RESEARCH ARTICLE

Financial Innovations for Scaling Up Green Hydrogen Investments in India

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Abstract

India's energy transition aims to balance economic growth with environmental sustainability, with green hydrogen playing a pivotal role. As a renewable energy solution, green hydrogen is crucial for decarbonizing hard-to-abate sectors like steel, cement, and heavy-duty transportation. However, significant financial, regulatory, and market challenges hinder its large-scale adoption. This study explores the financial barriers, opportunities, and sustainable financing mechanisms necessary to advance green hydrogen investments in India. It proposes actionable strategies to create a supportive ecosystem for the sector, aligned with India's net-zero targets. The research employs a multi-faceted methodology, including a comprehensive literature review, stakeholder analysis, and case study evaluation. It examines global best practices in green finance, reviews India's policy framework, and identifies barriers to green hydrogen financing. Key findings reveal high capital costs, uncertain returns, and a lack of risk mitigation instruments as significant financial barriers. Although mechanisms like green bonds, blended finance, and international climate funds hold promise, their application in India's green hydrogen sector remains limited. Regulatory uncertainties and underdeveloped infrastructure exacerbate these challenges. However, the National Hydrogen Mission and increasing private sector investments indicate growing momentum. The study recommends establishing a comprehensive national hydrogen policy with clear regulatory frameworks and developing financial mechanisms such as subsidies, green bonds, and risk-sharing instruments to mitigate investor concerns. It also suggests fostering public-private partnerships and international collaborations to mobilize capital and technology transfer. Incentivizing green hydrogen demand through mandates for industrial and transportation applications, along with strengthening research, innovation, and infrastructure investments, will help reduce production costs. Green hydrogen holds transformative potential for India's sustainable energy future, and overcoming financial and regulatory barriers through innovative strategies will enable the country to achieve its decarbonization and economic goals.

Key Words: *Green hydrogen; Energy transition; Financial barriers; Sustainable financing; Policy recommendations*

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1. Introduction

India's energy landscape is at a critical juncture as it seeks to balance economic growth with environmental sustainability. Central to this balance is the adoption of renewable energy technologies that align with the country's net-zero emission target by 2070 [1]. Among these technologies, green hydrogen has emerged as a transformative solution for decarbonizing hard-to-abate sectors such as steel, cement, heavy-duty transportation, and chemical production [2,3]. Unlike conventional hydrogen, which is produced using fossil fuels, green hydrogen is derived through water electrolysis powered by renewable energy sources such as wind and solar [4,5]. This makes green hydrogen a pivotal component of India's clean energy transition, contributing to energy security, industrial competitiveness, and global climate action [1,6]. Despite its potential, the deployment of green hydrogen at scale in India faces significant challenges. High capital costs associated with electrolysis technology, coupled with the need for large-scale renewable energy infrastructure, present major financial barriers [1,7]. For instance, the cost of green hydrogen production in India is currently estimated to be higher than $3 per kilogram, making it less competitive compared to hydrogen produced from natural gas [8]. Additionally, the absence of robust risk mitigation instruments, such as guarantees and insurance schemes, further deters private sector investment [9]. Regulatory uncertainties, including inconsistent policy frameworks and unclear incentives, exacerbate these financial challenges [1,2].

The global financing landscape offers valuable lessons for addressing these challenges. Mechanisms such as green bonds, which mobilized over $500 billion globally in 2022, demonstrate the potential of sustainable finance to attract capital for clean energy projects [2,10]. Similarly, blended finance approaches, combining public and private investments, have proven effective in de-risking renewable energy investments in emerging economies [9,11]. Carbon markets also provide a supplementary revenue stream by monetizing the environmental benefits of green hydrogen [12,13]. However, the adoption of these mechanisms in India's green hydrogen sector remains limited, underscoring the need for targeted policy interventions [14].

India's National Hydrogen Mission, launched in 2021, is a step in the right direction, aiming to position the country as a global hub for green hydrogen production and export [6,15]. The mission outlines ambitious targets for achieving 5 million metric tons of green hydrogen production annually by 2030, supported by renewable energy capacities exceeding 60 gigawatts (GW) [6]. While these targets highlight the government's commitment, they require significant financial support and innovative policy measures to become a reality [1,7]. This paper aims to analyze the financing landscape for green hydrogen development in India, focusing on both the challenges and opportunities. It will explore sustainable financing mechanisms, such as green bonds, blended finance, and international climate finance, while examining regulatory and market-based solutions to address investment barriers [1,9]. By proposing actionable strategies and policy recommendations, this study seeks to create an enabling environment that supports green hydrogen growth, aligns with India's Sustainable Development Goals (SDGs), and contributes to global decarbonization efforts [1,16].

The findings from this study will not only inform policymakers but also provide valuable insights for investors, industry stakeholders, and international development agencies. By addressing the financial and regulatory gaps in the green hydrogen sector, India can unlock its vast renewable energy potential, achieve industrial decarbonization, and emerge as a global leader in clean energy innovation [13,17].

2. Literature Review

2.1. Global and national perspectives on green hydrogen development

Green hydrogen, derived from renewable energy sources through electrolysis, is gaining prominence as a sustainable solution to decarbonize energy systems and hard-to-abate sectors such as steel, cement, and long-haul transportation. Globally, countries are making significant investments to scale up green hydrogen technologies, recognizing their potential to achieve net-zero emissions targets [2,18]. Key initiatives in regions such as Europe, the United States, and Japan showcase comprehensive policy frameworks supporting production, infrastructure development, and adoption [4,16].

Europe's Hydrogen Strategy, launched in 2020, includes a roadmap to install at least 40 GW of electrolyzer capacity by 2030 [19]. Similarly, the U.S. Infrastructure Investment and Jobs Act allocates significant funding for clean hydrogen hubs, illustrating the central role of public funding in early-stage market development. Japan and South Korea have established ambitious hydrogen strategies, focusing on integrating hydrogen into industrial processes and the transport sector [20].

India has recognized the strategic importance of green hydrogen as a critical element of its clean energy transition. The National Green Hydrogen Mission aims to produce 5 million tons of green hydrogen annually by 2030 and make India a global leader in hydrogen production and export [15]. This mission focuses on reducing costs, scaling domestic demand, and building infrastructure while addressing socio-economic priorities, such as job creation and energy security [11]. However, India's green hydrogen sector is still nascent, and significant efforts are required to address policy, financial, and infrastructural gaps [1].

2.2. Financing models for renewable energy and green hydrogen

The successful deployment of renewable energy technologies globally has relied on a range of innovative financing mechanisms, including green bonds, blended finance models, and public-private partnerships [9]. These mechanisms have helped de-risk investments, attract private sector participation, and scale renewable energy deployment. For instance, green bonds have mobilized billions of dollars in capital for renewable energy projects, with significant contributions from India's renewable energy sector [10].

Blended finance, which combines public and private capital to mitigate risks, has emerged as a critical tool in financing large-scale clean energy projects, particularly in developing economies [13,21]. Studies suggest that this model could be adapted for green hydrogen by leveraging government guarantees and concessional funding to lower project risks [7,22]. Despite the availability of these models, their application in green hydrogen faces unique challenges. The high capital intensity of hydrogen projects, coupled with the nascent state of the market, makes private investors cautious [23]. Furthermore, financing green hydrogen production, storage, and infrastructure requires addressing technology and market uncertainties, as evidenced by case studies from Europe and North America [1].

