The current status of the hydrogen value chain in India: a critical review

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Article Info

Article history:

Received May 18, 2024
Revised Aug 12, 2025
Accepted Oct 16, 2025

Keywords:

Green hydrogen
Hydrogen storage
Hydrogen transportation
Indian green hydrogen producers
Salt caverns

ABSTRACT

The Bharat is the largest economy with a humongous population that has increasing energy demands day by day. Clean energy sources like green hydrogen are necessary to balance climate change and meet energy demand, which also reduce carbon footprints in related energy sectors. This paper critically reviews the need of green hydrogen, production, storage and transportation strategies, the role of government schemes, and prominent private corporations working in the Indian green hydrogen sector. Efforts are made to analyze available data and current advisory regulations pertaining to the green hydrogen ecosystem in India. Based on this, suggestions are made for a research and development roadmap for establishing a green hydrogen value chain. This research paper suggests salt caverns as potential geological structures for hydrogen storage chains and also sheds light on potential collaborative initiatives and pilot projects for improving the efficiency and sustainability of the green hydrogen value chain across developing countries like India.

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1. INTRODUCTION

As populations grow and industrialization expands, energy demands increase correspondingly. Hydrogen finds wide-ranging applications across various sectors, with approximately 51% used in ammonia production, 31% in oil and gas refineries, 10% in CH_3OH production, and the remaining 8% serving other purposes. The transition towards a hydrogen-based economy policies are inclined to the reduction of GHG emissions as well as carbon footprints. Hydrogen offers a versatile and sustainable energy source that can be produced from electrolysis of water, or reforming of fossil fuels, and renewable energy sources.

India is the 5th largest economy with 2.87 trillion USD in 2020 and in second position with a 1.38 billion population. Projections suggest that by 2050, India will be in 2nd position in the economy with 1.65 billion people. Studies indicate a significant increase in India's energy demand, with projections suggesting a rise to 1930 million tonnes of oil equivalent (Mtoe) by 2042, up from 880 tonnes in 2020. India is in the third position in terms of GHG emissions, primarily CO_2, accounting for 6.94% (2.299 gigatonnes) of the total emissions in the world. This places it behind China and the USA, which contribute 28.6% and 14.57% of GHG emissions, respectively. The transport sector alone in India emits approximately 0.29 gigatonnes of

CO_2, constituting 13% of the country's total emissions as of 2017. As per the studies in 2020 reveal concerning air quality in India, with an average PM2.5 level of around 51.9 µg/m³. India's air quality ranks as the third worst globally, with 22 out of the world's 30 most polluted cities located within its borders [1]. These statistics highlight the urgent need for India to address its growing energy demands while simultaneously mitigating environmental impacts, particularly air pollution and greenhouse gas emissions. Transitioning to cleaner energy sources and implementing stricter environmental regulations are essential steps in achieving sustainable development and improving public health in the country.

India's significant consumption of hydrogen, comprising around 8% of the world's total, underscores its importance in the global hydrogen market. However, the majority of this consumption is attributed to grey hydrogen, derived from natural gas through processes like steam methane reforming (SMR) or auto-thermal reforming (ATR). In the fiscal year 2018-19, India's hydrogen consumption reached 6.6 million metric tonnes (MMT), with the fertilizer sector emerging as the largest consumer, accounting for 3.6 MMT, followed closely by the oil refineries sector [2]. Despite its widespread use, grey hydrogen poses environmental challenges due to the release of carbon dioxide into the atmosphere during its production process. Achieving cost parity between green hydrogen and grey hydrogen is crucial for the widespread adoption of clean hydrogen technologies. Currently, the cost of grey hydrogen ranges from INR 160 to 220 per kilogram, primarily dependent on natural gas prices, which are subject to volatility. In contrast, green hydrogen production costs are higher, ranging from INR 263 to 368 per kilogram. This higher cost is attributed to factors such as the cost of renewable electricity for electrolysis and the variability in electrolyzer technologies, which come at different price points [3]. It is also important to note that these cost estimates factor in exemptions on electricity duty and taxes, which significantly reduce the overall cost by 35%-40%. These exemptions play a vital role in making green hydrogen more competitive with grey hydrogen in the current market landscape. The Ministry of New and Renewable Energy (MNRE) established the National Hydrogen Energy Roadmap (NHERM) in 2006 to accelerate the research and commercialization of H2-based technologies in India. In 2021, India launched its H2 mission for green H2 production, aiming to reduce the cost of green hydrogen. The mission focuses on demonstrating, developing, and deploying H2 energy technologies in transportation and power production sectors while also building necessary infrastructure and addressing safety and standards concerns. By 2030, India is projected to have 411.8 million cars in operation, with a huge portion powered by gasoline and diesel [1]. This rise in vehicle numbers will increase demand for traditional fuels, necessitating strategies to manage their consequences. Efforts to improve fuel efficiency and substitute traditional fuels with alternatives like hydrogen fuel are already underway to mitigate these challenges. Additionally, high petrol and diesel fuel costs in India make the ownership of hydrogen fuel vehicles (HFVs) increasingly attractive, especially in areas with poor air quality [4].

