHM is rooted in an initial funding outlay of ₹19,744 crore, targeting the development of at least 5 million metric tonnes of annual GH output, substantial economic value creation, job generation, import reduction, and GHG reduction. The Mission's Policy and incentives portfolio includes Production-Linked Incentives (PLI) for domestic electrolyser and GH manufacturing, subsidies, demand-driven procurement frameworks, and a strong emphasis on quality and performance standards (Ministry of New and Renewable Energy, 2023). Through competitive bidding, strict certification standards, and targeted incentives, the Government aims to achieve cost and quality advantages—critical levers for stimulating private and foreign investment in the sector.

A distinguishing feature of India's approach is the integration of strategic Public-Private Partnerships (PPPs), which drive innovation, infrastructure development, and commercial demonstration. Strategic Hydrogen Innovation Partnerships (SHIPs) and dedicated R&D funds are being established to solve bottlenecks across the GH2 value chain. This multi-pronged coordination spans technical barriers (e.g., storage, transport), demand-side markets, and context-specific deployment challenges. The collaboration of industry leaders (such as Larsen & Toubro, Adani, Reliance Industries, Greenko) with public agencies has committed billions to projects spanning RE generation, electrolyser manufacturing, and hydrogen hubs. State-level coalitions such as Kerala's Kochi GH Hub, are anchoring regional industrial ecosystems for GH, with targeted applications in transportation, industry, and export. International alliances, for example, between Total Energies and Adani Green Energy, illustrate the global traction and knowledge transfer that fortify India's domestic capabilities and ambitions.

Yet, as highlighted in Policy workshops (e.g., the Indo-German Energy Forum), persistent challenges around cost structures, technology, and infrastructure must be addressed through both Policy design and collaborative investment. Frameworks such as the India Hydrogen Alliance (IH2A) have proposed multi-billion dollar development blueprints for hydrogen hubs and supply chains, underscoring the scale and urgency of coordinated public-private action needed for successful GH market creation and international competitiveness.

2.3 Socio-economic, environmental and sectoral impacts

Beyond technical feasibility and policy design, the literature emphasizes the wider socio-economic and sectoral ramifications of GH adoption in India. (Verma, Sharma and Mehta, 2024) find that Hydrogen, due to its superior energy density, non-toxicity, and zero-carbon end use when generated from renewables, is an attractive substitute for fossil fuels across multiple sectors. In India, the majority of current hydrogen consumption is in the production of chemicals and metals, with a minor but rapidly growing share envisioned for transportation, backup power, and distributed energy solutions. Analysis by (Maurya, Ghosh and Gunawat, 2024) and (Bhattacharyya et al., 2022) indicates that the integration of GH—and by extension, renewables—enables not just decarbonization but also substantial secondary benefits: job creation, energy independence, and long-term fiscal savings by offsetting fossil fuel imports. The clean energy expansion could help India avoid up to $240 billion in fossil fuel costs by 2047, saving consumers an estimated $2.5 trillion and averting millions of premature deaths from air pollution. Additional studies stress GH's potential to drive distributed energy access, especially in rural and remote communities, via microgrids and localized RE integration (Ministry of New and Renewable Energy, 2023; Roy, Bhowmik and Roskilly, 2024).

However, sector-specific analyses reveal critical nuances. Heavy industry, long-haul transport, and the power sector are the largest potential consumers of GH2, and each confronts unique decarbonization, technological, and infrastructure hurdles (Yesodharan et al., 2024). While coal dominates as an energy source for heavy industry, decarbonization efforts including GH fuel substitution, CCUS, and hybrid RE strategies, must be tailored to process requirements and supply logistics. (Jayakumar et al., 2022) elaborate on the need for a national hydrogen roadmap in transport, noting hurdles in supply-chain buildout, cost competitiveness (especially for fuel cell vehicles), and safety standards. The case for GH2 in transportation is strong, especially for long-haul shipping and aviation, but requires cost reductions, infrastructure development, and regulatory clarity.

Globally, GH2 is seen as a catalyst for not just environmental but also social and economic transformation. Research by (Sharma et al., 2023) and (Mneimneh et al., 2023) attest to GH's capacity to enable "just transitions," including new Green job opportunities, upskilling for affected workers, and sustainable rural development provided there is proactive planning and investment. Case studies from across Africa, Europe, and Southeast Asia reinforce that maximizing socio-economic gains from GH2 will hinge on local context: resource endowment, institutional readiness, public buy-in, and robust monitoring of environmental and water footprints. Conversely, multiple studies caution that realizing the full benefits of GH2 will require surmounting several hurdles: the substantial land, water, and energy footprint of large-scale electrolysis and RE buildout; high upfront capital costs; and the challenge of technological integration across legacy sectors. There are also calls to integrate social acceptance and information campaigns into Policy, as public trust and risk perception greatly influence deployment success, especially for applications in domestic heating, microgrids, and transport.