2.3. Challenges in scaling green hydrogen financing

India faces significant challenges in scaling up financing for green hydrogen. Financial barriers include limited availability of long-term financing, high upfront costs, and lack of risk-sharing instruments such as insurance and guarantees for hydrogen projects [6,24]. These

challenges are compounded by market barriers, such as limited demand for hydrogen due to high production costs and inadequate infrastructure for storage and transport [4,8]. The regulatory landscape for green hydrogen in India is also underdeveloped, with unclear policies, inconsistent incentives, and limited alignment with global standards [1,9]. Experiences from other countries highlight the importance of strong policy frameworks in attracting investments and building investor confidence [19,20].

To decrease the risks of the banks and thus facilitate the lending to smaller enterprises, the Magyar Nemzeti Bank [MNB] (Hungarian National Bank) started its own program called the Novekedesi Hitelprogram [NHP] (Funding for Growth Scheme program). The main objective of this project was to improve the conditions offered for micro-, small- and medium-sized enterprises through favorable financing from the central bank.

2.4. Opportunities for India

Despite these challenges, India has substantial opportunities to leverage its renewable energy resources for green hydrogen production. The falling costs of solar and wind power provide a competitive advantage, enabling cost-effective hydrogen production through renewable electrolysis [7,25]. Additionally, India's large industrial base, including steel and chemical sectors, offers significant potential for green hydrogen adoption [26].

International cooperation and climate finance can play a pivotal role in addressing the financing gap. For instance, multilateral organizations such as the International Finance Corporation (IFC) and the Asian Development Bank (ADB) have expressed interest in supporting green hydrogen projects in emerging economies [9,13]. Moreover, the global carbon market presents opportunities for generating additional revenue streams through the sale of carbon credits from green hydrogen production [16]. Policy measures such as tax incentives, subsidies for hydrogen production, and R&D funding can further create an enabling environment for green hydrogen development in India [27,28]. Infrastructure investments, including hydrogen pipelines and storage facilities, are critical to reducing transportation costs and improving market accessibility [1]. India's green hydrogen sector stands at the intersection of immense potential and formidable challenges. While the financing landscape presents significant barriers, adopting tailored financing models, strengthening policy frameworks, and leveraging international support can accelerate the development of this crucial sector. The insights from global experiences provide valuable lessons for India to navigate the complexities of scaling green hydrogen financing and realize its vision of a sustainable energy future.

2.5. Scientific novelty of the study

This study contributes novel insights into the financing and policy dimensions of green hydrogen development in India, addressing a critical gap in the existing literature. The specific aspects of its scientific novelty include:

2.5.1. Integration of finance and policy in green hydrogen development:

Unlike most studies that focus on either the technical aspects or the economic feasibility of green hydrogen, this research provides a comprehensive analysis of financial barriers, innovative financing mechanisms, and regulatory frameworks. It highlights the interplay between sustainable finance instruments, such as green bonds and blended finance, and policy support to create an enabling ecosystem for green hydrogen.

2.5.2. Context-specific application for India:

The study tailor's global best practices in green hydrogen financing to the Indian context, offering actionable strategies aligned with India's unique socio-economic and energy transition goals. By focusing on India's National Hydrogen Mission and state-level initiatives, it provides a nuanced understanding of localized challenges and opportunities.

2.5.3. Exploration of untapped financing mechanisms:

The research identifies and evaluates underutilized financial instruments in India's green hydrogen sector, such as carbon markets, concessional finance, and international climate funds. It proposes innovative ways to leverage these instruments to de-risk investments and lower the cost of green hydrogen production.

2.5.4. Stakeholder-centric approach:

This study adopts a stakeholder-driven framework, analyzing the roles of government bodies, private sector players, financial institutions, and international donors in advancing green hydrogen. It emphasizes the need for collaborative synergy among these entities to overcome financial and regulatory barriers.

2.5.5. Policy recommendations based on global and local synergies:

By comparing global policy frameworks with India's regulatory landscape, the study offers specific recommendations for a unified and robust national hydrogen policy. It also identifies strategic interventions to align state and central initiatives, reducing fragmentation in policy execution.

2.5.6. Future-ready insights on infrastructure and market development:

The research explores the critical role of infrastructure development and demand aggregation platforms in scaling green hydrogen production and utilization. It also highlights emerging opportunities in industrial decarbonization, green mobility, and export markets.

2.5.7. Alignment with Sustainable Development Goals (SDGs):

The study situates green hydrogen within the broader framework of India's SDGs and its 2070 net-zero target, demonstrating how financial and policy innovations can contribute to global climate action while supporting economic growth.

This multifaceted approach not only advances the academic discourse on green hydrogen but also provides practical guidance for policymakers, investors, and industry stakeholders in shaping a sustainable and competitive green hydrogen economy in India.

3. Methodology

The methodology for this research adopts a comprehensive, multi-pronged approach to analyze the financing landscape and development of green hydrogen in India. The study begins with a thorough literature review, exploring global and national perspectives on green hydrogen to identify research gaps and assess existing financing mechanisms such as green bonds, blended finance, and carbon markets, drawing parallels to India's context. Primary and secondary data are collected from government reports, industry publications, and academic journals, while case studies from international and domestic projects are analyzed to highlight financial, technological, and policy-related challenges.

A stakeholder analysis is conducted to identify key players—government bodies, private sector actors, financial institutions, and international donors—and assess their roles in fostering green hydrogen growth. A conceptual framework is developed, focusing on sustainable financing mechanisms and addressing regulatory and policy barriers. The research further assesses the financial, regulatory, and market challenges hindering green hydrogen adoption, while also exploring opportunities in infrastructure, technology development, and international markets.

Based on these findings, actionable policy and strategy recommendations are formulated, emphasizing tax incentives, risk mitigation tools, and public-private partnerships, all aligned with India's SDGs and net-zero emissions target by 2070. Finally, the study cross-references its findings with global best practices and existing financial and policy frameworks to ensure the practical applicability of the proposed solutions.

