

Advancing Energy Solutions Through the Green Hydrogen

Introduction

Green hydrogen is rapidly emerging as a cornerstone of the global transition to sustainable energy systems. Produced through the electrolysis of water and powered by renewable energy sources, it emits minimal greenhouse gases, making it a clean, versatile energy carrier. Hydrogen is categorized into various types based on production methods, with green hydrogen gaining significant global traction due to its potential to decarbonize hard-to-electrify sectors and help nations achieve ambitious climate targets. Beyond addressing emissions, green hydrogen offers

opportunities to drive economic growth, enhance energy security, and build a resilient, low-carbon future. To address challenges associated with green hydrogen, governments and industries worldwide are investing heavily in hydrogen strategies, infrastructure, and technologies to harness its transformative potential. This article explores the classification of hydrogen by production methods, examines the potential and significance of green hydrogen, reviews its applications, and analyses the global and national scenarios, along with the challenges and opportunities it presents for a

sustainable energy transition.

Hydrogen and its Types

Hydrogen (H₂), commonly referred to as the “fuel of the future,” is the simplest and most abundant element in the universe. It is a lightweight, storable, colourless, odourless, and highly flammable gas that produces no emissions on its own. **Its classification into various colours is based on the production methods and their sustainability,** emphasizing the environmental impact and facilitating the identification of eco-friendly practices that align with climate action objectives.

Hydrogen Color	Production Process	Energy Source	By product	GHG Footprint	
White	Naturally occurring	Naturally occurring, Industrial Waste	NA	NA	
Green	Electrolysis	Renewables: solar, wind, hydro, geothermal, tidal	Oxygen	Near Zero	
Pink		Nuclear heat / electricity	Nuclear waste, Oxygen	Medium	
Yellow		Solar or a mix of energy from electrical grid	Oxygen		
Red	Biomass Gasification + CCUS	Biomass	Carbon dioxide, sequestered through CCUS	Near Zero	
Blue	SMR, Gasification + CCUS	Natural gas and coal	Solid carbon	Low	
Turquoise	Pyrolysis	Natural gas		Medium to low	
Grey	SMR but no CCUS	Lignite Coal		Carbon dioxide	Medium
Brown	Gasification		Black Coal		Highest
Black					

Green Hydrogen as Fuel of the Future

Green hydrogen, a clean and

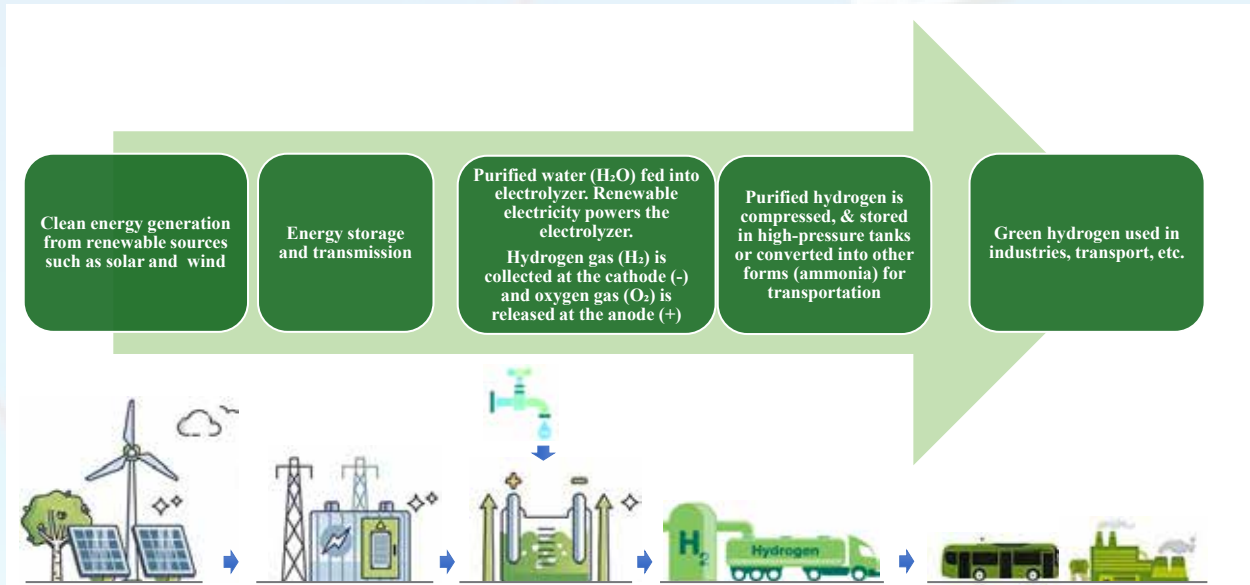
sustainable form of hydrogen, is produced through the electrolysis of water using electricity from

