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Hydrogen Role in Decarbonizing Industries and Transforming India's Energy Future

Dr. Anju Rathee Ahlawat

Assistant Professor, Department of Applied Science, Maharaja Surajmal Institute of Technology, C - 4, JanakPuri, New Delhi, India

Abstract: ***The primary value proposition of hydrogen lies in its ability to decarbonize hard - to - abate sectors, which have historically lacked feasible technical solutions. Hydrogen can effectively address many of these challenges and complement other efficiency measures. With decreasing costs of renewable electricity and advancements in electrolyser technology, green hydrogen is set to become cost - competitive with existing fuel options. As industries like steel, refining, and ammonia production face pressure to lower their carbon footprints, hydrogen's significance will only grow. By fulfilling national goals of emission reductions and boosting domestic manufacturing, hydrogen can position India as a global powerhouse for zero - carbon export products, such as green steel and green ammonia. With the right policy support, industry action, and increased investor interest, India has a unique opportunity to lead in the hydrogen energy ecosystem. By positioning itself as a low - cost, zero - carbon manufacturing hub, India can achieve its goals of economic development, job creation, and improved public health, while playing a pivotal role in the global transition to sustainable energy. Hydrogen has the potential to be a cornerstone of India's energy transition, enhancing industrial competitiveness in an increasingly decarbonized world, driving economic development, reducing CO2 emissions, and improving public health. As major countries invest heavily in hydrogen technologies, India stands poised to take a leadership role in advancing the global hydrogen economy***

Keywords: Green, Hydrogen, Energy, Decarbonisation, Net - Zero Emission, Carbon

1. Introduction

Climate change including rise in global temperature, generation of greenhouse gases beyond certain levels, ozone depletion, environmental pollution, disbalancing of ecosystems, rise in level of sea etc and many others related and intertwined phenomena are impacting our planet adversely. Impact on life that is incidental to climate change is evident.

Necessity of fulfilling the need of world to reduce carbon dioxide emissions to zero or net - zero level has been critically felt worldwide and now countries are working to achieve it.

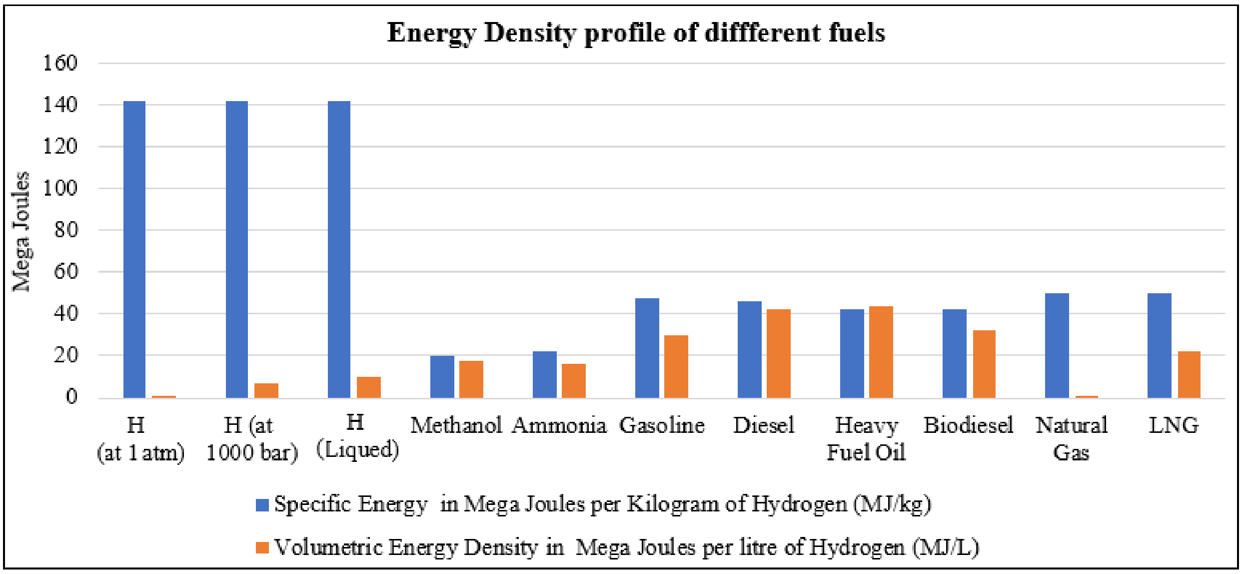
Energy Sector is getting ready to embrace a unique change where replacement of fossil fuel by emerging low carbon technologies is targeted to achieve full or deep decarbonisation.