Since India is one of the fastest growing economies and considering its humongous population, energy needs are going to increase exponentially. However, more than 70% of energy needs come from the fossil fuel-based energy system. Hence, India is trying to make the fast transition towards the hydrogen economy, realizing its potential to fulfill the goal of achieving an environmentally friendly and sustainable solution for energy needs. However, India is in the pilot stages of its transition towards a hydrogen economy, and considering the challenges in the deployment of hydrogen, it becomes imperative to assess the current scenario of the hydrogen economy in India and its future projections. The contemporary challenges and their plausible solutions as well as the scope of improvements in the hydrogen value chain have been discussed in this article. The article also encapsulated the current status of hydrogen-powered vehicles in India. Apart from that, the study comprehensively presented the codes, regulations, and standards available globally that are relevant to the hydrogen value chain. The study also addresses the gap in adapting the existing regulations to align with the international best practices or developing codes and standards tailored to the local environment in India. Overall, the study attempts to address every element of the hydrogen value chain and offer valuable insights for all researchers and stakeholders.

2. HYDROGEN PRODUCTION

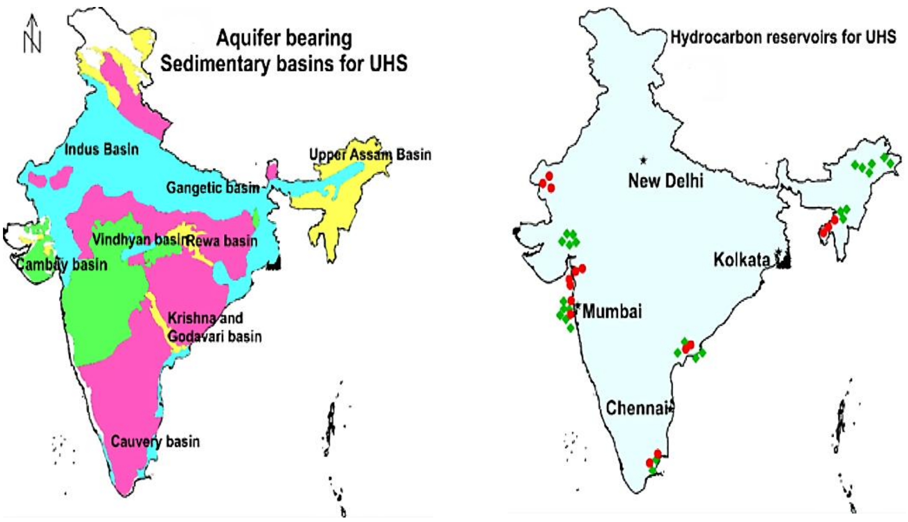
India, blessed with abundant renewable energy resources, indeed has a strategic advantage in the production of green hydrogen. Leveraging these resources can not only help them meet domestic energy demands sustainably but also position them as key players in the global green hydrogen market. The declining costs of renewable energy technologies further bolster the economic viability of green hydrogen production. As renewables become increasingly cost-competitive, the prices of green hydrogen are expected to decrease, making them more attractive compared to grey hydrogen. Various institutes/industries, including both government-funded public sector units and private corporations, are working on hydrogen production research in India. A subsidiary of Adani Group, Adani New Industries Ltd. (ANIL), has announced a strategic partnership with TotalEnergies SE of France to invest USD 50 billion in India over the next decade, for green hydrogen production and the development of related ecosystems. Reliance Industries Ltd. (RIL) has set ambitious goals to establish green hydrogen production infrastructure by 2025. Indian Oil Corporation Ltd. (IOCL) has planned to replace 10% of hydrogen with green hydrogen in two steps by 2030. The signing of an MoU between Indian Oil Corporation (IOCL) and Greenko ZeroC Private Limited in July 2022 outlines an investment of USD 6.2 billion for infrastructure related to renewable and green hydrogen value chains. GAIL, India's leading natural gas company, on May 12, 2022, announced the installation of one of the largest proton exchange membrane (PEM) electrolysers of 10 MW capacity at GAIL's Vijaipur Complex in the Guna district of Madhya Pradesh, India, for generating around 4.3 metric tonnes of green hydrogen per day. In June 2022, Bharat Petroleum Corporation Limited (BPCL) invited bids for the installation of a 5 MW electrolyzer system. Furthermore, BPCL has also signed a five-year MoU with the Government of Odisha in April 2022 to explore the feasibility of setting up a renewable energy plant and a green hydrogen plant. Bharat Petroleum Corporation Ltd. (BPCL) has also forged a partnership with the Bhabha Atomic Research Centre (BARC) to develop alkaline electrolyzer technology. National Thermal Power Corporation Ltd. (NTPC), India's largest electricity producer, has planned to allocate approximately 5 GW of capacity towards the green hydrogen and ammonia business, which would help NTPC achieve 60 GW in green portfolios by 2032. In August 2022, Larsen & Toubro (L&T) commissioned a green hydrogen plant at its AM Naik Heavy Engineering Complex in Hazira, Gujarat, India, with daily production capacity of 45 kilograms of green hydrogen. In January 2022, L&T entered into an MoU with HydrogenPro AS, a leading electrolyzer technology and manufacturing company based in Norway, to establish a gigawatt-scale manufacturing unit for alkaline water electrolyzers in India [4].