renewable sources like solar, wind, or hydropower. **This process splits water into**

hydrogen and oxygen, emitting only water vapor and leaves no greenhouse gases or other harmful residues. When it needs to turn into energy, hydrogen stored in specific tanks is

channelled into a fuel cell. There it binds again with oxygen from the air and electricity is obtained. Thus, the only by-product of the process is water, resulting in a clean, sustainable system in which

zero CO₂ is emitted to produce energy. As a zero-pollution fuel, green hydrogen offers immense potential as both an energy carrier and a raw material.



Potential and Significance of Green Hydrogen

Green hydrogen is quickly establishing itself as a key driver in the global shift toward sustainable energy systems. Recognized as a vital solution for achieving carbon neutrality, it plays a central role in the energy transition being explored by economies worldwide. With a **high gravimetric energy density of approximately 33.33 kWh per kilogram** (~ 3-times that of diesel or gasoline by weight), green hydrogen serves as an efficient fuel for energy-intensive applications requiring compact storage, such as aviation, shipping, and long-haul transportation. This highlights its vast potential to advance decarbonization, enhance energy security, foster economic growth, and sustainably power the future.

One of the most significant advantages of green hydrogen is its **balancing ability to address the intermittent nature of renewable energy sources**. By storing surplus energy generated during peak production periods, green hydrogen **ensures a consistent and reliable energy supply**, bridging the gap between energy generation and consumption. Moreover, being an extremely light element, green hydrogen **can be stored in compressed tanks** that are lighter and more manageable than lithium batteries, making transportation more efficient and convenient. It also **enhances energy security** by diversifying energy sources, reducing reliance on fossil fuel imports, mitigating supply chain risks, and reduce vulnerabilities to price shocks in global energy markets.

Green hydrogen provides a means to cut greenhouse gas emissions in industries where direct electrification is difficult, or by replacing grey hydrogen as a feedstock in industries like ammonia production, refining, and petrochemicals. As the world strives to meet ambitious Net Zero targets, **green hydrogen plays a critical role in decarbonizing hard-to-abate sectors such as steel, cement, chemicals, shipping, and aviation industries, that have traditionally relied on fossil fuels and contributed significantly to global emissions**. Green hydrogen fuels hydrogen fuel cell vehicles (FCEVs), including cars, buses, trucks, and trains, offering a zero-emission alternative to internal combustion engines.

