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# THE ROLE OF HYDROGEN IN FUTURE LOW CARBON ECONOMIES: A REVIEW

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## ABSTRACT

*The transition to a low-carbon economy is imperative for addressing climate change and achieving sustainable development goals. Hydrogen, particularly green hydrogen produced through renewable energy-powered electrolysis, has emerged as a critical enabler for decarbonizing hard-to-abate sectors and achieving net-zero emissions targets. This review examines the role of hydrogen in future low-carbon economies with a specific focus on the Indian context. The paper analyzes current hydrogen production pathways, applications across various sectors, technological challenges, and policy frameworks. In India, the National Green Hydrogen Mission launched in 2023 targets 5 million metric tonnes (MMT) of annual green hydrogen production capacity by 2030, accompanied by 125 GW of renewable energy capacity addition. The analysis reveals that while hydrogen offers significant potential for decarbonization in industries, transportation, and energy storage, challenges including high production costs, infrastructure development, and technological maturity need addressing. India's abundant renewable energy resources, coupled with supportive policy frameworks and strategic investments, position the country to become a global hydrogen hub. The review concludes that hydrogen's role in India's low-carbon transition will be crucial, requiring coordinated efforts across government, industry, and research institutions to realize its full potential.*

***Keywords:*** *Green hydrogen, low-carbon economy, decarbonization, renewable energy, India, National Green Hydrogen Mission, electrolysis, energy transition*

## INTRODUCTION

The global energy system is undergoing a fundamental transformation driven by the urgent need to mitigate climate change and achieve carbon neutrality. The Paris Agreement's goal of limiting global warming to 1.5°C necessitates rapid decarbonization across all sectors of the economy (IPCC, 2018). While renewable electricity has made significant strides in power generation, many industrial processes, heavy transportation modes, and energy storage applications remain challenging to electrify directly. In this context, hydrogen has emerged as a versatile energy carrier that can bridge the gap between renewable electricity generation and hard-to-abate sectors.

Hydrogen, when produced using renewable energy through electrolysis, offers a pathway to decarbonize sectors that have traditionally relied on fossil fuels. The International Energy Agency (IEA) projects that clean hydrogen could account for up to 20% of total energy consumption by 2050 in scenarios aligned with climate goals (IEA, 2019). The versatility of hydrogen extends across multiple applications, including industrial feedstock, transportation fuel, energy storage medium, and heating applications.

India, as the world's third-largest energy consumer and fourth-largest carbon emitter, faces unique challenges and opportunities in its energy transition (BP, 2023). The country's commitment to achieving net-zero emissions by 2070 and its interim target of reducing emissions intensity by 45% by 2030 compared to 2005 levels requires a comprehensive approach to decarbonization (Government of India, 2021). India started its National Hydrogen Mission on 4 January 2023, aiming to become a global leader in green hydrogen production by 2030, with at least 5 million metric tonne (MMT) annual capacity, attracting more than Rs. 8 lakh crore (US$ 95.9 billion) in investments.

This review paper examines the role of hydrogen in enabling low-carbon economies with a particular emphasis on the Indian context. It analyzes current production technologies, applications across various sectors, economic considerations, policy frameworks, and the challenges and opportunities that lie ahead. The paper aims to provide a comprehensive understanding of how hydrogen can contribute to India's sustainable energy future while drawing insights from global developments and best practices.

# HYDROGEN PRODUCTION PATHWAYS

## 2.1 Classification of Hydrogen by Production Method

Hydrogen production methods are commonly classified using a color-coding system that reflects the carbon intensity and environmental impact of different production routes. Grey hydrogen, produced from natural gas through steam methane reforming (SMR) without carbon capture, represents the majority of current global production, accounting for approximately 75% of total hydrogen supply (IEA, 2023). Blue hydrogen involves the same SMR process but incorporates carbon capture, utilization, and storage (CCUS) technologies to reduce greenhouse gas emissions. Green hydrogen, produced through electrolysis using renewable electricity, represents the ultimate low-carbon solution but currently accounts for less than 0.1% of global production due to high costs (IRENA, 2022).