There are different methods available for hydrogen production, categorized based on the energy source and production process. Grey hydrogen is produced from fossil fuels, primarily SMR or coal gasification. These conventional processes release CO_2 emissions, making grey hydrogen a carbon-intensive fuel. Fossil fuels contribute to green hydrogen production using SMR or coal gasification. This allows for the capture and storage of CO_2 emissions, reducing the environmental impact compared to grey hydrogen. Green hydrogen is produced through water electrolysis using renewable electricity from sources such as solar, wind, or hydroelectric power. This process splits water molecules into hydrogen and oxygen, with no greenhouse gas emissions, making green hydrogen a clean and sustainable fuel. Turquoise hydrogen is produced through natural gas pyrolysis, a process that involves heating natural gas at elevated temperatures to produce hydrogen and solid carbon. This method has the potential to reduce CO_2 emissions compared to conventional steam methane reforming. Pink hydrogen is produced through water electrolysis using electricity generated by nuclear power plants. Like green hydrogen, pink hydrogen is produced without emitting CO_2, but it relies on nuclear energy as the primary power source.

3. HYDROGEN STORAGE TECHNIQUES

The physical storage of hydrogen presents several challenges, including issues related to efficiency, hydrogen loss over time, and compatibility with existing infrastructure. Gaseous hydrogen is typically stored in high-pressure tanks, which require operating pressures of 350 to 700 bar [5]. On the other hand, liquid hydrogen storage necessitates cryogenic temperatures, as hydrogen liquefies at -252.8 °C at 1 atmosphere pressure [6]. However, both methods have drawbacks, such as poor efficiency and hydrogen loss over time. Hydrogen storage contributing entities include IIT Mumbai, IIT Guwahati, IIT Chennai, NIT Tiruchirapalli, NEERI Nagpur, NFTDC Hyderabad, BHU Varanasi, IARC Hyderabad, and Thiagarajar COE Madurai. Salt caverns represent promising geological structures for underground storage of hydrogen, similar to their utilization for natural gas and compressed air. They are artificial chambers created through controlled solution mining techniques within salt domes and salt beds. Salt caverns exhibit strong sealing properties, making them ideal for gas storage applications [7]. While India has limited known reserves of salt-based deposits, primarily found in the northern-western parts of the country, recent exploration efforts by agencies like Indian Strategic Petroleum Reserves Limited (ISPRL) have identified potential salt formations for strategic crude oil storage [8]. The Neoproterozoic-Cambrian Bikaner-Nagaur basin in Rajasthan, for example, has geological characteristics conducive to hydrocarbon reservoirs, including salt deposits [9]. The identification of salt beds in regions with similar geological characteristics holds promise for future hydrogen storage sites in India [2], [10].