Application of Green Hydrogen	
Industry	<ul style="list-style-type: none"> • Steel Manufacturing: Green hydrogen replaces coking coal in the Direct Reduction Iron (DRI) process, reducing CO₂ emissions. • Chemical Industry: Used as a feedstock for ammonia (fertilizers), methanol, and plastics, replacing grey hydrogen to lower emissions. • Oil Refining: Employed in hydrocracking and desulfurization processes, offering a cleaner alternative to conventional hydrogen
Energy Storage and Production	<ul style="list-style-type: none"> • Power Generation: Used in fuel cells or hydrogen turbines to produce electricity with water vapor as the only by product. • Energy Storage: Stores excess renewable energy (e.g., wind, solar) for later use, ensuring grid stability and supply during peak demand. • Hydrogen Blending: Blended with natural gas for use in existing pipelines, reducing the carbon intensity of natural gas systems.
Transport	<ul style="list-style-type: none"> • Commercial transportation accounts for approximately 13% of today's global CO₂ emissions. Green hydrogen may be key fuel decarbonise this sector which are difficult to electrify. • Fuel Cell Vehicles (FCEVs): Powers cars, buses, trucks, and trains, especially for long distances and heavy-duty transport. Hydrogen fuel cells provide a higher energy density than batteries, making them more suitable for long-range travel. • Aviation and Shipping: Provides a cleaner fuel option for aviation and maritime industries, reducing dependence on fossil fuels.
Domestic and commercial use	<ul style="list-style-type: none"> • Heating and Cooling: Used for residential and commercial heating through hydrogen boilers or Combined Heat and Power (CHP) systems, offering a low-carbon alternative to natural gas. • Power Backup: Small-scale hydrogen fuel cells can provide backup power for homes, hospitals, data centres, and other critical business facilities, providing a clean electricity alternative to diesel generators.
Green Hydrogen in Agriculture	<ul style="list-style-type: none"> • Green hydrogen can be used to power farming machinery such as tractors, harvesters, other farming equipment, and producing fossil-based fertilizers.
Decentralized Power Solutions	<ul style="list-style-type: none"> • Powers remote areas and islands where extending traditional energy grids is challenging, using hydrogen-based microgrids.

Green hydrogen supports global climate action by enabling significant GHG emission reductions. According to the Hydrogen Council, **hydrogen could abate 80 gigatons of CO₂ emissions cumulatively by 2050**, with an annual reduction potential of 7 gigatons, representing 20% of the required global reductions by mid-century. This sector also holds transformative economic

potential, offering extensive **opportunities for job creation** across the value chain, from manufacturing and infrastructure development to research and technological innovation. Moreover, local production of green hydrogen can **substantially reduce reliance on fossil fuel imports**. Renewable energy-based hydrogen production can **spur economic development**

in rural and remote areas rich in renewable energy resources, while green hydrogen derived from waste biomass presents an avenue for farmers to generate supplementary income, further supporting rural economies.

Global Hydrogen Market and Growth Projections

Hydrogen has been used in industries since the 19th century

to power cars, airships, and spacecraft. As the global push for decarbonization intensifies, hydrogen is emerging as a critical solution. Countries like the United States, Russia, China, France, and Germany already utilize hydrogen extensively, while nations such as Japan aim

to transition into full-fledged hydrogen economies. **Nations with abundant renewable energy resources, including India, Australia, and parts of the Middle East, are positioning themselves as global hubs for green hydrogen production and exports.** Green hydrogen is

especially vital for decarbonizing sectors that are hard to electrify, such as heavy industry, aviation, and shipping. Its role in replacing fossil fuels and acting as an energy storage medium makes it indispensable in combating climate change and achieving net-zero targets.



The global green hydrogen market is poised for substantial growth, driven by the clean energy transition. **Research estimates the green hydrogen market size at \$8.78 billion in 2024, is projected to surge to \$165.84 billion by 2033, reflecting a robust CAGR of 38.5%.** This growth is fuelled by advancements in electrolyzer and smart grid technologies, increased government initiatives, and rising awareness of green hydrogen's environmental benefits. Enhanced grid stability contributes to the growing adoption of green hydrogen in the utilities sector, supporting their critical role in maintaining safe and efficient operations across electrical networks. Key drivers of this gigantic

market include global net-zero commitments, rising demand from hard-to-abate sectors, and expanding applications in clean mobility for heavy transport, shipping, and aviation. **Countries worldwide are developing National Hydrogen Roadmaps to integrate hydrogen into their energy systems strategically.** By investing in infrastructure, advancing production technologies, and fostering international collaborations, hydrogen is set to become a cornerstone of a resilient, low-carbon global economy.