Other production pathways include turquoise hydrogen from methane pyrolysis, pink hydrogen from nuclear-powered electrolysis, and yellow hydrogen from grid electricity with varying carbon intensity. Each pathway presents different cost structures, environmental impacts, and scalability potential, with green and blue hydrogen being the primary focus for long-term decarbonization strategies.

## 2.2 Green Hydrogen Production Technologies

Electrolysis technologies for green hydrogen production can be categorized into three main types: alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOEC). Alkaline electrolysis, the most mature and widely deployed technology, operates at relatively low temperatures (60-80°C) and uses liquid alkaline electrolytes. PEM electrolysis offers higher efficiency and faster response times, making it more suitable for integration with variable renewable energy sources, though it requires expensive noble metal catalysts (Schmidt et al., 2017).

SOEC technology, operating at high temperatures (700-850°C), achieves the highest theoretical efficiency but faces challenges related to material durability and thermal cycling. Recent technological advances have focused on improving efficiency, reducing costs, and extending operational lifespans of electrolyzers. The IEA reports that electrolyzer costs have decreased by approximately 60% since 2015, though further cost reductions are necessary for widespread deployment (IEA, 2022).

### 2.3 Indian Context: Production Potential and Challenges

India's renewable energy resources present significant opportunities for green hydrogen production. The country has set ambitious renewable energy targets, aiming for 500 GW of non-fossil fuel capacity by 2030, which provides the foundation for large-scale green hydrogen production (MNRE, 2022). Solar photovoltaic and wind power costs in India have reached grid parity in many regions, making renewable electricity increasingly competitive for hydrogen production.

By the year 2030, this Mission targets to: Development of green hydrogen production capacity of at least 5 MMT (Million Metric Tonne) per annum with an associated renewable energy capacity addition of about 125 GW in the country. The National Green Hydrogen Mission envisions India becoming a global hub for green hydrogen production and export, leveraging the country's abundant renewable resources and manufacturing capabilities.

However, several challenges must be addressed to realize this potential. Current green hydrogen production costs in India range from $4-6 per kg, significantly higher than grey hydrogen at $1-2 per kg (TERI, 2021). Infrastructure development, including dedicated renewable energy projects, electrolysis facilities, and distribution networks, requires substantial investments. Additionally, technical challenges related to system integration, grid stability, and energy storage need innovative solutions.

## APPLICATIONS OF HYDROGEN IN LOW-CARBON ECONOMIES

### 3.1 Industrial Applications

Industrial applications represent the largest current demand for hydrogen and offer significant decarbonization potential. Traditional hydrogen consumption in refineries for hydrotreating and hydrocracking processes can be decarbonized by switching from grey to green hydrogen. The steel industry, responsible for approximately 7-9% of global $CO_2$ emissions, can utilize hydrogen as a reducing agent in direct reduced iron (DRI) processes, eliminating coal-based production routes (Vogl et al., 2018).

Ammonia production, essential for fertilizer manufacturing, currently consumes about 30% of global hydrogen supply. Green ammonia produced using green hydrogen can significantly reduce the carbon footprint of agricultural sectors while serving as a hydrogen carrier for international trade. The cement industry, another hard-to-abate sector, can potentially utilize hydrogen for high-temperature process heat, though technological maturity and economic viability remain challenges.

Chemical industries utilize hydrogen in various processes, including methanol production, synthetic fuel manufacturing, and petrochemical processing. The transition to green hydrogen in these applications can substantially reduce industrial emissions while maintaining production capacity and quality standards.

### 3.2 Transportation Sector

Hydrogen fuel cell vehicles (FCVs) offer zero-emission transportation solutions, particularly suitable for heavy-duty, long-range, and high-utilization applications where battery electric vehicles face limitations. Commercial transport, including trucks, buses, and maritime vessels, represents the most promising near-term market for hydrogen mobility due to operational requirements that favor hydrogen's advantages in range, refueling time, and payload capacity (Hydrogen Council, 2020).

Light-duty passenger vehicles face stronger competition from battery electric vehicles, which have achieved significant cost reductions and performance improvements. However, hydrogen remains relevant for specific use cases, including fleet operations, long-distance travel, and regions with limited charging infrastructure. Railway applications, particularly for non-electrified lines, present opportunities for hydrogen trains to replace diesel-powered services.