Finally, the strategic interplay between decentralization, geopolitics, and energy independence is receiving more attention. Scholars such as (Braga, Gouvea and Gutierrez, 2024) and (Van de Graaf et al., 2020) argue that as countries pursue hydrogen sovereignty, a global GH divide may emerge based on RE and water resource availability. This could reshape global supply chains and trade patterns, creating new centres of economic power and necessitating international policy coordination, areas that require further study in the Indian context as the country scales up its hydrogen ambitions.

3 Research Methodology

This study employed a mixed-methods strategy to illuminate the role of GH2 in India's efforts to achieve Net Zero carbon emissions by 2070. The study's integration of quantitative surveys and qualitative interviews enabled a multidimensional analysis of policy efficacy, industry readiness, infrastructure status, and stakeholder viewpoints. Key theoretical constructs, including Policy coherence, regulatory consistency, stakeholder confidence, industry capacity, and barriers to adoption, were operationalized with specific indicators, enabling both macro-level analysis of national policy frameworks and micro-level examination of implementation practices. Fifty stakeholders, including high-ranking Government and business officials, and prominent figures in the hydrogen industry and finance, were surveyed using structured Likert-scale and multiple-choice questions to measure their opinions on policy, industry trends, and technical challenges. To round out the quantitative part, four in-depth interviews were conducted, two with public officials and two with leaders in the private sector. These interviews delved into qualitative topics such as investor sentiment, safety protocols, regulatory bottlenecks, and scalability strategies, and we thematically analyzed the interview results.

Secondary sources, such as official Policy papers, Company reports, and scholarly articles, were also part of the data-gathering process. By utilizing three sources of information, we were able to place the survey and interview results into context and compare India's methods with those of other countries. The quantitative data was analysed using SPSS for descriptive statistics, correlation and regression, while the qualitative replies were structured according to recurrent themes and strategic priorities. Sampling was guided by inclusion criteria emphasizing expertise, decision-making roles, and direct involvement in GH2, with convenience sampling facilitating access to respondents but introducing some selection bias. The combination of stakeholder surveys with interviews and secondary data review yielded a nuanced, data-driven understanding of enablers and barriers within the Indian GH2 sector. Limitations included the small sample size, possible response bias in self-reported data, and the dynamic nature of the policy and industry landscape, which may impact the currency of secondary sources. For researchers, politicians, and business executives in India who are committed to promoting GH2 adoption and decarbonization, this technique provides valuable insights that can inform strategic recommendations.

4 Results and Discussion

This research delves into the changing function of GH2 as India moves closer to its goal of Net-Zero carbon emissions, with a particular emphasis on the NGHM programme that began in January 2023. By 2030, the goal is to manufacture 5 million tonnes per annum of GH2, with India poised to surpass the US and EU as the leading producers. The GH2 ecosystem in India is characterized by a diverse array of ongoing and planned projects totalling a capacity of roughly 10.55 MTPA, although many remain in early development stages. The Government has committed significant financial resources, including ₹197.44 billion (approximately USD 2.37 billion), dedicated to GH promotion, demonstrating a robust Policy push.

4.1 Institutional and project landscape

The Indian GH2 infrastructure and project portfolio comprises over 143 recorded initiatives, with pilot and demonstration plants distributed across Rajasthan, Madhya Pradesh, Haryana, and other States. Key projects include ACME Cleantech's green ammonia and hydrogen production, Bharat Petroleum's refinery-based hydrogen production, and emerging hubs by Government-linked entities such as SJVN and NTPC. Despite promising growth, the cumulative installed electrolyser power approximates only 5–6 MW, corresponding to 3,000–4,000 tons annual hydrogen production. The development status highlights a nascent sector that has yet to gain full momentum through scale-up.