Various end use sectors are being decarbonised very effectively [1] by rise in adoption of alternative fuels, solar, wind, hydel projects, lithium - ion batteries etc. Also, it is difficult to decarbonise some sectors [10] viz heavy industry, heavy transport with existing low - or zero - carbon technologies. However, world is hopeful to decarbonize these hard - to - abate sectors by switching to Hydrogen and or more specifically green Hydrogen. Apart from that, it is also expected that increase in generation of cost - effective green Hydrogen, developing its transportation means and making it available near to its end use will not only decarbonise the world, boost economic development too and improve public health & quality of life.

1) Hydrogen as fuel

Hydrogen element is existing in most abundance on earth. It was discovered by Henry Cavendish in 1766. Its name is meant as water creator - hydro (water) + gen (generation) - as its combustion releases only H_2O. It carries energy. Energy content per unit of mass (also called specific energy) is higher [6] than other hydro carbon fuels while volumetric energy density is lowest. So, after liquefaction, it becomes easy in transportation and a useful fuel for consumption. It can also be stored easily. Energy density profile [2] of different fuels as compared with Hydrogen is given below:

Fuel Type	Specific Energy in Mega Joules per Kilogram of Hydrogen- (MJ/kg)	Volumetric Energy Density in Mega Joules per litre of Hydrogen (MJ/L)
H (at 1 atm)	142	1
H (at 1000 bar)	142	7
H (Liqued)	142	10
Methanol	20	18
Ammonia	22	16
Gasoline	48	30
Diesel	46	42
Heavy Fuel Oil	42	44
Biodiesel	42	32
Natural Gas	50	1
LNG	50	22



Hydrogen is simplest element of universe that is lightest is atomic mass. It is most abundant element but generally available with in compound formation. Its availability in elemental form is rare. It is always extracted from hydrogen containing compounds. It is classified [9] into various "colors" based on its production methods, environmental impact of production method, source of the energy used in the process. Details of main classifications is as under:

Color	Process	Source	Net - Zero Emissions suitability	Remarks
Grey	Steam Methane Reforming (SMR) or Gasification	Methane or Coal	High CO_2 emission	Unsuitable
Blue	SMR or Gasification with carbon capture (85 - 95 %)	Methane or Coal	85 - 95 % emission of CO2 captured & stored (CCS). Rest is emitted.	Better option but has limitations: CCS associates additional cost; Upstream leakages of Methane occurs which is more potent Green House Gas (GHG)
Turquoise	Pyrolysis	Methane	Carbon of methane becomes carbon black (solid) which is easier to store than CO_2 in gaseous form.	Carbon black (solid) has market value. Turquoise H_2 is at pilot stage
Green	Electrolysis	Renewable Electricity	Net Zero route	Commercial scale yet to achieve.

Apart from above, Pink (or Red) Hydrogen and Yellow Hydrogen are also two more categories which are made through electrolysis powered by nuclear energy and a mix of renewable & nuclear energy respectively. These represents a transition towards greener production methods.

2) Green Hydrogen for deep decarbonising:

Though the use of Hydrogen for various purposes is not new, the first industrial water electrolyser was developed in 1888. Hydrogen is increasingly recognized as a vital energy carrier for achieving deep decarbonization, particularly in hard - to - abate sectors. While existing low - carbon technologies—such as solar, wind, and energy efficiency—are effective in decarbonizing areas like power generation and light transportation, hydrogen's unique properties make it essential for more challenging industries. Key sectors that could benefit from carbon - free hydrogen include:

a) Iron and Steel Production: Traditional methods emit significant CO2, but hydrogen can replace carbon - intensive processes.
b) Fertilizer Manufacturing: Hydrogen is a critical feedstock, and using green hydrogen can significantly reduce emissions.
c) Refining and Methanol Production: Hydrogen can be utilized in processes that currently rely on fossil fuels.
d) Maritime Shipping: As shipping accounts for a large share of global emissions, hydrogen is being explored as a cleaner alternative.

