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GREEN HYDROGEN: FUEL OF THE FUTURE

The global energy system is in dire need of a sustainable model for the energy transition. Can hydrogen live up to the hype?


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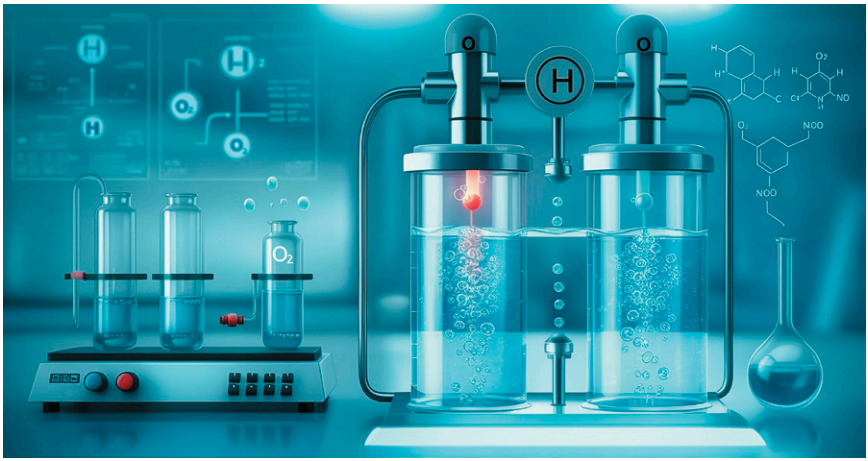

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THE RISE OF GREEN HYDROGEN

The global energy system must transform into a sustainable model that meets growing needs, supports decarbonisation and ensures resilient communities

The world needs more energy than ever before. As populations grow and economies expand, energy demand is skyrocketing. Yet this rising demand must be balanced against the urgent need to reduce carbon dioxide emissions and address environmental challenges.

Carbon-free Option

Green hydrogen is uniquely positioned to link renewable electricity with various applications. As a complement to electrification, bioenergy and direct renewable energy use, green hydrogen offers versatility in addressing hard-to-decarbonise sectors, such as heavy-duty transport, steel, heating and power production.

Unlike fossil fuels, green hydrogen's potential is intrinsically tied to renewable energy sources like solar and wind, whose potential far exceeds global energy demand today and in any future scenario. Most importantly, green hydrogen is the only genuine zero-carbon option for hydrogen production.

Globally, green hydrogen is becoming the centrepiece of the international climate agenda. Current efforts to reduce greenhouse gas (GHG) emissions are insufficient to limit global warming to below two degrees Celsius by the end of

the century. As a result, nations are embedding green hydrogen into their decarbonisation strategies.

In 2019, only five countries had a hydrogen strategy; by 2020, that number grew to nearly 20, with leaders like Australia, Canada, the United States, Germany and Japan spearheading efforts.

With rapidly declining renewable energy costs, India has a unique opportunity to lead the global hydrogen transition. Solar electricity tariffs in the country have reached record lows of Rs 1.99 per kWh, making green hydrogen production increasingly cost-effective.

India is also on its path to becoming a global leader in clean energy by implementing a clear strategy to reduce green hydrogen prices to below $2 per kg by 2030, making it competitive with traditional energy sources.

Scalable and Versatile

Green hydrogen is the gold standard of hydrogen production—clean, sustainable and infinitely scalable. It is produced by splitting water into hydrogen and oxygen using electricity from renewable sources such as wind or solar. This process, known as electrolysis, is entirely carbon-free, provided the electricity used is renewable.

The journey from water to green hydrogen involves three key steps.

The first is electrolysis, in which electricity powers an electrolyser and separates water into hydrogen and oxygen. This is followed by compressing the hydrogen and storing it for distribution. Finally, the stored hydrogen is used across industries

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to fuel zero-emission vehicles, power industrial processes or be integrated into energy grids.

The Hydrogen Spectrum

Hydrogen is not a monolithic energy source—it is classified based on production methods and carbon footprints.