Aquifers in sedimentary basins like the Indus-Ganga-Brahmaputra (IGB) basin are highly porous and permeable, making them suitable candidates for storing large volumes of hydrogen [11]. However, injecting hydrogen into aquifers can pose challenges such as geo-mechanical failures due to pressure buildup from displaced water and potential migration to adjacent lithologies in the absence of impermeable structures. Depleted gas and oil reservoirs (DGOR) represent another well-categorized geological system suitable for hydrogen storage [12]. These reservoirs, which have been previously utilized for hydrocarbon extraction, offer several advantages for hydrogen storage. DGOR is well-characterized geologically due to the presence of hydrocarbons. They are typically located at greater depths and exhibit porous and permeable features, making them conducive to hydrogen storage [2]. India possesses 26 sedimentary basins categorized based on their potential for oil and gas reservoirs. Basins classified under Category I, such as the Krishna-Godavari (KG), Mumbai Offshore, and Rajasthan basins, have been actively producing hydrocarbons. DGOR within these basins, which may no longer be in use or have been decommissioned, offer potential storage sites for hydrogen. Despite these advantages, there are challenges associated with using DGOR for hydrogen storage [13]. The presence of unmined hydrocarbons within DGOR poses a risk of hydrogen loss due to displacement and mixing with residual hydrocarbons. This could result in significant hydrogen losses and reduce the overall storage efficiency of DGOR [14]. Similar to aquifers and salt caverns, the geological and mineralogical composition of the host rock in DGOR must be carefully evaluated to mitigate the risk of hydrogen loss and ensure safe and efficient storage. While DGOR offers promising potential for hydrogen storage, careful consideration of geological factors and mitigation of hydrogen loss are essential to maximize storage efficiency and safety. Figure 1(a) represents aquifer bearing sedimentary basins for underground hydrogen storage (UHS), and Figure 1(b) represents hydrocarbon reservoirs in India for underground hydrogen storage (UHS) [2].



(a) (b)

Figure 1. Geopolitical sedimentary basins and hydrocarbon reservoirs in India: (a) aquifer bearing sedimentary basins for underground hydrogen storage (UHS) and (b) hydrocarbon reservoirs in India for underground hydrogen storage (UHS) [2]

4. HYDROGEN TRANSPORTATION

Liquid hydrogen, liquid organic hydrogen carriers (LOHCs), and ammonia are among the most practical forms of hydrogen export. These storage strategies involve energy-intensive conversion processes like cooling, pressurization, chemical conversion, and release [15]. Transporting hydrogen fuel in large volumes and over long distances is primarily feasible through sea transportation. Hydrogen is typically converted into liquid form using three main methods which are mentioned further [16], [17]. i) Liquid hydrogen: Hydrogen is liquefied at extremely low temperatures and stored in specially designed containers. However, the transportation of liquid hydrogen is challenging due to its propensity to boil and evaporate when exposed to increased temperatures. Complex control systems are required to maintain the liquefied state during transportation [18], [19]. ii) Ammonia: Hydrogen can be chemically converted into ammonia for easier and safer transportation. Ammonia has a higher energy density and is more stable than gaseous hydrogen. It can be transported using existing infrastructure and technologies commonly used in the chemical industry [20]-[22]. iii) Liquid-organic hydrogen carriers (LOHCs): LOHCs are chemical compounds that reversibly bind and release hydrogen. They offer a convenient method for storing and transporting hydrogen, as they can carry enormous quantities of hydrogen in a safe and stable liquid form [23]. LOHCs can be regenerated at the destination to release the stored hydrogen [24]. Figure 2 represents the stages of green hydrogen transportation [3].

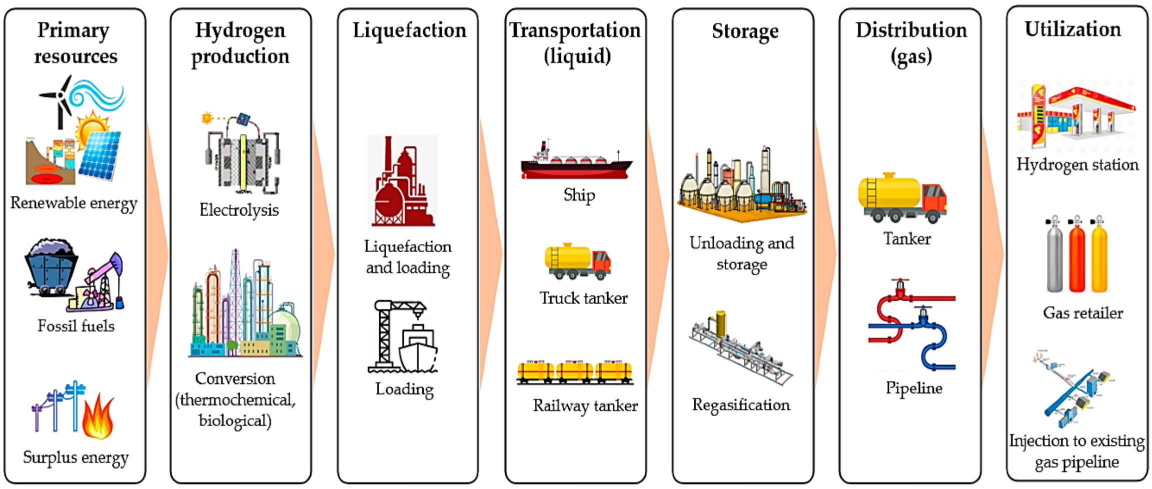


Figure 2. Stages of green hydrogen transportation [3]