India's Advancement in Green Hydrogen Industry

India has achieved remarkable progress in the green hydrogen

sector, establishing itself as a frontrunner in the global shift toward sustainable energy. Backed by comprehensive policy frameworks, vast renewable energy potential, and dynamic public-private partnerships, India is paving the way for a green energy revolution while making a substantial contribution to global climate objectives. **This progress is underpinned by robust policy support, including the National Green Hydrogen Mission, which promotes large-scale production and adoption.**

National Green Hydrogen Mission (NGHM): It was launched by the Ministry of New and Renewable Energy (MNRE) in January 2023 with a budget allocation of ₹ 19,744 crores.

Cabinet approves National Green Hydrogen Mission with an outlay of Rs 19,744 crore
Rs 17,490 crore for SIGHT program

Outcomes

- Hydrogen production capacity to reach 5 MMT per annum
- Addition of 125 GW renewable energy capacity by 2030
- Creation of over 6 lakh jobs
- Reduction in fossil fuel imports of over Rs 1 Lakh crore
- Reduction of 50 MMT of annual greenhouse gas emissions

*MMT - Million Metric Tonne
*SIGHT - Strategic Interventions for Green Hydrogen Transition Program

This initiative aims to position India as a global leader in green hydrogen production and exports, targeting the **production of 5 million metric tonnes (MMT) annually by 2030**. Earlier, in February 2022, the Government introduced the Green Hydrogen Policy, which supports projects for producing, transmitting, and distributing green hydrogen. To enhance transparency and credibility, MNRE also launched the **Green Hydrogen Certification Scheme**, establishing a framework to measure, monitor, and certify production. Additionally, the **Green Hydrogen Standard** defines sustainable production methods for the industry. Under this mission, the **Strategic Interventions for Green Hydrogen Transition (SIGHT) program** offers ₹ 17,490

crores in incentives, with ₹ 4,440 crores for electrolyzer manufacturing and ₹ 13,050 crores for hydrogen production. Moreover, **Production-Linked Incentive (PLI) schemes** further promote domestic manufacturing in this sector. Considering environmental regulations, the MNRE has introduced a **Greenhouse Gas Emissions Standard**, capping non-biogenic GHG emissions at 2 kgCO₂ per kilogram of hydrogen (kgH₂), applicable to both electrolysis-based and biomass-based production methods. The NGHM has also supported infrastructure development. India has **established Green Hydrogen Industrial Clusters**, including the Kochi Green Hydrogen Hub, Kerala Green Hydrogen Valley, and Gujarat's Mundra and Rapar clusters, aiming to produce 3

MMT annually in Gujarat alone by 2030, with two more Green Hydrogen Hubs planned in near future. To drive innovation in the sector, **₹ 400 crores have been allocated under the NGHM for research and development (R&D)**. These funds are aimed at advancing technologies and solutions to make green hydrogen production more efficient and cost-effective.

Additionally, **India is actively fostering international collaborations** to accelerate its green hydrogen initiatives and strengthen its position in the global energy transition.

Key bilateral agreements include the **Indo-German Green Hydrogen Roadmap**, focusing on joint research, technology transfer, and sustainable hydrogen infrastructure development.



India has also partnered with the European Union, Denmark, and Japan to advance green hydrogen technologies, establish supply chains, and develop export markets. On global platforms, India is a prominent member of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and hosted its 41st Steering Committee Meeting in 2024. Additionally, India participates in the Green Hydrogen Catapult, a coalition aimed at accelerating hydrogen production and deployment globally. Collaborating with the International Solar Alliance (ISA), India has launched the Green Hydrogen Innovation Centre to drive innovation and address challenges in hydrogen adoption. These collaborations aim to enhance India's capacity to produce and export green hydrogen.