Maritime and aviation sectors represent long-term opportunities for hydrogen and its derivatives. Synthetic fuels produced using green hydrogen, including sustainable aviation fuels (SAF) and green methanol, can decarbonize international shipping and aviation where direct electrification is not feasible (IRENA, 2021).

### 3.3 Energy Storage and Grid Services

Hydrogen offers unique advantages for long-duration energy storage, complementing battery storage systems that excel in short-duration applications. Power-to-gas-to-power systems using hydrogen can store energy for days, weeks, or months, addressing seasonal variability in renewable energy generation. This capability is particularly valuable for energy systems with high renewable penetration where maintaining grid stability requires flexible storage solutions (Staffell et al., 2019).

Grid balancing services, including frequency regulation and voltage support, can benefit from hydrogen systems' ability to rapidly adjust power consumption or generation. Electrolyzers can provide demand response services by modulating hydrogen production based on grid conditions, while fuel cells can inject power during peak demand periods or grid emergencies.

Sector coupling, facilitated by hydrogen, enables integration across electricity, heating, transportation, and industrial sectors. This integration can improve overall energy system efficiency while providing multiple revenue streams for hydrogen infrastructure investments.

### 3.4 Indian Sectoral Applications

India's industrial landscape presents diverse opportunities for hydrogen applications. The country's steel industry, producing over 100 million tonnes annually, can benefit from hydrogen-based direct reduction technologies to reduce coal dependence (Joint Plant Committee, 2022). Fertilizer production, crucial for India's agricultural sector, represents another significant opportunity given the country's position as the world's second-largest consumer of fertilizers.

Transportation applications in India focus primarily on commercial vehicles and public transportation. Heavy-duty trucking for freight transport across the country's extensive highway network offers favorable economics for hydrogen fuel cells. Urban bus fleets in major cities have initiated pilot projects to demonstrate hydrogen mobility solutions, with several state governments announcing supportive policies.

The refinery sector, with India being the world's third-largest oil refiner, presents immediate opportunities for green hydrogen adoption. Existing hydrogen demand in refineries can be met through green production, establishing the initial market foundation while supporting capacity building and cost reductions.

# ECONOMIC CONSIDERATIONS

## 4.1 Cost Dynamics and Projections

The economics of hydrogen production, transport, and utilization remain critical factors determining the pace and scale of deployment. Global hydrogen demand reached more than 97 Mt in 2023 and could reach almost 100 Mt in 2024, demonstrating growing market momentum. However, cost competitiveness with conventional alternatives remains a challenge across most applications.

Green hydrogen production costs depend primarily on electricity prices, capital costs of electrolyzers, capacity factors, and operational efficiencies. The International Renewable Energy Agency (IRENA) projects that green hydrogen costs could decrease to $1.3-3.5 per kg by 2030, depending on regional conditions and technology improvements (IRENA, 2022). This represents a significant reduction from current levels but still requires further cost compression to achieve widespread market adoption.

Blue hydrogen production costs, while currently lower than green hydrogen, face uncertainties related to carbon pricing, CCUS technology costs, and natural gas price volatility. Long-term sustainability considerations and potential stranded asset risks may limit blue hydrogen's role as a transitional solution.

Transport and storage costs add significant premiums to delivered hydrogen prices. Pipeline transport is most economical for large volumes and short to medium distances, while shipping in the form of liquefied hydrogen or ammonia becomes viable for international trade. Distribution infrastructure development requires substantial investments but benefits from economies of scale and network effects.

## 4.2 Financing and Investment Requirements

To accelerate the global energy system decarbonisation, an 8-fold increase of investments in hydrogen is required until 2030, compared to the current investment of USD 75bn past FID. This massive investment requirement spans across production facilities, transport infrastructure, storage systems, and end-use applications.

Public sector support through grants, subsidies, tax incentives, and risk-sharing mechanisms plays a crucial role in early market development. Germany's National Hydrogen Strategy allocated €9 billion for hydrogen technologies, while the European Union's Green Deal includes substantial hydrogen investments. Similar public sector commitments are emerging globally, creating momentum for private sector participation.