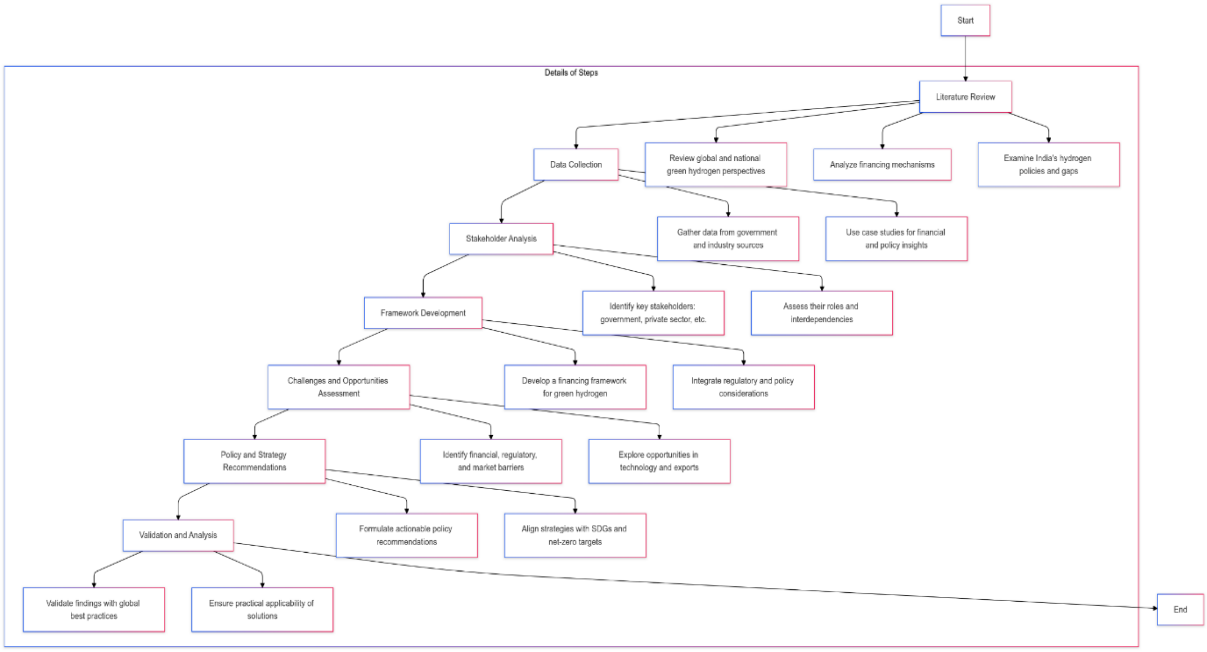

Figure 1: *Methodology.*

4. Financing Landscape for Green Hydrogen in India

4.1. Current status of investment in green hydrogen

4.1.1. Overview of public, private, and international investments.

As shown in table 1 about the current status of investments in green hydrogen development in India, based on public, private, and international contributions.

Table 1: *Current status of investments in green hydrogen development in India, based on public, private, and international contributions:*

Investment Type	Key Contributions	Sources
Public investments	Government funding for National Hydrogen Mission; allocation of ₹800 crore for pilot projects and R&D.	Harichandan et al. [1]; Sharma et al. [6].
	State-level initiatives (e.g., Gujarat and Maharashtra exploring green hydrogen hubs).	Manna et al. [26]; Jha et al. [29].
Private investments	Reliance Industries pledging $10 billion for renewable energy, including green hydrogen.	Soundarrajan et al. [25]; Sharma, et al. [30].
	Adani Group planning to invest $20 billion in green hydrogen and related infrastructure.	Jayachandran et al. [3]; Pradhan et al. [28].
	Indian Oil Corporation Limited (IOCL) partnerships for scaling green hydrogen production.	Gupta, et al. [5]; Sharma, et al. [30].
International investments	Collaboration with global agencies like the International Finance Corporation (IFC) and Asian Development Bank (ADB).	International Finance Corporation [31]; Sarangi [32].
	Bilateral partnerships with countries such as Japan and Germany to develop green hydrogen infrastructure.	Lee [20]; Sontakke et al. [11]
	Funding from Green Climate Fund (GCF) for pilot green hydrogen projects.	Volz [13]; Hassan et al. [2].

Key findings

- **Government commitment to green hydrogen:** The Indian government is actively investing in green hydrogen through the National Hydrogen Mission with a significant allocation of ₹800 crore to support pilot projects, research, and development (R&D). This demonstrates the government's intent to build a strong foundational framework for green hydrogen development. State-level initiatives, particularly in Gujarat and Maharashtra, are also emerging as key players in developing green hydrogen hubs, showcasing the growing regional focus on the sector.

- **Strong role of private sector:** Major private sector players such as Reliance Industries and Adani Group are making substantial commitments to green hydrogen, with investments totaling over $30 billion. Reliance's $10 billion commitment and Adani's $20 billion investment underline the significant private sector confidence in the green hydrogen sector's potential. Indian Oil Corporation Limited (IOCL) is also actively pursuing green

hydrogen through partnerships to scale production. These efforts by large corporations show the industry's growing interest in this market and the willingness to drive innovation and commercial scaling.

- **International partnerships and support:** India is leveraging international partnerships to accelerate green hydrogen development. Notable collaborations include those with countries like Germany and Japan, who have made significant contributions to green hydrogen infrastructure development. The International Finance Corporation (IFC) and Asian Development Bank (ADB) are involved in providing financial support and facilitating market development. Additionally, funding from multilateral bodies like the Green Climate Fund (GCF) has been directed toward pilot projects to test green hydrogen viability.

- **Diversification of investment sources:** The investment landscape is highly diversified, combining public sector initiatives that ensure policy direction and funding, private sector investments that bring in substantial capital for infrastructure and scaling, and international finance that injects both capital and global expertise into the sector. This mix of investment sources ensures that India's green hydrogen sector is being approached from multiple angles, making it more resilient and adaptable to global trends while addressing local needs.

- **Collaborative efforts and global alignment:** India's collaboration with international organizations and countries emphasizes a global alignment of green hydrogen goals, which is crucial for scaling production, lowering costs, and sharing technology. The collaborative nature of these investments suggests that India is positioning itself as an emerging leader in green hydrogen, benefiting from both domestic and international support. The green hydrogen sector in India is attracting substantial investment across public, private, and international sectors. The Indian government's active role in funding and creating supportive policies is complemented by strong private sector involvement from leading corporations. International collaborations further enhance India's capacity to develop a competitive green hydrogen market. These combined efforts create a promising environment for scaling green hydrogen projects and achieving India's sustainable energy and climate goals.

4.1.2. Role of government subsidies and incentives

As shown in table 2 about the role of government subsidies and incentives in promoting green hydrogen development in India.

Table 2: *Role of government subsidies and incentives in promoting green hydrogen development in India.*

Policy/Initiative	Details	Impact/Amount Allocated	Sources
National green hydrogen mission	Launched to boost green hydrogen production and R&D.	₹19,744 crore allocated; ₹17,490 crore for projects and ₹1,466 crore for R&D.	Harichandan et al. [1]; Sharma et al. [6].
Capital subsidies for electrolyzer	Subsidies offered to reduce the cost of electrolyzer manufacturing.	Target to bring hydrogen production cost below $1/kg by 2030.	Prakash et al. [33]; Sarangi [32].
Production-Linked Incentive (PLI) scheme	PLI scheme for renewable energy manufacturing includes green hydrogen projects.	₹4,500 crore allocated under the scheme.	Jha et al. [29]; Sontakke et al. [11].

Tax exemptions and Accelerated depreciation	Tax incentives for green hydrogen producers and infrastructure developers.	10-year tax holiday for renewable energy projects under Section 80-IA of IT Act.	Sharma et al. [6]; Soundarrajan et al. [25].
State-level subsidies	States offering specific incentives to attract green hydrogen investments.	Gujarat and Maharashtra providing land and capital subsidies for projects.	Gupta et al. [5]; Volz [13].
Blended finance instruments	Leveraging public funds to de-risk green hydrogen projects.	India exploring collaboration with IFC and GCF.	International Finance Corporation [31]; Sarangi [32].
Custom duty reductions	Reduced import duties on key components like electrolyzers.	Custom duties on electrolyzer imports cut by 5%-10%.	Sharma et al. [6]; Lee [20].