4.2 Policy framework and fiscal incentives

Comprehensive policies under NGHM include auction mechanisms that offer subsidies scaled to projected hydrogen prices, with upfront financial incentives aimed at reducing the cost gap against grey hydrogen. Table 1 summarizes key Policy perceptions from the stakeholder survey:

y Parameter	Mean Score (1 to 5)	% Respondents Agreeing or Strongly Agreeing
Effectiveness of Government Policies	3.84	60%
Clarity of Regulations	3.36	38%
Adequacy of Financial Incentives	3.10	27%
Alignment with Industry Needs	3.39	46%
Government-Industry Collaboration	3.26	30%

Table 1. Stakeholder Perception of Policy Framework

Although a majority viewed Government Policies as supportive, considerable scepticism persists regarding clarity, implementation, and financial incentives. Notably, only about a third of respondents considered current subsidies sufficient, indicating an imperative to strengthen financial mechanisms to spur industrial uptake. Slight bureaucratic inertia and regulatory delays further hinder adoption, echoing concerns of fragmented institutional coordination.

4.3 Corporate progress and financial health

Analysis of selected major industry players such as JSW Energy, Reliance Energy, Adani Energy, Greenko and Hero Future Energies, reveals a spectrum of readiness and strategic commitment (Table 2):

Company	Annual GH Investment (₹ Cr)	Renewable Energy Share (%)	ROE (%)	Debt-to-Equity Ratio	Total Assets (₹ Cr)
JSW Energy	200	65	10.4	0.5	42,320
Reliance Energy	N/A (part of ₹1.3 L Cr capex)	1.35	8.8	0.44	16,00,000
Adani Energy	10,000 (pledged)	100	17.4	4.0	1,42,193
Greenko	5,778	100	10.2	3.9	94,752
Hero Future Energies	299	100	5.0	2.3	1,089

Table 2. Corporate Investments and Financial Indicators

JSW Energy shows steady growth in renewable share and strong financial health, marked by stable Return on Equity (ROE) and low leverage. Reliance Energy, despite immense capital expenditures, maintains a portfolio dominated by conventional energy, reflecting gradual transition. Adani and Greenko, both fully renewable operators, are heavily investing in GH, though their high leverage ratios demand careful fiscal management. Hero Future Energies is at an early stage with fluctuating investments and low profitability, signaling initial development phases.

4.4 Stakeholder readiness and collaboration

The survey's internal reliability (Cronbach's alpha = 0.942) confirms the consistency of stakeholder responses. Respondents exhibit moderate confidence in technological (mean = 2.54) and workforce readiness (mean = 2.36), highlighting capacity gaps. Financial readiness scored higher (mean = 2.86), though still subdued relative to ideal preparedness. Industry-wide collaboration remains lukewarm with a mean score of 3.04, reflecting limited but emerging cooperative structures.

Correlation analysis validates significant positive relationships between readiness dimensions and collaboration (Table 3):

Variables	Correlation Coefficient (Spearman's rho)	Significance (p-value)
Technological vs Collaboration	0.435	0.002
Financial vs Collaboration	0.542	0.000
Workforce vs Collaboration	0.467	0.001

Table 3. Corporate Investments and Financial IndicatorsCorrelations Between Readiness and Collaboration

These results underline the importance of simultaneous advancement in technology, finance, and skilled labor to foster inter-organizational partnership necessary for GH scaling.

4.5 Infrastructure, investment and scalability challenges

Respondents provided guarded appraisals of the existing infrastructure. Roughly 60% felt the current GH2 infrastructure is inadequate for large-scale adoption. Investment strategies are perceived as inconsistent, with a significant number unsure about concrete expansion plans. Financing, though catalyzed by government incentives, remains insufficiently coordinated to assuage risk. Table 4 encapsulates key infrastructural and financial findings:

Dimension	Mean Score	% Respondents Agreeing or Strongly Agreeing
Existing Infrastructure Adequacy	2.36	<10%
Investment Plans	2.88	23%
Financial Support	3.44	43%
Perceived Investment Risk	3.52	48% (Higher score implies higher perceived risk)
Infrastructure Development Need	3.94	70%

Table 4. Infrastructure and Investor Perception

Crucially, scalability is strongly linked to storage capabilities and government-private sector collaboration (rho > 0.6). Yet transportation logistics for hydrogen remain costly and inefficient, demanding urgent technological interventions.

4.6 Safety concerns and risk mitigation

Safety protocols for GH2 received mixed evaluations. Only 28% believed organisational adherence to safety regulations is robust, while 36% indicated inadequacies in emergency preparedness. Training and awareness were highlighted as critical deficits, with calls for specialised programmes to manage hydrogen's volatility.

Also, significant percentage of respondents expressed concerns over the maturity of regulatory frameworks governing GH2 safety, with incidents of leakage and explosion perceived as low but not negligible. Continuous investment in leak-proof infrastructure and advanced safety technologies is crucial for maintaining operational integrity and public acceptance.