Green hydrogen is produced by splitting water using electricity from renewable sources such as solar, wind or hydropower. This is the cleanest form of hydrogen, emitting zero carbon dioxide. It stands out as the only genuinely zero-carbon option for hydrogen production. It is crucial for decarbonising hard-to-electrify sectors like heavy industry, transport and power generation.

The high cost of production due to expensive electrolysers and renewable energy infrastructure requires significant scaling to become cost competitive.

Blue hydrogen is made from natural gas via steam methane reforming (SMR) or auto thermal reforming (ATR) with carbon capture and storage (CCS). However, at best, CCS efficiency is limited to 85%- 95%. This is a transitional solution leveraging existing natural gas infrastructure and reduces emissions compared to grey hydrogen. It is suitable for countries with abundant natural gas reserves. Methane leaks during gas extraction and transportation diminish its environmental benefits.

Gray hydrogen is produced from natural gas or coal through SMR or ATR without capturing carbon dioxide emissions. It is economically viable due to established technology and infrastructure and widely used in industries such as ammonia synthesis and oil refining.

High greenhouse gas emissions make it unsuitable for long-term climate goals, as it emits approximately 10 tonnes of carbon dioxide for every tonne of hydrogen produced.

Pink hydrogen is produced via electrolysis using electricity from nuclear power. It offers reliable and consistent energy for hydrogen production, is unaffected by weather or time of day and is valuable for countries with established atomic infrastructure. Its drawbacks are the high capital costs of nuclear plants, concerns about nuclear safety, waste disposal and public acceptance.

Thus, green hydrogen's scalability and zero-carbon credentials make it critical to a global energy transition. OB

THE GLOBAL MARKET AND INDIA

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Green hydrogen is emerging as a critical element in the energy transition and in achieving net-zero emissions by 2050

The global green hydrogen market is experiencing rapid growth. In 2024, it was valued at $7.98bn and is expected to grow at a compound annual growth rate (CAGR) of 38.5% from 2025 to 2030.

Big Ambitions

With technological advancements driving down the high cost of electrolysis, particularly proton exchange membrane (PEM) and alkaline electrolysers, green hydrogen is becoming more competitive with other energy sources like natural gas. Further, regions such as Europe and the US are investing in localised manufacturing of electrolysers to reduce dependency on imports and build domestic green hydrogen

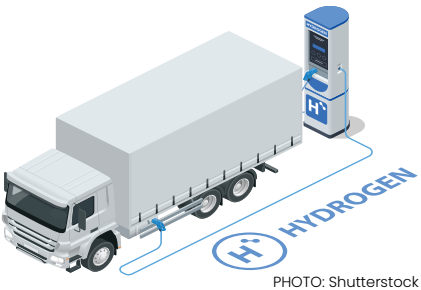
industries, strengthening the business landscape.

Favourable government policies and subsidies are accelerating the development of green hydrogen infrastructure. Notable initiatives include hydrogen roadmaps in countries like Germany, Japan and Australia, which focus on creating ecosystems for green hydrogen production, distribution and utilisation.

Heavy industries that are difficult to electrify, such as steel, cement and chemical production, are adopting green hydrogen to decarbonise their operations. Additionally, the transportation sector, including trucks, ships and even aircraft, is exploring hydrogen fuel cells as a clean alternative to diesel and jet fuel.

In 2020, leading European automotive manufacturers revealed plans to transition their truck fleets to hydrogen power by 2040. Additionally, Airbus is developing hydrogen-powered aircraft, with plans to launch commercial flights by 2035.

Carbon pricing schemes and markets, including carbon taxes and emissions-trading schemes (ETS), significantly impact the development and deployment of green hydrogen. In the European Union (EU), carbon pricing mechanisms are becoming a significant driver for green hydrogen projects. The EU's ETS, for example, is incentivising companies to produce green hydrogen to offset emissions from other sectors.



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Large energy, finance and industrial corporations are establishing hydrogen projects that combine green hydrogen production with carbon credit generation. Investors increasingly consider carbon credits tied to green hydrogen as part of their environmental, social and governance (ESG) portfolios.