Key findings

The table presents a comprehensive overview of the government subsidies and incentives available for green hydrogen development in India. These policies are designed to foster the growth of a sustainable hydrogen economy and attract private and international investments. However, a closer look reveals both positive aspects and areas for improvement.

- **Financial support through national green hydrogen mission**

Strengths: The National Green Hydrogen Mission is the cornerstone of India's efforts to position itself as a leader in green hydrogen. The ₹19,744 crore allocation reflects a serious commitment to scaling up production and advancing research in the sector. The substantial funding for projects (₹17,490 crore) highlights the government's strategic direction to build large-scale infrastructure.

Challenges: While the funding is significant, the mission's success will depend on its efficient deployment and the timely achievement of objectives. This includes ensuring that funds are allocated to promising and innovative projects and maintaining transparency in their distribution. Additionally, while the mission aims to reduce hydrogen production costs, achieving the targeted price of $1/kg by 2030 will require overcoming substantial technological and cost barriers, especially in electrolyzer technology.

- **Capital subsidies for electrolyzers**

Strengths: Offering capital subsidies for electrolyzer production is an important step to reduce costs for hydrogen producers. Electrolyzers are one of the most expensive components in the green hydrogen value chain, and this initiative helps bring down the upfront capital investment for projects, making them more attractive to investors.

Challenges: The subsidy could be more effectively targeted towards cutting-edge technologies that ensure the long-term scalability of electrolyzers, rather than just focusing on cost reduction. Furthermore, the dependency on government subsidies may hinder innovation in the long term, as it could discourage private sector competition.

- **Production-Linked Incentive (PLI) scheme**

Strengths: The PLI scheme is an innovative approach to attract domestic manufacturing investments, which is crucial for ensuring long-term supply chain resilience. The ₹4,500 crore

allocated under this scheme can significantly bolster the domestic manufacturing of hydrogen-related technologies, including electrolyzers and fuel cells.

Challenges: The success of the PLI scheme will depend on its execution. If not structured correctly, it might result in short-term gains rather than fostering long-term technological and market growth. The scheme also needs to be evaluated periodically to ensure it effectively addresses challenges such as scaling production capacities and reducing costs in line with global competition.

- **Tax exemptions and accelerated depreciation**

Strengths: Offering tax holidays and depreciation benefits creates a favorable environment for investors by improving the project's financial viability. The 10-year tax holiday under Section 80-IA of the IT Act, particularly for renewable energy projects, provides a long-term incentive that can attract significant private capital.

Challenges: While tax incentives are a key attractor for investment, their effectiveness is dependent on their integration with other government policies. Additionally, the long-term nature of these incentives might limit their immediate impact, particularly for early-stage projects that require initial capital investment.

- **State-level subsidies**

Strengths: State-level initiatives, such as those by Gujarat and Maharashtra, have the potential to accelerate green hydrogen adoption by providing region-specific advantages, including land and capital subsidies. This decentralized approach aligns with India's federal structure and allows states to take a more active role in the energy transition.

Challenges: There is a risk of inconsistency between states in terms of the level of support provided, which could lead to disparities in the development of green hydrogen infrastructure. Additionally, state-level subsidies might create competition rather than cooperation, potentially resulting in inefficient allocation of resources across regions.

- **Blended finance instruments**

Strengths: Blended finance mechanisms, which involve a combination of public and private funds, play a crucial role in de-risking investments, particularly in an emerging sector like green hydrogen. Leveraging international support from institutions like the IFC and GCF can help India overcome financing gaps in early-stage projects.

Challenges: The reliance on blended finance must be managed carefully to avoid overdependence on external funding sources, which may not always be predictable or aligned with national priorities. There is also the challenge of scaling these blended finance mechanisms to the magnitude required for a national-level transition to green hydrogen.

- **Custom duty reductions**

Strengths: Reducing import duties on electrolyzer and other green hydrogen components is a necessary step to reduce the upfront costs of establishing green hydrogen production facilities. These measures help offset some of the high capital expenditures associated with early-stage development.

Challenges: While custom duty reductions make imported equipment more affordable, the country must focus on developing its domestic manufacturing capabilities in the long term. Over-reliance on imports could expose India to global supply chain disruptions and reduce the economic benefits of fostering a domestic green hydrogen industry.

The government's subsidies and incentives play a critical role in jumpstarting India's green hydrogen sector. The strategic allocation of funds through programs like the National Green Hydrogen Mission and PLI scheme, combined with tax exemptions and custom duty reductions, provides the financial support needed for green hydrogen to become competitive.

However, to maximize their effectiveness, these initiatives must be accompanied by strong implementation mechanisms, periodic assessments, and alignment with long-term sustainability goals. There is also a need for closer coordination between federal and state policies to ensure that resources are optimally allocated and that there are no discrepancies in the support provided to different regions. Finally, while government subsidies help address initial challenges, the long-term viability of the green hydrogen sector will depend on technological advancements, market demand, and a competitive private sector.

4.2. Key stakeholders and their roles

4.2.1. Government bodies, private sector players, financial institutions, and international donors

As shown in table 3 about the key stakeholders and their roles in promoting green hydrogen development in India.

Table 3: *Key stakeholders and their roles in green hydrogen development in India.*

Stakeholder	Role	Examples/Initiatives	Sources
Government Bodies	Formulating policies, providing subsidies, and creating a conducive regulatory environment.	- Ministry of New and Renewable Energy (MNRE): National Green Hydrogen Mission. - NITI Aayog: Green Hydrogen policy roadmap for India. - State Governments: Gujarat and Maharashtra offering land and financial incentives for green hydrogen projects.	Harichandan et al. [1]; Pradhan et al. [28]. Jha et al. [29]; Sarangi [32]. Volz [13]; Lee [20].
Private Sector Players	Investing in green hydrogen projects, technology development, and infrastructure.	- Reliance Industries: $10 billion investment in green hydrogen and renewable energy. - Adani Group: Plans to invest $20 billion in green hydrogen and allied sectors. - Indian Oil Corporation Limited (IOCL): Partnering with private firms for electrolyzer deployment.	Sharma et al. [6]; Soundarrajan et al. [25]. Harichandan et al. [1]; Gupta et al. [5]. Sharma, et al. [30].

Financial Institutions	Providing funding, de-risking instruments, and innovative financing solutions.	- Indian Renewable Energy Development Agency (IREDA): Green financing for hydrogen projects. - State Bank of India (SBI): Committed to financing renewable energy, including hydrogen. - Green Bonds: Increasing issuance to finance green hydrogen projects.	Jha et al. [29]; Sarangi [32]. Prakash et al. [33]. Gupta et al. [5]; Volz [13].
International Donors	Supporting green hydrogen development through grants, technical expertise, and capacity building.	- Green Climate Fund (GCF): Funding pilot green hydrogen projects in India. - Asian Development Bank (ADB): Supporting policy development and project funding. - Bilateral Partnerships: Collaborations with Germany and Japan for technology transfer and infrastructure development.	Volz [13]; International Finance Corporation [31]. Sontakke et al. [11]; Sarangi [32]. Harichandan et al. [1]; Lee [20].