4.7 Statistical testing and hypotheses

Regression analysis examining links between policy effectiveness and adoption readiness demonstrated limited explanatory power (pseudo $R^2 \sim 0.126$), implying Policy alone cannot drive industry preparedness. In contrast, technological, financial, and workforce readiness significantly predicted collaboration propensity among stakeholders (correlations > 0.4, $p < 0.01$).

Financial support mechanism was the primary factor inversely correlated with risk perceptions ($r = -0.31$, $p < 0.05$), suggesting that Government and institutions play a significant role in de-risking investments. Meanwhile, infrastructure adequacy showed negligible impact on risk perception, highlighting the need for more integrated ecosystem strengthening.

Safety-related regression analysis confirmed that workforce training and emergency preparedness substantially reduce the likelihood of incidents, supporting a dedicated focus on capacity building alongside technological upgrades.

5 Conclusion

This study critically examined the evolving role of GH2 in India's transition towards Net-Zero Carbon Emissions by 2070, focusing on Policy frameworks, industry readiness, financial mechanisms, and operational enablers. The findings reveal that while National Policies and incentive schemes provide a foundational push for GH2 deployment, their direct impact on industrial preparedness is moderate. This underscores the importance of synchronized and pragmatic implementation, where Policy intent translates effectively into actions on the ground. Key internal factors, such as technological maturity, availability of skilled workforce, and financial stability within firms, emerged as critical determinants enabling collaborative innovation and scaling of GH2 technologies. The study also highlighted that infrastructure development and financial instruments, including concessional loans and risk-sharing mechanisms, are pivotal in reducing investment risks and encouraging broader participation by private and financial sectors.

Furthermore, the research emphasized the necessity of a systems approach to overcoming scalability challenges in GH2 adoption. Adequate hydrogen storage capacity, robust partnerships between public and private stakeholders, and aligned regulatory frameworks are essential to ensure a smooth transition from pilot projects to commercial-scale operations. Safety protocols and training were equally identified as key to building trust and operational reliability, given hydrogen's inherent risks.

In conclusion, advancing India's GH2 ecosystem requires integrated efforts that combine Policy clarity, technological advancements, human capital development, financial innovation, and safety assurance. Such a comprehensive approach will not only accelerate domestic adoption but also position India as a competitive player in the global GH2 economy, contributing significantly to its Sustainable Development Goals and Climate goals. Continued research and adaptive governance will be vital to sustaining momentum and addressing emerging challenges in this dynamic sector.

References

Aggarwal, P. (2017) '2°C target, India's climate action plan and urban transport sector', *Travel Behaviour and Society*, 6, pp. 110–116. Available at: https://doi.org/10.1016/j.tbs.2016.11.001.

Ampah, J.D., Jin, C., Liu, H., *et al.* (2024) 'Prioritizing Non-Carbon Dioxide Removal Mitigation Strategies Could Reduce the Negative Impacts Associated with Large-Scale Reliance on Negative Emissions', *Environmental Science & Technology*, 58(8), pp. 3755–3765. Available at: https://doi.org/10.1021/acs.est.3c06866.

Ampah, J.D., Jin, C., Afrane, S., *et al.* (2024) 'Race towards net zero emissions (NZE) by 2050: reviewing a decade of research on hydrogen-fuelled internal combustion engines (ICE)', *Green Chemistry*, 26(16), pp. 9025–9047. Available at: https://doi.org/10.1039/D4GC00864B.

Arto, I. *et al.* (2016) 'The energy requirements of a developed world', *Energy for Sustainable Development* [Preprint]. Available at: https://doi.org/10.1016/j.esd.2016.04.001.

Bhattacharyya, R. *et al.* (2022) 'Estimating minimum energy requirement for transitioning to a net-zero, developed India in 2070', *Current Science*, 122(5), p. 517. Available at: https://doi.org/10.18520/cs/v122/i5/517-527.

Braga, H., Gouvea, R. and Gutierrez, M. (2024) 'The Green Hydrogen Economy and the Global Net Zero Agenda: A Green Powershoring & Green Watershoring Perspective', *Modern Economy*, 15(01), pp. 23–48. Available at: https://doi.org/10.4236/me.2024.151002.