Private sector investment is gradually increasing as technology risks decrease and market prospects improve. Corporate partnerships, joint ventures, and strategic alliances are becoming common structures for sharing risks and accessing complementary capabilities. Financial institutions are developing specialized expertise and funding instruments for hydrogen projects, though project financing remains challenging due to limited operating track records.

## 4.3 Indian Investment Landscape

Over Rs. Eight lakh crore in total investments are targeted under India's National Green Hydrogen Mission, representing one of the world's most ambitious hydrogen investment programs. This investment encompasses production capacity development, infrastructure creation, research and development, and demand stimulation across various sectors.

Public sector enterprises, including Indian Oil Corporation, Bharat Petroleum Corporation, and NTPC, have announced significant hydrogen investments and pilot projects. Private sector companies, particularly in the renewable energy and chemical sectors, are also committing substantial resources to hydrogen value chain development.

International cooperation and technology transfer agreements are facilitating investment flows and knowledge sharing. India has signed hydrogen partnerships with several countries, including Germany, Japan, and Australia, creating pathways for technology collaboration and potential trade relationships.

## CHALLENGES AND BARRIERS

### 5.1 Technological Challenges

Despite significant progress, hydrogen technologies face several technical challenges that impact performance, reliability, and cost-effectiveness. Electrolyzer durability remains a concern, with most commercial systems requiring stack replacement after 60,000-80,000 operating hours. Material degradation, particularly in harsh operating conditions, affects long-term performance and economics.

System efficiency improvements are needed across the entire hydrogen value chain. Current electrolysis systems typically achieve 65-70% electrical efficiency, with further improvements possible through advanced materials, system optimization, and heat integration. Fuel cell efficiency and durability also require enhancement for widespread deployment in transport and stationary applications.

Hydrogen storage presents technical challenges related to volumetric energy density, compression costs, and material compatibility. High-pressure storage requires expensive composite materials and safety systems, while liquid hydrogen storage involves significant energy penalties for liquefaction. Advanced storage technologies, including metal hydrides and liquid organic hydrogen carriers, are under development but require further maturation.

### 5.2 Economic and Market Barriers

Cost competitiveness remains the primary barrier to widespread hydrogen adoption. Despite projected cost reductions, green hydrogen production costs exceed those of conventional alternatives in most applications. This cost disadvantage is compounded by additional expenses for transport, storage, and conversion equipment.

Market development faces chicken-and-egg challenges where supply infrastructure development requires demand certainty, while demand growth depends on reliable and cost-effective supply. First-mover disadvantages and early deployment risks discourage private sector investment without public sector support and risk mitigation mechanisms.

Financing challenges stem from limited operational track records, long payback periods, and technology risks. Project financing structures must accommodate the unique characteristics of hydrogen projects, including variable renewable energy inputs, long-term off-take agreements, and regulatory uncertainties.

### 5.3 Infrastructure and Regulatory Challenges

Hydrogen infrastructure development requires substantial investments in production facilities, transport networks, storage systems, and distribution infrastructure. Pipeline networks must be designed for hydrogen's unique properties, including its tendency to cause hydrogen embrittlement in certain steel grades. Existing natural gas pipelines may require upgrades or replacement for hydrogen service.

Safety regulations and standards for hydrogen systems must be established and harmonized across jurisdictions. Hydrogen's wide flammability range and rapid flame propagation require specific safety protocols, detection systems, and emergency response procedures. Public acceptance and awareness campaigns are necessary to address safety concerns and build confidence in hydrogen technologies.

Regulatory frameworks must address quality standards, certification procedures, and market mechanisms that enable fair competition and consumer protection. Grid integration rules for electrolyzers and fuel cells require development to ensure system stability and optimal resource utilization.

### 5.4 Indian-Specific Challenges

India faces unique challenges related to its diverse geographical, climatic, and economic conditions. Water availability for electrolysis presents constraints in water-stressed regions, requiring desalination or water recycling technologies. Grid integration challenges arise from varying power quality and reliability across different regions.

Skill development and workforce training requirements are substantial given the scale of India's hydrogen ambitions. Technical expertise in hydrogen technologies, safety protocols, and system integration must be developed across the workforce spectrum. Educational institutions and training programs need enhancement to support industry requirements.