In addition, hydrogen shows promise for high - emission sectors like heavy - duty trucking and aviation, potentially becoming the preferred solution for specific applications. Moreover, the production of hydrogen through water electrolysis not only supports renewable electricity generation but also serves as an effective energy storage mechanism. As the costs of renewable energy decrease, the cost of hydrogen production is expected to fall, enhancing its competitiveness in the energy market. Beyond its environmental benefits, hydrogen can also help reduce reliance on oil imports, boost domestic job markets, and enable participation in the global energy transition, presenting significant economic opportunities. As countries and companies set ambitious net - zero emission targets, the momentum behind hydrogen is growing. Its potential to decarbonize hard - to - abate sectors is increasingly recognized, making it a focal point in the transition toward a sustainable energy future.

3) Challenges:

Green hydrogen, while a promising energy carrier with various potential applications, currently represents a small fraction of global hydrogen production. Globally, about 120

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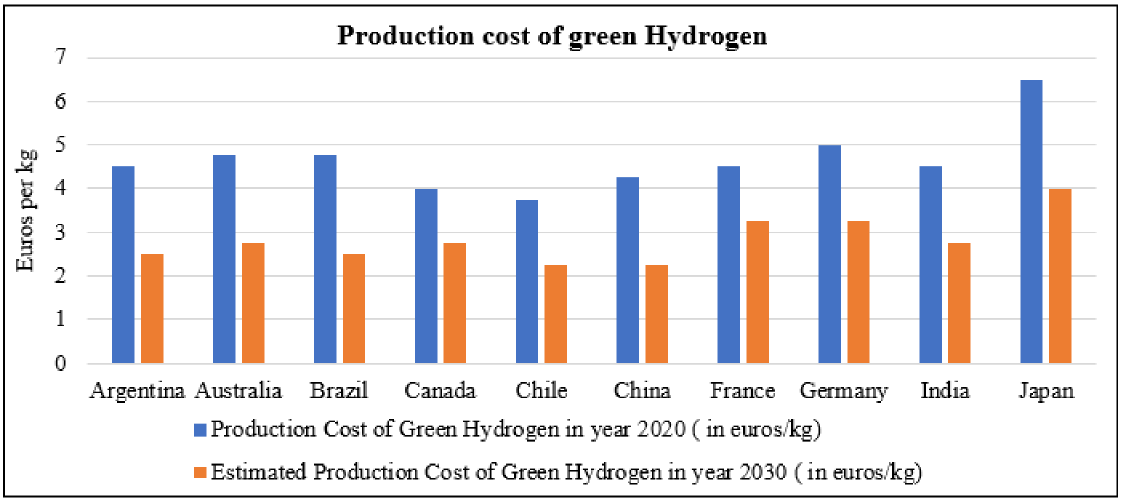
million tonnes of hydrogen are produced each year, with approximately [2, 7] two - thirds being pure hydrogen and one - third as mixtures with other gases. The majority of this hydrogen is used in crude oil refining and in the synthesis of ammonia and methanol, which together account for nearly 75% of total demand.

Currently, the production landscape is dominated by fossil fuels, with natural gas and coal responsible for about 95% of hydrogen production. Electrolysis, which generates hydrogen through the splitting of water, contributes only around 5% of the total output and is primarily a by - product of chlorine production. Unfortunately, there is little significant production of green hydrogen from renewable sources, as most efforts are still in the demonstration phase.

This reliance on fossil fuels not only limits the potential for decarbonization but also highlights the need for greater investment in and development of green hydrogen technologies. As green hydrogen projects scale up and become more economically viable, it could play a transformative role in various sectors, contributing to a more sustainable and low - carbon future. Green hydrogen faces several barriers [5, 4], that hinder its potential role in the energy transition:

a) **Lack of Dedicated Infrastructure**: The existing infrastructure for transporting and storing hydrogen is insufficient, limiting its widespread adoption.
b) **Energy Losses**: The electrolysis process incurs energy losses that can reduce overall efficiency.
c) **Value Recognition**: The economic benefits of green hydrogen are not fully recognized in markets, making it challenging to attract investment.
d) **Sustainability Challenges**: Ensuring that the entire supply chain for green hydrogen is sustainable can be difficult.
e) **High Production Costs**: Current production costs mainly due to investment in electrolyser [2, 3, 7] remain high compared to fossil fuel alternatives. As of 2020, alkaline electrolyser costs were about USD 750 - 800 per kilowatt (kW). However, higher capacity and load factors economises the production cost.