Key insights

- **Collaborative synergy:** The involvement of multiple stakeholders, from government bodies to private sector players, creates a synergetic environment for green hydrogen development. Public-private partnerships (PPPs) are a key strategy to bridge financing gaps, foster innovation, and build infrastructure. However, effective collaboration between these stakeholders is essential for minimizing bureaucratic hurdles and ensuring alignment on policy, financing, and technological development.

- **Policy and regulatory framework:** The government's proactive role in providing subsidies, incentives, and regulatory clarity is crucial for creating a stable market environment. However, the success of green hydrogen projects will heavily depend on the consistency and enforceability of policies across regions.

- **Private sector's role:** The private sector is likely to play a significant role in the commercialization of green hydrogen, especially as large corporations bring significant investments. However, it is crucial that the benefits of this growth are distributed equitably across the market, enabling small and medium enterprises (SMEs) to participate and innovate.

- **Financial mechanisms:** Financial institutions need to overcome the hesitancy related to high-risk, capital-intensive projects by developing tailored financial instruments, such as blended finance and green bonds. These will help mitigate risks and bring more diverse capital into the green hydrogen sector.

- **Global support:** While international donors provide crucial support, India's success in green hydrogen will depend on its ability to integrate global expertise with local needs.

The focus should be on long-term capacity building and infrastructure development, rather than relying solely on international funding for short-term projects.

In conclusion, the collaborative efforts of these stakeholders—along with strategic policy and financial mechanisms—are essential to creating a viable and competitive green hydrogen economy in India.

4.3. Emerging opportunities

4.3.1. Potential areas for investment, technology development, and market expansion

Green hydrogen presents several promising areas for investment, technology development, and market expansion in India.

With its potential to play a pivotal role in decarbonizing India's energy sector, the following emerging opportunities are crucial for shaping the future of green hydrogen development in the country:

- **Investment opportunities in green hydrogen infrastructure**

Renewable energy integration: Green hydrogen production is intrinsically linked to renewable energy sources like solar and wind. As India continues to expand its renewable energy capacity, the integration of green hydrogen production facilities with renewable power plants presents a key investment opportunity. Projects that combine renewable energy with hydrogen production could benefit from reduced costs and optimized energy use [30].

Storage and transport infrastructure: The development of large-scale storage solutions for green hydrogen, such as underground storage, will be essential for overcoming its intermittency and ensuring stable supply. Investments in transportation infrastructure for hydrogen delivery and distribution, including pipelines and transport tanks, are also crucial for scaling up green hydrogen adoption [30].

- **Technology development in green hydrogen production**

Electrolysis technology: Electrolyzer are at the heart of green hydrogen production, and advancements in this technology could significantly reduce production costs. Innovations in proton exchange membrane (PEM) electrolyzer and alkaline electrolyzer will increase efficiency and decrease operational costs.

Moreover, exploring hybrid renewable energy systems that pair solar, wind, and storage with electrolysis could offer scalable solutions for green hydrogen production [11].

Advanced hydrogen storage solutions: Research into solid-state storage, metal hydrides, and other innovative hydrogen storage methods will be crucial for increasing the viability of green hydrogen as a fuel source.

This will enable safer and more efficient storage options, essential for widespread adoption [34].

Fuel cell development: Fuel cell technology, which is pivotal for utilizing green hydrogen in various sectors such as transportation and industry, is another area where technological advances will unlock greater market potential.

Investments in fuel cell R&D could enable more affordable and efficient vehicles, particularly in the heavy-duty transport sector [7].

- **Market expansion in industrial applications**

Decarbonization of hard-to-abate sectors: Green hydrogen offers significant potential for industries like steel, cement, and chemicals, which are traditionally difficult to decarbonize. Investing in green hydrogen-based solutions for these industries will enable them to meet stricter emission standards while tapping into new markets for low-carbon products [35].

Mobility and transport: The hydrogen mobility sector is an emerging opportunity in India, especially in fuel-cell electric vehicles (FCEVs) for public transportation and freight. Government incentives and infrastructure development for hydrogen refueling stations can accelerate the adoption of hydrogen as a clean fuel for buses, trucks, and trains [15].

- **Policy and regulatory support for green hydrogen**

Government incentives and subsidies: As India seeks to foster a green hydrogen economy, policy frameworks and financial incentives will play a crucial role. These may include subsidies for hydrogen production, tax benefits for R&D, and low-interest loans for green hydrogen projects. Additionally, the integration of green hydrogen into India's renewable energy policy can drive both domestic and foreign investments [11].

Public-private partnerships: Collaboration between the government, private sector, and research institutions can help mitigate the risks associated with green hydrogen projects. Public-private partnerships (PPPs) in infrastructure development, technology research, and large-scale hydrogen production can reduce costs and improve the commercial viability of green hydrogen projects [36].

- **International collaboration and export potential**

Hydrogen export: India has the potential to emerge as a leading exporter of green hydrogen, particularly to regions like Europe and Japan, which are aggressively pursuing hydrogen as part of their energy strategies. Developing a robust export market can generate additional revenue streams and position India as a leader in the global green hydrogen economy [2].

Collaborations with international organizations: Partnerships with international organizations, including the International Renewable Energy Agency (IRENA) and the Hydrogen Council, can provide access to technical expertise, funding, and global markets, further boosting India's green hydrogen potential [4].

These opportunities represent a crucial pathway for India to leverage green hydrogen for its energy transition, supporting the country’s broader climate and development goals.

Strategic investments, technological advancements, and a conducive policy environment will be key to realizing these opportunities and scaling up green hydrogen to meet India’s growing energy demands.

5. Challenges in financing green hydrogen development

5.1. Financial barriers

As shown in table 4 about the financial barriers in the green hydrogen sector, focusing on high capital costs, uncertain returns, and the lack of risk mitigation instruments in India.

Table 4: *Financial barriers in the green hydrogen sector, focusing on high capital costs, uncertain returns, and the lack of risk mitigation instruments in India.*

Barrier	Description	Quantitative Data	Citations
High capital costs	Initial investment required for setting up green hydrogen production, storage, and distribution infrastructure.	- Capital cost for electrolyzer: Estimated at $600-900 per kW [35]. - Total cost of green hydrogen production: Estimated to be between $3-6 per kg [2]. - Green hydrogen price volatility: Fluctuations of up to 30-40% annually due to market dynamics [15].	Harichandan, et al. [35]; Hassan et al. [2]. Pandey et al. [15];
Uncertain returns	The variability of returns on investment due to fluctuating hydrogen prices, technological uncertainties, and regulatory changes.	- Return on Investment (ROI): Estimated ROI for early-stage projects at only 5-7% due to initial market risks [6].	Sharma et al. (2023)[1].
Lack of risk mitigation instruments	Absence of financial products to mitigate risks associated with green hydrogen projects such as price volatility, technological failures, and policy shifts.	- Lack of insurance products for green hydrogen: Only 15% of projects have access to risk-mitigation tools like insurance [11]. - Private equity involvement: Risk-adjusted returns still low due to high perceived risk [4].	Sontakke et al. [11]; Sarker et al. [4].