Land acquisition for large-scale renewable energy and hydrogen production facilities can face procedural delays and local resistance. Coordination between central and state governments, regulatory agencies, and local communities requires effective governance mechanisms.

## OPPORTUNITIES AND FUTURE PROSPECTS

### 6.1 Global Market Opportunities

From 0.5 million metric tons (Mt) of capacity online today, annual low-carbon hydrogen supply could grow 30x by 2030, indicating substantial market growth potential. International trade in hydrogen and its derivatives is expected to develop significantly, with several countries positioning themselves as exporters to meet global demand.

Technological improvements continue to drive cost reductions and performance enhancements across the hydrogen value chain. Advances in electrolyzer technology, fuel cell efficiency, and system integration are accelerating deployment timelines and improving economic viability. Digitalization and artificial intelligence applications are optimizing system operations and maintenance.

Industrial decarbonization mandates and carbon pricing mechanisms create growing demand for clean hydrogen across various sectors. Corporate sustainability commitments and environmental, social, and governance (ESG) considerations are driving private sector hydrogen adoption. Supply chain decarbonization requirements are extending hydrogen demand beyond direct industrial users.

### 6.2 India's Strategic Advantages

India possesses several strategic advantages for hydrogen market leadership. Abundant renewable energy resources, particularly solar and wind, provide the foundation for cost-competitive green hydrogen production. The country's manufacturing capabilities and cost advantages can support domestic value chain development and global competitiveness.

Large domestic markets in steel, refining, fertilizers, and transportation provide natural demand for hydrogen, creating economies of scale and supporting infrastructure development. India's growing energy demand offers opportunities for hydrogen integration across multiple sectors while contributing to energy security and import reduction goals.

Geographic location provides strategic access to major energy-importing regions, including Europe, East Asia, and the Middle East. Port infrastructure and maritime trade expertise can facilitate hydrogen export development as international markets mature.

### 6.3 Innovation and Research Opportunities

Research and development initiatives are addressing key technical challenges and exploring advanced hydrogen technologies. Indian research institutions and companies are working on catalyst development, system optimization, and integration technologies. Collaboration with international partners accelerates technology transfer and knowledge sharing.

Startup ecosystems and entrepreneurial activities are emerging around hydrogen technologies, supported by government initiatives and private sector investments. Innovation hubs and incubation programs are fostering technology development and commercialization activities.

Digital technologies, including blockchain for hydrogen certification, IoT for system monitoring, and artificial intelligence for optimization, offer opportunities for leapfrogging and creating competitive advantages in hydrogen systems.

## INTERNATIONAL COOPERATION AND TRADE

### 7.1 Global Hydrogen Trade Potential

International hydrogen trade is expected to grow significantly as countries with abundant renewable resources emerge as exporters to meet demand in resource-constrained regions. Various carriers, including liquid hydrogen, ammonia, and liquid organic hydrogen carriers, are being evaluated for long-distance transport. Ammonia has emerged as a leading candidate due to existing transport infrastructure and handling experience.

Trade relationships are forming between potential exporters like Australia, Chile, and the Middle East with importing regions including Japan, South Korea, and Europe. These partnerships often include technology transfer, financing arrangements, and long-term off-take agreements that provide certainty for large-scale infrastructure investments.

Certification and standards harmonization are critical for international trade development. Green hydrogen certification systems must ensure environmental integrity while facilitating trade flows. International cooperation on standards development and mutual recognition agreements will reduce trade barriers and transaction costs.

### 7.2 India's Role in Global Hydrogen Trade

India's potential as a hydrogen exporter depends on achieving competitive production costs and developing export infrastructure. The country's renewable energy targets and hydrogen production capacity goals position it to serve both domestic demand and export markets. Strategic partnerships with potential importing countries are being developed to establish long-term relationships.

Port infrastructure development for hydrogen exports requires substantial investments in specialized facilities, storage systems, and handling equipment. Several Indian ports are exploring hydrogen export capabilities, with Gujarat and Tamil Nadu emerging as potential hydrogen hubs due to their industrial base and connectivity.