The Key Players

The global green hydrogen market is characterised by a mix of established energy giants, industrial players and new entrants focusing on innovation and sustainability. Some key players are: Plug Power, US, a pioneer in hydrogen fuel cells and hydrogen generation systems and Siemens Energy, Germany, which is actively developing hydrogen technologies, particularly in electrolysis systems.

Others include Iberdrola of Spain, one of the world's largest renewable energy companies, Air Products and Chemicals, US, which invests heavily in hydrogen production and distribution infrastructure and Enel Green Power, Italy, who are working on producing green hydrogen from their extensive renewable energy portfolio, especially in Europe.

Germany has been one of the earliest adopters of green hydrogen and has committed to investing heavily in the technology. In 2020, the

German government announced its National Hydrogen Strategy, which aims to make the country a global leader in green hydrogen production.

Japan has long been a leader in hydrogen technology and is investing in green hydrogen to decarbonise its industrial and transport sectors. Japan's hydrogen strategy includes developing an entire hydrogen supply chain, from production to storage and distribution.

With vast renewable energy resources, Australia focuses on large-scale hydrogen production for export markets, supported by government-funded research and infrastructure development.

The US has shown strong interest in green hydrogen, particularly in states like California, where active efforts exist to use hydrogen in transportation. The US federal government is also ramping up support for hydrogen initiatives as part of its climate policy.

The European green hydrogen market also accounted for a significant share of revenue in 2024. The EU is positioning itself as a global leader in green hydrogen, with several initiatives under the European Green Deal aimed at fostering the development of a hydrogen economy.

What is India's Take?

As the world's third-largest emitter of greenhouse gases, India has its own set of challenges in reducing its carbon footprint. Green hydrogen presents a viable solution to decarbonise sectors, including those difficult to electrify.

In November 2021, India launched its National Hydrogen Mission to position itself as a global leader in green hydrogen production. India has allocated Rs 19,744 crores for this and set a target to produce 5mn metric tonnes (MMT) of green hydrogen annually by 2030.

In 2022, the government announced its Green Hydrogen Policy, which offers incentives such as reduced transmission charges for renewable energy used for hydrogen production, open access for renewable energy developers and prioritising renewable power to green hydrogen producers. This policy aims to bring down the cost of hydrogen production and make India a competitive player.

Several Indian states have also introduced their hydrogen policies. Gujarat, for example, has announced plans to establish a hydrogen hub, leveraging its renewable energy capacity and strategic ports. Other states like Andhra Pradesh and Karnataka are also actively involved in green hydrogen projects to contribute to the nation's overall hydrogen targets.

India is also encouraging partnerships between the government and private entities to scale up green hydrogen production, as well as international collaborations for hydrogen production and technology exchange. It has signed memorandums of understanding with Japan, Germany and the UAE to facilitate the exchange of knowledge and technology. OB

ROADBLOCKS ALONG THE WAY

Industries that can benefit from green hydrogen need extensive retooling to incorporate hydrogen into their processes, which poses a significant financial burden

Green hydrogen holds transformative potential in combating climate change, but its adoption depends on addressing the challenges of cost, infrastructure and technology.

Technical Challenges

Green hydrogen produced through electrolysis is estimated to cost between $3 and $7 per kg, which is expensive compared to grey hydrogen ($1–2 per kg) and blue hydrogen ($2–3 per kg). This cost difference is due to the expensive electrolysis machinery and the dependence on costly renewable energy, which makes it less competitive.

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Further, electrolysis, which splits water into hydrogen and oxygen, suffers from 30–35% energy losses. This makes green hydrogen less attractive than direct electrification solutions such as battery storage. Electrolyser technologies rely on expensive materials such as platinum and iridium. Limited mass production and economies of scale further inflate costs.

Infrastructure Limitations

Hydrogen's unique properties, such as being highly flammable and the smallest molecule, necessitate specialised infrastructure for safe and efficient storage, transport and distribution. Retrofitting natural gas pipelines or constructing new hydrogen-specific systems requires significant investment.

Many industries that could benefit from green hydrogen, such as steel, refining and chemicals, need extensive retooling to incorporate hydrogen into their processes. These sectors are reliant on fossil fuels and the transition to hydrogen-based systems would involve high costs for new equipment, retrofitting existing plants, and re-engineering production lines. This represents a significant financial burden, especially when the economic benefits are not immediately apparent.