5.1.1. Key observations

- **High capital costs for green hydrogen projects:** One of the most significant financial barriers to scaling up green hydrogen in India is the high initial capital expenditure required for infrastructure setup. These costs are driven by the expense of technologies like electrolyzer (ranging from $600 to $900 per kW) and the need for large-scale hydrogen production facilities [35]. The capital-intensive nature of green hydrogen production, coupled with the current early stage of the technology, increases the financial risks associated with investment, making it less attractive for private sector funding without substantial government incentives or subsidies [2].

- **Uncertain returns and market volatility:** The returns on green hydrogen investments are highly uncertain due to price volatility in the hydrogen market and fluctuating technological advancements. Green hydrogen prices can fluctuate by 30-40% annually, depending on market conditions, such as changes in renewable energy prices and global demand [15]. As a result, investors may hesitate to commit significant capital, fearing that their returns will not justify the risks. Additionally, the current low price of hydrogen compared to fossil fuels makes it challenging for green hydrogen projects to achieve competitive returns on investment, with early-stage projects often struggling to offer returns higher than 5-7% [30].

- **Lack of risk mitigation instruments:** The green hydrogen sector faces a significant gap in risk mitigation tools, which further deters investment. There is limited availability of insurance products or financial instruments that can help mitigate the risks associated with price volatility, technological failure, or changes in government policies. Research indicates that only about 15% of green hydrogen projects have access to such risk mitigation mechanisms [11]. This absence of effective risk-sharing instruments makes financing more challenging, particularly for large-scale projects that need to secure long-term investments with manageable risks. Without these instruments, financial institutions and investors perceive green hydrogen projects as high-risk, further raising the capital cost and hindering project scaling [4].

- **Lack of established financing channels:** While there are some financing channels for renewable energy projects, specific funding mechanisms for green hydrogen are still in the early stages of development. There is a limited presence of dedicated financial products such as green bonds or low-interest loans tailored for green hydrogen investments. Furthermore, the green hydrogen market remains relatively underdeveloped, making it difficult for financial institutions to assess and price the associated risks accurately. This lack of tailored financial instruments prevents the channeling of necessary capital into the sector, stifling innovation and development [4,11].

- **Inadequate government support for scaling:** While there is some government interest in promoting green hydrogen through policy incentives, such as subsidies and tax breaks, these efforts remain insufficient to address the large financial barriers hindering the sector's growth. More comprehensive and sustained government action is needed to reduce the upfront financial burden and make green hydrogen a viable investment opportunity for the private sector. A robust policy framework that guarantees long-term support for green hydrogen projects is essential to lower the financial risks and attract both domestic and international investments [6].

In conclusion, the key financial barriers—high capital costs, uncertain returns, the lack of risk mitigation tools, limited financing channels, and insufficient government support—pose significant challenges to the large-scale development of the green hydrogen sector in India. Overcoming these barriers will require coordinated efforts from the government, private sector, and financial institutions to create an enabling environment for green hydrogen investments.

5.2. Regulatory and policy challenges

Policy gaps and regulatory uncertainties.

5.2.1. Policy gaps

India's green hydrogen sector is still in its nascent stages, and one of the key hurdles to its growth is the lack of a cohesive and comprehensive policy framework. While there have been recent efforts to promote clean energy technologies, the policy landscape for green hydrogen remains fragmented and insufficiently developed. A clear national strategy on green hydrogen is yet to be fully articulated, which creates confusion among investors and stakeholders. This lack of clarity makes it difficult to establish a long-term vision that can guide investments in the sector. The existing policies, such as the National

Hydrogen Energy Mission (NHEM), have laid the groundwork for the sector but lack robust implementation mechanisms and fail to address the specific needs of green hydrogen production and distribution. There is a need for a policy that not only encourages green hydrogen production but also facilitates its integration into the existing energy infrastructure, addressing regulatory aspects like grid access and transportation standards for hydrogen [1].

5.2.2. Regulatory uncertainties

Regulatory uncertainty is another major challenge for the green hydrogen industry in India. While the government has made strides in formulating policies around renewable energy, green hydrogen faces issues of inconsistent regulatory support. For example, the classification of green hydrogen as an eligible renewable energy source in certain states remains unclear. Additionally, inconsistent carbon pricing, lack of standardized certification mechanisms, and unclear regulatory standards for green hydrogen production (e.g., purity, storage, and distribution) further complicate the development of the sector [4].

India's regulatory environment for hydrogen overlaps with multiple sectors such as energy, transport, and industry, yet there is no integrated regulatory body to oversee the development of green hydrogen. This fragmented oversight leads to a lack of coordination across different policy and regulatory frameworks, slowing down the potential for green hydrogen to gain traction in the market. Furthermore, the absence of clear regulations around safety protocols and handling of hydrogen as a flammable substance raises concerns about its widespread use [6]. To overcome these challenges, there is a clear need for a unified, forward-looking policy framework that can reduce uncertainties, provide financial incentives, and set clear standards for green hydrogen production, storage, and distribution. This will help create a stable regulatory environment that encourages investments and supports the scaling up of green hydrogen technology.

5.3. Market and infrastructure barriers

5.3.1. Limited domestic demand and underdeveloped infrastructure

The development of green hydrogen in India faces significant market and infrastructure barriers, particularly in terms of limited domestic demand and underdeveloped infrastructure, both of which hinder the rapid scaling of this technology.

- **Limited domestic demand**: Despite India’s ambitious renewable energy targets, the demand for green hydrogen remains nascent. This is partly due to the relatively high cost of production compared to conventional hydrogen and fossil fuels. As of now, green hydrogen is primarily in the research and development phase, with limited adoption in sectors like heavy industries, transportation, and power generation. The domestic market for green hydrogen is constrained by a lack of immediate commercial applications and insufficient end-user industries, which limits the economic incentives for producers [11]. The need for large-scale hydrogen utilization infrastructure is critical to foster domestic demand. Key sectors such as steel, cement, and chemicals could become major consumers of green hydrogen, but they are yet to integrate this energy source at scale. Without guaranteed demand from these sectors, the market for green hydrogen remains underdeveloped [30].

- **Underdeveloped infrastructure:** India's hydrogen infrastructure is still in its infancy. While there are some pilot projects, the country lacks a comprehensive network for the storage, transportation, and distribution of hydrogen. The infrastructure for both green hydrogen production and utilization is costly and requires significant investments. The absence of a robust pipeline network and distribution system further limits the potential for scaling green hydrogen [11].

Additionally, hydrogen storage solutions are under-researched and costly, with limited domestic capabilities to support large-scale storage and transportation of hydrogen. This limitation creates a significant barrier for the large-scale integration of hydrogen into the national energy grid.

The necessary infrastructure for the production, storage, and distribution of green hydrogen requires substantial capital investment, and without clear government incentives and market demand, private investors remain hesitant [35].

In summary, the limited domestic demand and underdeveloped infrastructure in India pose significant hurdles to the growth of the green hydrogen sector. Addressing these barriers requires strong policy interventions, financial support, and market creation strategies that incentivize both demand and infrastructure development.

6. Sustainable Financing Mechanisms for Green Hydrogen

As shown in table 5 about the comprehensive overview of key sustainable financing mechanisms for green hydrogen in India.