Dixit, A.C. *et al.* (2024) 'Barriers for adoption of green hydrogen in Indian transportation sector: A fuzzy ISM approach', *E3S Web of Conferences*. Edited by D.A. Joshi, N.B. Ibrahim, and D.M. Sangeetha, 559, p. 03011. Available at: https://doi.org/10.1051/e3sconf/202455903011.

Dong, Z.Y. *et al.* (2022) 'A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future', *International Journal of Hydrogen Energy* [Preprint]. Available at: https://doi.org/10.1016/j.ijhydene.2021.10.084.

Fuhrman, J. *et al.* (2023) 'Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system', *Nature Climate Change* [Preprint]. Available at: https://doi.org/10.1038/s41558-023-01604-9.

Ghosh, P. and Roy, A. (2024) 'Green-hydrogen - the game changer of India's journey towards energy sustainability: A socio-legal study', *E3S Web of Conferences*. Edited by E. Zervas, 585, p. 10008. Available at: https://doi.org/10.1051/e3sconf/202458510008.

Van de Graaf, T. *et al.* (2020) 'The new oil? The geopolitics and international governance of hydrogen', *Energy Research & Social Science*, 70, p. 101667. Available at: https://doi.org/10.1016/j.erss.2020.101667.

Gupta, S., Kumar, R. and Kumar, A. (2024) 'Green hydrogen in India: Prioritization of its potential and viable renewable source', *International Journal of Hydrogen Energy*, 50, pp. 226–238. Available at: https://doi.org/10.1016/j.ijhydene.2023.08.166.

Harichandan, S., Kar, S.K. and Rai, P.K. (2023) 'A systematic and critical review of green hydrogen economy in India', *International Journal of Hydrogen Energy*, 48(81), pp. 31425–31442. Available at: https://doi.org/10.1016/j.ijhydene.2023.04.316.

Harrison, T. and Kostka, G. (2014) 'Balancing Priorities, Aligning Interests: Developing Mitigation Capacity in China and India', *Comparative Political Studies* [Preprint]. Available at: https://doi.org/10.1177/0010414013509577.

Irena (2017) *Remap Renewable Energy Prospects for India*. Available at: https://www.connaissancedesenergies.org/sites/connaissancedesenergies.org/files/pdf-pt-vue/irena_remap_india_paper_2017_0.pdf.

Ishaq, H., Dincer, I. and Crawford, C. (2022) 'A review on hydrogen production and utilization: Challenges and opportunities', *International Journal of Hydrogen Energy* [Preprint]. Available at: https://doi.org/10.1016/j.ijhydene.2021.11.149.

Jamasb, T. (2017) 'Electricity storage: Friend or foe of the networks?', *Nature Energy*, 2(6), p. 17092. Available at: https://doi.org/10.1038/nenergy.2017.92.

Janardhanan, N., Zusman, E. and Moinuddin, M. (2024) 'Sub-national Drivers of India's Green Hydrogen Development', (June), pp. 32–40.

Jayakumar, A. *et al.* (2022) 'Can hydrogen be the sustainable fuel for mobility in India in the global context?', *International Journal of Hydrogen Energy*, 47(79), pp. 33571–33596. Available at: https://doi.org/10.1016/j.ijhydene.2022.07.272.

Khare, V., Nema, S. and Baredar, P. (2013) 'Status of solar wind renewable energy in India', *Renewable and Sustainable Energy Reviews* [Preprint]. Available at: https://doi.org/10.1016/j.rser.2013.06.018.

King, J. (2021) 'Hydrogen and Net Zero - A crucial role in decarbonisation strategies', *FST Journal* [Preprint]. Available at: https://doi.org/10.53289/cnlo5061.

Koshy, J. (2023) 'India's green hydrogen move may worsen pollution if steps are not in place, says study', *The Hindu*.

Kumar, J.C.R. and Majid, M.A. (2020) 'Renewable energy for sustainable development in India: Current status, future prospects, challenges, employment, and investment opportunities', *Energy, Sustainability and Society* [Preprint]. Available at: https://doi.org/10.1186/s13705-019-0232-1.

Madheswaran, D.K. *et al.* (2024) 'Green hydrogen: Paving the way for India's decarbonization revolution', *Environmental Science and Pollution Research* [Preprint]. Available at: https://doi.org/10.1007/s11356-024-34250-5.

Maurya, V., Ghosh, P. and Gunawat, A. (2024) 'STI Policy Push Towards Hydrogen Economy in India', in *Green Energy and Technology*, pp. 107–118. Available at: https://doi.org/10.1007/978-981-99-6237-2_6.

Ministry of New and Renewable Energy (2023) *Brief on Green Hydrogen*. Available at: https://mnre.gov.in/en/hydrogen-overview/.