Country	Production Cost of Green Hydrogen in year 2020 (in euros/kg)	Estimated Production Cost of Green Hydrogen in year 2030 (in euros/kg)
Argentina	4.5	2.5
Australia	4.75	2.75
Brazil	4.75	2.5
Canada	4	2.75
Chile	3.75	2.25
China	4.25	2.25
France	4.5	3.25
Germany	5	3.25
India	4.5	2.75
Japan	6.5	4



To enhance the competitiveness of green hydrogen, it's essential to increase the utilization of electrolysers, improve the cost - effectiveness of renewable electricity, and address infrastructure needs. Recognizing the value of green hydrogen will be crucial in overcoming these barriers and facilitating its broader adoption in the energy market

4) Global Developments

Despite the challenges faced by green hydrogen, its utility in specific applications is increasingly providing economic value compared to traditional alternatives, contributing to the gradual formation of a hydrogen market. Hydrogen can be utilized in several ways [8]. World is focussed on developing use cases in following areas:

a) Direct Combustion: Employed in industrial processes, particularly in iron and steel production and refining.
b) Electricity Generation: Used in fuel cells to generate electricity, providing a clean power source for various applications.
c) Transportation Fuel: Hydrogen serves as a fuel for light - duty vehicles, buses, trucks, trains, and has potential applications in shipping and aviation.
d) Energy Storage and Grid Balancing: Acts as a storage solution for renewable energy, helping to balance supply and demand in the power sector. It can also be co - fired in thermal power plants.
e) Chemical Feedstock: Crucial for the production of ammonia (used in fertilizers), methane, and methanol, underpinning several industrial processes.

At least 43 countries are now establishing strategies or roadmaps for developing a hydrogen economy. Most government - related research and development funding for hydrogen is concentrated in regions like Europe, the United States, India, Japan, and China, indicating a growing commitment to advancing hydrogen technologies.

As these efforts continue, the potential for hydrogen to play a significant role in the energy transition becomes increasingly clear, not only in reducing emissions but also in creating economic opportunities across multiple sectors.

5) Indian Ecosystem

Energy consumption in India has doubled over the past 20 years and is projected to increase by at least 25% by 2030. Currently, India imports over 40% of its primary energy needs, costing more than USD 90 billion annually. Key sectors, including mobility and industrial production, heavily rely on imported fossil fuels.

The significance of green hydrogen in achieving energy independence for India is immense. By leveraging renewable energy sources like solar, wind, and hydropower for green hydrogen production, India can enhance its energy security while reducing reliance on fossil fuels. This approach not only ensures a stable and reliable energy supply but also allows for local production, minimizing the need for costly and environmentally harmful imports.

Additionally, green hydrogen can be generated from waste biomass, providing farmers and local communities with an extra revenue stream, thus fostering economic growth at the grassroots level.

To capitalize on this potential, India has launched the National Green Hydrogen Mission, with an investment of ₹19, 744 crores (INR) aimed at achieving a production capacity of 5 million metric tonnes (MMT) of green hydrogen per annum. The mission [10, 1] will support the transition from fossil fuels and fossil fuel - based feedstocks to renewable alternatives. Key initiatives include:

a) Transitioning from hydrogen derived from fossil fuels to green hydrogen in ammonia production and petroleum refining.
b) Blending green hydrogen into city gas distribution systems.
c) Using green hydrogen in steel production.
d) Developing synthetic fuels (such as green ammonia and green methanol) to replace fossil fuels in various sectors, including mobility, shipping, and aviation.

India is rapidly becoming a leader in renewable energy, with the fastest - growing capacity in the world. As the country aims for energy independence by 2047 and targets net - zero emissions by 2070, green hydrogen plays a crucial role in this vision. With abundant renewable resources, India has the potential to produce green hydrogen not just for domestic use but also for global markets. The mission also aims to position India as a global leader in the technology and manufacturing of electrolysers and other enabling technologies for green hydrogen.

Through these comprehensive efforts, India is poised to leverage its renewable energy potential, reduce dependency on imports, and lead the transition to a sustainable energy future.

2. Conclusion

Green hydrogen holds enormous promise for decarbonizing various sectors, significantly reducing carbon emissions, and bolstering energy independence. Its sustainable production through renewable resources makes it an appealing option for transitioning to a low - carbon future. By replacing traditional fossil fuels in transportation and industry, green hydrogen can provide a consistent and reliable energy source, underscoring its critical role in world energy strategy and overall economic resilience.

An integrated policy approach is essential to overcoming initial resistance to green hydrogen and achieving significant market penetration. With such approach, policymakers can effectively support the growth of the green hydrogen market, drive innovation, and ensure its integration into the broader energy landscape. This comprehensive approach will help unlock the potential of green hydrogen as a critical component of the transition to a sustainable and low - carbon future.

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