Table 5: *Comprehensive overview of key sustainable financing mechanisms for green hydrogen in India.*

Financing Mechanism	Description	Potential Applications	Challenges	Citations
Blended Finance Approaches	Blended finance refers to the strategic use of public and philanthropic funds to attract private investments, reducing risks and improving the financial viability of green hydrogen projects. This mechanism can support early-stage development or high-risk projects.	- Development of pilot projects in green hydrogen production. - Commercialization of green hydrogen technologies, especially in sectors like transportation and heavy industry. - Deployment of green hydrogen infrastructure (e.g., production facilities, storage systems).	- Risk-sharing structures may not be sufficient to attract private investment. - Reliance on public funds can limit scalability. - Lack of well-defined frameworks and standards in the hydrogen sector.	Taghizadeh-Hesary, et al. [9].
Green Bonds	Green bonds are debt instruments issued to raise capital specifically for projects that have environmental benefits. In the context of green hydrogen, these bonds can help finance large-scale production and	- Financing large-scale green hydrogen production plants. - Developing hydrogen storage and transportation infrastructure.	- Limited investor base in emerging economies like India, especially for high-risk sectors such as hydrogen. - Underdeveloped green bond markets, limiting the availability of funds.	Bansal, et al. [10].

	infrastructure development projects.	- Funding research and development initiatives for green hydrogen technology.	- Regulatory challenges in ensuring transparent and accountable use of funds.	
Carbon Markets	Carbon markets allow green hydrogen producers to earn revenue by offsetting their emissions through the sale of carbon credits. These markets help create an additional income stream, making green hydrogen production more financially viable.	- Offsetting costs of green hydrogen production by monetizing carbon credits. - Encouraging investments in green hydrogen projects through the sale of carbon credits. - Enhancing the financial sustainability of hydrogen projects by integrating into international carbon markets.	- Volatile prices in carbon markets can lead to unpredictable revenue streams. - Regulatory uncertainties surrounding the issuance and trading of carbon credits. - Limited awareness and adoption of carbon credits in developing economies.	Medisetty, et al. [7].
International Climate Finance	International climate finance refers to funds provided by multilateral and bilateral sources, such as the Green Climate Fund (GCF), to support climate change mitigation and adaptation efforts. Green hydrogen projects in India can leverage such funds for development and scaling.	- Funding the initial phases of green hydrogen production and infrastructure development. - Supporting large-scale, capital-intensive green hydrogen projects. - Aligning projects with global climate goals to access international funds.	- Dependence on international sources of financing may delay project implementation. - Slow disbursement of funds can create cash flow challenges. - Regulatory and policy uncertainties around climate finance usage.	Kar, et al. [37].
Public-Private Partnerships (PPP)	PPPs involve collaboration between the government and private sector entities to co-finance green hydrogen projects. These partnerships combine public funding and private sector expertise, ensuring that projects receive sufficient financial and technical support.	- Large-scale green hydrogen infrastructure (e.g., production plants, storage, and distribution systems). - Pilot projects and demonstration initiatives in partnership with private companies. - Accelerating the transition of hydrogen technologies from the research stage to commercial use.	- Complex regulatory frameworks and the difficulty in aligning the interests of both sectors. - Challenges in establishing fair and transparent profit-sharing models. - Potential delays in project execution due to bureaucratic processes.	Sontakke, et al. [11].
Green Venture Capital	Green venture capital involves investments made by venture capital firms in early-stage, high-risk green hydrogen startups. These investments help stimulate innovation and scale-up technology solutions that can make green hydrogen more cost-competitive.	- Supporting innovative startups focused on green hydrogen production, storage, and distribution technologies. - Funding research and development of next-generation hydrogen technologies. - Encouraging private sector involvement in new hydrogen business models.	- High-risk nature of early-stage investments makes it difficult to attract capital. - Long timelines to profitability, making it less attractive to some investors. - Uncertain market conditions and infrastructure readiness could deter venture capital funding.	Sharma, et al. [30].

This detailed table provides a comprehensive overview of key sustainable financing mechanisms for green hydrogen in India, emphasizing their roles, potential applications, and challenges. The mechanisms include Blended Finance Approaches, Green Bonds, Carbon Markets, International Climate Finance, Public-Private Partnerships, and Green Venture Capital, each of which can play a critical role in supporting green hydrogen development. The citations provide insights from leading research articles on financing strategies for the energy transition in India.

7. Policy and Strategy Recommendations

7.1. Creating an enabling policy environment

7.1.1. Establish a comprehensive national hydrogen policy

India requires a unified, comprehensive policy framework for green hydrogen that clearly outlines the roles of various stakeholders, targets, and pathways for the sector. This policy should encompass all aspects of the green hydrogen value chain—production, storage, transportation, distribution, and end-use. Such a framework can enhance investor confidence and align state and central government initiatives to avoid policy fragmentation.

7.1.2. Streamline regulatory approvals

Bureaucratic hurdles significantly delay the implementation of green hydrogen projects. A single-window clearance system can simplify regulatory approvals for hydrogen-related projects, reducing delays and ensuring faster deployment. This system should harmonize approvals across environmental, industrial, and infrastructure departments.

7.1.3. Introduce certification standards

Establish robust certification mechanisms to differentiate green hydrogen from other forms of hydrogen (such as grey or blue). These standards should include well-defined criteria for renewable energy inputs, emissions, and sustainability metrics, ensuring the credibility of green hydrogen in domestic and international markets.

7.1.4. Supportive carbon pricing framework

Introduce a transparent carbon pricing mechanism to incentivize industries to transition from fossil fuels to green hydrogen. A carbon tax or cap-and-trade system can create a favourable market for low-carbon products, thereby stimulating hydrogen adoption.

7.2. Incentivizing private investment

7.2.1. Tax incentives and subsidies

Offer tax holidays for green hydrogen producers and users, particularly in hard-to-abate sectors such as steel, cement, and chemicals. Additionally, provide subsidies for capital investments in electrolyzer manufacturing, renewable energy integration, and hydrogen storage infrastructure. For example, extending production-linked incentives (PLI) to include hydrogen production equipment could reduce upfront costs.

7.2.2. Risk mitigation mechanisms

Establish financial instruments like guarantees, insurance products, and concessional loans to de-risk private sector investments in green hydrogen projects. These instruments can reduce investor hesitation by mitigating risks associated with market volatility, technological failures, and policy uncertainties.

7.2.3. Green bonds and carbon credits

Facilitate the issuance of green bonds specifically for green hydrogen projects. These bonds can attract domestic and international capital, especially from environmentally-conscious investors. Furthermore, promote carbon markets where green hydrogen producers can monetize their environmental benefits through the sale of carbon credits.

7.2.4. Blended finance models

Encourage blended finance approaches by combining public funds with private capital to lower risks for investors. This can be particularly useful for early-stage projects and pilot demonstrations.

7.3. Building infrastructure and market demand

7.3.1. Public investments in infrastructure

Large-scale public investments are essential for building critical infrastructure such as hydrogen pipelines, refuelling stations, and storage facilities. These investments will reduce supply chain costs and enable the widespread adoption of green hydrogen across industries and regions.