Mitchell, C. (2016) 'Momentum is increasing towards a flexible electricity system based on renewables', *Nature Energy* [Preprint]. Available at: https://doi.org/10.1038/NENERGY.2015.30.

Mneimneh, F. *et al.* (2023) 'Roadmap to Achieving Sustainable Development via Green Hydrogen', *Energies*, 16(3), p. 1368. Available at: https://doi.org/10.3390/en16031368.

Pandey, I. and Kumari, S. (2023) 'Indian Green Hydrogen Framework: An Assessment', *EAI Endorsed Transactions on Energy Web*, 10, pp. 1–7. Available at: https://doi.org/10.4108/ew.4701.

Pollitt, M.G. and Chyong, C.K. (2021) 'Modelling net zero and sector coupling: Lessons for european policy makers', *Economics of Energy and Environmental Policy* [Preprint]. Available at: https://doi.org/10.5547/2160-5890.10.2.MPOL.

Rajamani, L. and Werksman, J. (2018) 'The legal character and operational relevance of the Paris Agreement's temperature goal', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* [Preprint]. Available at: https://doi.org/10.1098/rsta.2016.0458.

Roy, D., Bhowmik, M. and Roskilly, A.P. (2024) 'Technoeconomic, environmental and multi criteria decision making investigations for optimisation of off-grid hybrid renewable energy system with green hydrogen production', *Journal of Cleaner Production*, 443, p. 141033. Available at: https://doi.org/10.1016/j.jclepro.2024.141033.

Schmid, G. (2012) 'The development of renewable energy power in India: Which policies have been effective?', *Energy Policy* [Preprint]. Available at: https://doi.org/10.1016/j.enpol.2012.02.039.

Sharma, G.D. *et al.* (2023) 'Socio-economic aspects of hydrogen energy: An integrative review', *Technological Forecasting and Social Change*, 192, p. 122574. Available at: https://doi.org/10.1016/j.techfore.2023.122574.

Sholapurkar, R.B. and Mahajan, Y.S. (2015) 'Review of Wind Energy Development and Policy in India', *Energy Technology & Policy* [Preprint]. Available at: https://doi.org/10.1080/23317000.2015.1101627.

Shukla, A.K., Sudhakar, K. and Baredar, P. (2017) 'Renewable energy resources in South Asian countries: Challenges, policy and recommendations', *Resource-Efficient Technologies* [Preprint]. Available at: https://doi.org/10.1016/j.reffit.2016.12.003.

Slorach, P.C. and Stamford, L. (2021) 'Net zero in the heating sector: Technological options and environmental sustainability from now to 2050', *Energy Conversion and Management* [Preprint]. Available at: https://doi.org/10.1016/j.enconman.2021.113838.

Sokołowski, M.M. (2022) 'Making the Electricity Sector Emission-Free', in *Energy Transition of the Electricity Sectors in the European Union and Japan*. Available at: https://doi.org/10.1007/978-3-030-98896-8_3.

The Economic Times (2024) 'India's coal import rises 8% to 268 MT in FY24', *Indiatimes*.

Tongia, R. and Patel, U. (2024) 'Benchmarking Green Hydrogen in India's Energy Transition: Expensive but Important for Some Uses'.

Verma, P., Sharma, B. and Mehta, P. (2024) 'Green Hydrogen Production: Impacts on Environmental Sustainability Scale', in *Green Hydrogen Economy for Environmental Sustainability. Volume 1: Fundamentals and Feedstocks, Part 2 - Green Hydrogen Production: Impacts on Environmental Sustainability Scale*. American Chemical Society, pp. 29–48. Available at: https://doi.org/10.1021/bk-2024-1473.ch002.

Yan, Y. *et al.* (2020) 'Techno-economic analysis of low-carbon hydrogen production by sorption enhanced steam methane reforming (SE-SMR) processes', *Energy Conversion and Management*, 226(October), p. 113530. Available at: https://doi.org/10.1016/j.enconman.2020.113530.

Yesodharan, V. *et al.* (2024) 'Role of Green Hydrogen in Decarbonizing Heavy Industries in India', in, pp. 99–116. Available at: https://doi.org/10.1021/bk-2024-1474.ch005.

Zabeltitz, C. Von (1994) 'Effective use of renewable energies for greenhouse heating', *Renewable Energy*, 5(1–4), pp. 479–485. Available at: https://doi.org/10.1016/0960-1481(94)90419-7.