Indian Public Sector Enterprises (PSEs), owing to its scale,

operational diversity, and role in national economy (~12% of the national GDP), play a pivotal role in advancing the adoption of green hydrogen, aligning with the nation's ambitious clean energy and decarbonization goals. Major energy-focused PSEs are actively exploring green hydrogen applications in refining, power generation, natural gas blending, and transport. Some PSEs are leveraging their resources and expertise to pilot projects, including electrolyzer manufacturing, establishment of hydrogen fuelling stations, developing hydrogen-based transport systems while integrating green hydrogen into existing industrial processes. Some PSEs are actively financing green hydrogen projects, and contributing to research and development (R&D) by collaborating with academic institutions and international organizations to enhance hydrogen production efficiency

and reduce costs. Overall, PSE's proactive engagement is crucial for accelerating India's green hydrogen economy and supporting climate action goals.

Challenges and Opportunities in Adoption of Green Hydrogen

Despite its immense potential, the widespread adoption of green hydrogen faces several challenges. One of the primary challenges is cost. Generating energy from renewable sources, which is essential for producing green hydrogen through electrolysis, remains expensive. Although advancements in technology and economies of scale are gradually reducing costs, green hydrogen production is still more expensive than hydrocarbon-based alternatives. Additionally, the energy consumption required for hydrogen production, especially green hydrogen, is higher than other fuels, making efficiency improvements critical. Safety concerns also present a hurdle, as

green hydrogen is highly volatile and flammable, necessitating stringent safety measures to prevent leaks and potential explosions. Furthermore, scaling up production and infrastructure to meet growing demand requires substantial investment, posing a significant challenge to its adoption. Global adoption of hydrogen technologies depends heavily on collaboration between governments, industries, and research institutions. Expanding international partnerships is essential to promote knowledge exchange, technology transfer, and investment in hydrogen projects. Equally important are supportive policies, including government incentives, subsidies, and regulations, to reduce initial costs and risks, enhance competitiveness, and accelerate the transition to green hydrogen. Despite these challenges, the green hydrogen sector is expected to evolve rapidly with ongoing technological advancements, stronger collaborations, and a robust policy framework, paving the way for a cleaner, more sustainable future.

However, declining renewable energy costs have created an opportunity for green hydrogen to become more competitive. Solar energy is now ten times cheaper than it was a decade ago, and wind energy costs have dropped by more than half, significantly reducing the electricity costs required for the electrolysis process. Innovations, large-scale renewable energy projects, and public-private partnerships are expected to help overcome these obstacles, positioning green hydrogen as

a cornerstone of global energy systems, driving sustainable industrial transformation, and supporting climate goals.

Conclusion and Way Forward

Green hydrogen stands as a transformative solution in the global pursuit of a low-carbon and sustainable future. Its ability to decarbonize hard-to-abate sectors, support energy storage, and replace fossil fuels places it at the forefront of clean energy systems. As global energy demand continues to grow, green hydrogen offers a scalable and versatile pathway to align energy consumption with climate action goals, particularly for industries and applications that are challenging to electrify. While the potential of green hydrogen is undeniable, realizing its promise requires overcoming critical challenges, including high production costs, infrastructure gaps, and safety considerations. Continuous innovation in electrolyzer efficiency, renewable energy generation, and hydrogen storage technologies will play a pivotal role in addressing these hurdles. Additionally, supportive government policies, financial incentives, and international collaborations are essential to accelerate its adoption and scale up production. India, with its National Green Hydrogen Mission, is uniquely positioned to emerge as a global leader in the green hydrogen economy. By leveraging its abundant renewable energy resources and investing in research, infrastructure, and strategic initiatives, India can drive industrial decarbonization, enhance energy security, and

contribute significantly to global climate goals. As nations worldwide integrate green hydrogen into their energy strategies, India's proactive approach could serve as a model for sustainable and inclusive development.

Looking ahead, the expansion of the global green hydrogen market must be guided by sustainability, equity, and innovation. As countries and industries advance toward net-zero targets, green hydrogen is poised to play a central role in reshaping energy markets, reducing emissions, and fuelling economic growth. By fostering international partnerships and prioritizing clean energy transitions, stakeholders can ensure that green hydrogen becomes a cornerstone of a resilient and sustainable global energy system, driving progress toward a low-carbon future.