7.3.2. Sectoral decarbonization mandates

Mandate the use of green hydrogen in specific sectors, such as fertilizers, refineries, and heavy-duty transportation. For example, policies could require a minimum percentage of hydrogen consumption in industrial processes to be sourced from renewable energy.

7.3.3. Export promotion policies

Develop export-oriented policies to position India as a global green hydrogen hub. This includes building infrastructure for hydrogen liquefaction, shipping terminals, and establishing bilateral trade agreements with hydrogen-importing countries like Japan and Germany.

7.3.4. Demand aggregation platforms

Establish platforms where industries can aggregate their hydrogen demand to achieve economies of scale.

This could make green hydrogen projects more viable and encourage industries to adopt the fuel.

7.4. Promoting research, innovation, and collaboration

7.4.1. Increase R&D funding

Allocate dedicated funding for research and development of advanced green hydrogen technologies. This includes improving electrolyzer efficiency, developing innovative storage solutions, and exploring hybrid renewable energy systems for hydrogen production.

7.4.2. Foster public-private partnerships (PPPs)

Leverage the strengths of the private sector to innovate and scale pilot projects. The government can facilitate such collaborations by providing co-funding and access to public infrastructure.

7.4.3. Enhance international collaboration

Partner with international organizations, research institutions, and countries leading in green hydrogen technologies. Such partnerships can facilitate technology transfer, capacity building, and access to global best practices. Examples include joint R&D initiatives with countries like Germany and Japan.

7.4.4. Innovation hubs

Establish regional innovation hubs focused on green hydrogen to encourage startups and research institutions to develop cost-effective solutions. These hubs can be integrated with existing renewable energy clusters to leverage synergies.

7.5. Aligning with climate and energy goals

7.5.1. Integrate with renewable energy policies

Ensure that green hydrogen policies are aligned with India's broader renewable energy targets.

For instance, link the growth of hydrogen production to the expansion of solar and wind energy capacities, enabling cost-effective electrolyzer operations.

7.5.2. Leverage international climate finance

Actively pursue funding from multilateral organizations like the Green Climate Fund (GCF) and the International Finance Corporation (IFC). These funds can support large-scale green hydrogen projects and help bridge financing gaps.

7.5.3. Adopt a regional focus

Tailor policies to local strengths by identifying regions with abundant renewable energy resources. For example, Gujarat and Maharashtra can focus on industrial green hydrogen hubs, while states with high solar and wind capacities can prioritize hydrogen production.

7.5.4. Align with SDGs and net-zero targets

Position green hydrogen development as a cornerstone of India's strategy to achieve its Sustainable Development Goals (SDGs) and the 2070 net-zero emissions target. This alignment can attract international support and reinforce India's leadership in global climate action.

7.6. Capacity building and workforce development

7.6.1. Skill development programs

Launch training programs to build a skilled workforce capable of handling green hydrogen technologies, from production to distribution. Collaborate with technical institutions and industry to design relevant curricula.

7.6.2. Awareness campaigns

Conduct public awareness campaigns to highlight the economic and environmental benefits of green hydrogen, fostering acceptance and interest among industries and consumers.

7.6.3. Institutional strengthening

Strengthen institutions like the Ministry of New and Renewable Energy (MNRE) to effectively implement green hydrogen policies and coordinate between stakeholders. By implementing these detailed recommendations, India can create a conducive environment for green hydrogen development, unlocking its potential to transform the energy landscape and drive sustainable growth [38].

8. Conclusion

Green hydrogen presents transformative potential to address India's dual challenge of achieving economic growth and meeting ambitious climate goals. This study highlights the pivotal role of green hydrogen in decarbonizing sectors like steel, cement, heavy-duty transport, and chemicals, while also aligning with the nation's Sustainable Development Goals (SDGs) and 2070 net-zero target.

8.1. Key findings

8.1.1. Policy and governance

The National Green Hydrogen Mission is a critical step forward, but fragmented policies and inconsistent regulations hinder scalability. A unified and comprehensive national framework is needed to integrate production, storage, transportation, and end-use infrastructure, supported by streamlined regulatory approvals and robust certification standards.

8.1.2. Financing challenges and opportunities

Addressing high capital costs, uncertain returns, and inadequate risk mitigation tools is crucial. Sustainable financing mechanisms—such as green bonds, blended finance, and carbon markets—are currently underutilized but hold significant potential. Leveraging

international climate finance and public-private partnerships can fill investment gaps and de-risk large-scale projects.

8.1.3. Technological and infrastructure advancements

Innovations in electrolyzer technology, hydrogen storage, and fuel cells are essential to reduce production costs and enhance efficiency. Concurrently, significant investments are needed to develop infrastructure for storage, pipelines, and refuelling stations, enabling scalability and integration with the energy system.

8.1.4. Private sector and global collaboration

Major private sector players like Reliance and Adani are driving investments, indicating confidence in the sector's potential. Collaborations with international partners, such as Germany and Japan, will enhance technology transfer, infrastructure development, and export capacity, further positioning India as a global green hydrogen hub.

8.1.5. Market development

Domestic demand creation remains a key hurdle. Policy-driven mandates for industrial and transportation applications, combined with incentives for hard-to-abate sectors, will foster market growth.

Demand aggregation platforms can further optimize economies of scale, making projects viable and accessible to a broader range of industries.

8.2. Future research directions

To overcome existing barriers and accelerate the green hydrogen transition, future research should focus on the following areas:

8.2.1. Cost reduction and efficiency improvements

- Development of next-generation electrolyzer (e.g., solid oxide and advanced proton-exchange membrane technologies) to improve efficiency and reduce costs.
- Exploration of hybrid renewable systems combining solar, wind, and storage for cost-effective hydrogen production.

8.2.2. Advanced hydrogen storage and transport

- Research into innovative storage solutions such as metal hydrides, liquid organic hydrogen carriers (LOHCs), and underground storage for better scalability and safety.
- Technological solutions for the development of cost-efficient hydrogen pipeline networks and long-distance transportation.

8.2.3. Policy framework optimization

- Analysis of global best practices in green hydrogen policies to design India-specific strategies.

- Long-term studies on the impact of carbon pricing, tax benefits, and subsidies on green hydrogen adoption across industrial and mobility sectors.

8.2.4. Market and end-use expansion

- Studies to quantify green hydrogen demand in emerging sectors like ammonia production, marine fuel, and aviation.
- Socio-economic assessments of the impact of green hydrogen adoption, including job creation, regional equity, and local energy security.

8.2.5. Integration into energy systems

- Research on green hydrogen's role in grid stabilization and renewable energy integration, particularly in addressing intermittency challenges.
- Development of frameworks to couple hydrogen production with smart energy systems and AI-driven energy management tools.

8.2.6. Export potential and geopolitical implications

- Studies on global hydrogen trade dynamics, including India's competitiveness as an exporter to Europe, Japan, and other markets.
- Analysis of geopolitical risks and strategies to ensure energy security in the context of green hydrogen exports.

8.2.7. Blended finance models and risk mitigation instruments

- Evaluation of blended finance models for hydrogen projects in developing economies, with a focus on scalability.
- Design of tailored financial instruments such as insurance schemes and guarantees to attract private capital and de-risk investments.

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