The Economic Landscape

Electrolysers cost $800–1,500 per kW of installed capacity, and capital expenditures form a significant portion of production costs. However, advancements and scaling are projected to reduce costs by 60–70% by 2030.

Further, renewable electricity accounts for 50–70% of production costs, with geographic variability influencing competitiveness. For instance, regions with abundant solar and wind resources, such as West Asia, have a cost advantage compared to Europe. OB

INDIA'S PUSH FOR SCALE

Green hydrogen can revolutionise the energy landscape, but achieving this vision requires a multifaceted approach towards fostering innovation and incentivising production

India has taken significant steps with its green hydrogen push. However, achieving cost competitiveness remains a primary challenge and economies of scale are key to unlocking green hydrogen's economic viability.

Lining Up Initiatives

The capital-intensive electrolysis process is a significant factor in the high cost of green hydrogen. However, deployment at a larger scale enables more efficient supply chains, optimised operations and

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reduced per-unit costs for electricity and water.

The International Renewable Energy Agency (IRENA) estimates that green hydrogen could reach a competitive cost of $1.5–2 per kg by 2030. This makes green hydrogen comparable to grey hydrogen, which dominates industrial and energy markets due to its lower cost.

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Indian corporations are already aligning their green hydrogen strategies with the principles of economies of scale. For instance, Reliance Industries has announced an investment of Rs 75,000 crore over three years to establish a comprehensive ecosystem for new energy and materials.

This initiative includes installing solar photovoltaic module factories, advanced energy storage battery facilities and green hydrogen production units. The company plans to develop the Dhirubhai Ambani Green Energy Giga Complex in Jamnagar, which will house these manufacturing units.

The Adani group will invest $20bn over the next decade to expand its renewable energy capabilities. This investment aims to triple its renewable power generation capacity, including a foray into green hydrogen production.

The Indian Oil Corporation is establishing a green hydrogen plant at its Mathura refinery with a Rs 2,000 crore investment, aiming to reduce production costs through industrial integration. The National Thermal Power Corporation is developing pilot projects to deploy scalable hydrogen solutions, exploring integration with significant renewable energy plants.

Elsewhere in the world, Germany is advancing with gigawatt-scale electrolyser manufacturing to meet future green hydrogen demand. In the US, the Inflation Reduction Act offers a clean hydrogen production tax credit for hydrogen produced with low carbon intensity. This incentive is designed to make large-scale hydrogen projects financially viable, aligning with IRENA's recommendation that scaling up production and deployment accelerates market competitiveness.

Japan invests in hydrogen infrastructure and technology, including developing hydrogen supply chains and international partnerships, to secure a stable hydrogen supply.

These initiatives demonstrate a global commitment to scaling up green hydrogen production, leveraging economies of scale and technological advancements to drive down costs and enhance market competitiveness.

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Planning for the Future

India's green hydrogen initiatives are at a critical juncture where economies of scale can drive the transition from a high-cost niche technology to a commercially viable energy solution. By leveraging scale in electrolyser manufacturing and deployment, as mentioned in the IRENA report, the cost of green hydrogen can be significantly reduced, enabling India to achieve its energy security, decarbonisation and economic growth objectives.

However, there are some critical things which India needs to do at this juncture. First, the country must promote research and development in green hydrogen technology to achieve economies of scale for widespread adoption.

A dedicated production-linked incentive (PLI) scheme can be drafted to incentivise domestic production of electrolysers and other hydrogen technologies. This will not only bring the cost down but also promote the manufacturing of critical components in India. It is also critical to encourage investors to invest in green hydrogen technology. Subsidies and tax regimes should also be developed for the sector.

Further, it is necessary to invest in hydrogen storage facilities and transportation infrastructure, such as pipelines and hydrogen fuelling stations. Finally, building a skilled workforce to make the most of this opportunity is crucial. This can be achieved through investing in training and education programmes to develop skilled manpower for the green hydrogen sector. OB

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