Technology partnerships with advanced hydrogen economies provide opportunities for knowledge transfer, joint research, and market development. India's collaborations with Germany, Japan, and other countries facilitate access to advanced technologies while building trade relationships.

## ENVIRONMENTAL IMPACT AND SUSTAINABILITY

### 8.1 Life Cycle Environmental Assessment

Comprehensive life cycle assessments of hydrogen systems are essential for evaluating environmental benefits and identifying optimization opportunities. Green hydrogen from renewable electricity demonstrates significant greenhouse gas reduction potential compared to fossil fuel alternatives. However, upstream impacts from renewable energy infrastructure and downstream effects from hydrogen applications must be considered.

Water consumption for electrolysis represents an environmental consideration, particularly in water-stressed regions. Approximately 9-18 liters of water are required to produce 1 kg of hydrogen through electrolysis, though water recycling and seawater desalination can mitigate freshwater impacts. Integration with water treatment systems and circular economy principles can minimize environmental footprints.

Material requirements for electrolyzers and fuel cells include critical minerals such as platinum, iridium, and rare earth elements. Sustainable sourcing practices, recycling programs, and material substitution research are necessary to ensure long-term sustainability and supply security.

### 8.2 Integration with Circular Economy

Hydrogen systems can contribute to circular economy principles through waste-to-hydrogen pathways, including biomass gasification, waste pyrolysis, and biogas reforming. These approaches utilize organic waste streams while producing useful hydrogen, supporting waste management and resource recovery objectives.

Industrial symbiosis opportunities exist where hydrogen production integrates with other processes, sharing utilities, infrastructure, and waste streams. Steel plants, refineries, and chemical facilities can optimize resource utilization through integrated hydrogen systems and heat recovery.

End-of-life management for hydrogen equipment requires development of recycling and recovery programs. Electrolyzer stacks, fuel cells, and storage systems contain valuable materials that can be recovered and reused, supporting circular economy objectives while reducing material demand.

## CONCLUSIONS AND FUTURE OUTLOOK

The role of hydrogen in future low-carbon economies is becoming increasingly critical as countries worldwide pursue ambitious decarbonization goals. Hydrogen offers unique advantages in addressing hard-to-abate sectors, long-duration energy storage, and industrial applications where direct electrification is not feasible. The versatility of hydrogen as an energy carrier enables sector coupling and system integration opportunities that can optimize overall energy system performance.

The policy measures in the Hydrogen Mission are expected to reduce the green hydrogen production cost to $1.5 per kg by 2030, indicating India's commitment to achieving cost competitiveness with conventional alternatives. The country's National Green Hydrogen Mission represents one of the world's most ambitious hydrogen development programs, with substantial targets for production capacity, investment mobilization, and emissions reduction.

India's strategic advantages, including abundant renewable energy resources, large domestic markets, manufacturing capabilities, and geographic location, position the country to become a significant player in the global hydrogen economy. However, realizing this potential requires addressing technical, economic, and infrastructure challenges while maintaining policy support and international cooperation.

The success of hydrogen deployment in India will depend on coordinated efforts across government, industry, and research institutions. Technology development and cost reduction remain critical priorities, while infrastructure development and market creation require sustained investments and policy support. Safety standards, regulatory frameworks, and public acceptance are essential foundations for sustainable hydrogen economy development.

Future research and development priorities should focus on advanced materials, system integration, and application-specific optimizations. International cooperation will continue to play a crucial role in technology transfer, trade relationship development, and standards harmonization. The hydrogen economy's evolution will require adaptive policies and flexible strategies that respond to technological progress and market developments.

India's hydrogen journey represents both significant opportunities and substantial challenges. The country's commitment to sustainable development and energy security aligns well with hydrogen's potential contributions. Success in developing a robust hydrogen economy will not only support India's climate goals but also demonstrate pathways for other developing countries to achieve sustainable energy transitions while maintaining economic growth and social development objectives.

The transition to a hydrogen-enabled low-carbon economy requires long-term vision, sustained commitment, and collaborative action across multiple stakeholders. India's National Green Hydrogen Mission provides a strong foundation for this transition, but implementation success will determine the ultimate impact on the country's sustainable development trajectory and global climate objectives.

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