5. GOVERNMENT SUPPORT FOR GREEN HYDROGEN AND ITS ECOSYSTEM

The vision to establish India as the global hub for the production, utilization, and export of green hydrogen and its derivatives reflects a bold step towards achieving self-reliance in clean energy and inspiring the global transition towards cleaner alternatives. This ambitious mission aligns with India's goals of reducing carbon emissions, minimizing reliance on fossil fuel imports, and assuming leadership in the clean energy sector. By focusing on green hydrogen, India aims to drive significant decarbonization of its economy while fostering technological innovation and market leadership in the renewable energy space. India's Green Hydrogen Mission, through the approval of Rs. 19.74 crores total outlay, aims to produce 5 MMT green hydrogen, establish 60 -100 GW electrolyser capacity and 125 GW renewable energy capacity for green hydrogen production by 2030 [4]. This mission not only contributes to India's Aatmanirbhar Bharat (self-reliant India) vision but also positions the country as a key player in the global clean energy transition. Through concerted efforts in research, development, and infrastructure, India can harness its vast renewable energy potential to produce Green Hydrogen efficiently and sustainably. This will not only benefit the environment but also create economic opportunities, enhance energy security, and propel India towards a greener and more prosperous future.

6. CODES AND REGULATIONS FOR HYDROGEN VALUE-CHAIN

Efficient storage and seamless transport of hydrogen are essential for realizing its potential as a green energy source. Although investments totaling approximately USD 6.5 billion have been committed, with a huge portion allocated to the Middle East, this has not resulted in a significant increase in hydrogen pipeline capacity, which currently stands at about 5,000 km. Most of these pipelines are located in grey hydrogen hubs and industrial areas. Additionally, infrastructure for hydrogen-fuelled mobility is expanding, with over 1,100 refueling stations globally. However, the majority of these stations are concentrated in countries like China, South Korea, and Japan. One major challenge hindering the development of a hydrogen economy is the lack of a comprehensive set of hydrogen codes and standards. These standards are crucial for ensuring the quality and safety of hydrogen production, storage, transportation, and usage. Establishing robust codes and standards will be vital for building trust in hydrogen technologies and promoting their widespread adoption. The establishment of an independent Hydrogen Safety Authority (HSA) was recommended by the 2016 Dr. Kasturirangan Report at the national level to oversee all safety aspects related to hydrogen energy and fuel cells [25].

7. HYDROGEN VALUE-CHAIN IN INDIA - STANDARDS, SCOPE OF IMPROVEMENTS

7.1. Hydrogen production

Updating the IS 16509:2020 standard to include provisions for solid oxide electrolysis (SOECs) and proactively developing standards for hydrogen production through alternative means such as natural gas or biomass pyrolysis are both critical steps in ensuring that India’s regulatory framework remains relevant and supportive of emerging technologies in the green hydrogen sector. For the IS 16509:2020 standard, incorporating requirements from the outline of the UL LLC 2264A standard for SOECs provides a solid foundation for addressing the specific characteristics and performance criteria of this technology. This update ensures that the standard remains comprehensive and aligns with international best practices, facilitating the deployment and adoption of SOECs in electrolytic hydrogen production. Similarly, developing standards for hydrogen production through alternative means like natural gas or biomass pyrolysis recognizes the importance of these technologies as transitional pathways towards green hydrogen. By proactively establishing standards for these processes, India can ensure that they meet safety, efficiency, and environmental sustainability requirements, thereby facilitating their integration into the hydrogen value chain.

7.2. Hydrogen storage

The absence of standards for bulk storage of liquid hydrogen presents a gap in India's regulatory framework for hydrogen storage. Developing and adopting standards such as CGA P-12, NFPA 55, and EIGA Doc 06/19 provides a comprehensive and internationally recognized framework for ensuring the safe and efficient storage of liquid hydrogen. These standards cover various aspects, including the design, construction, operation, and maintenance of liquid hydrogen storage facilities, as well as safety measures to mitigate risks associated with handling and storage. Expanding the scope of the IS 7285: Part 1:2018 standard for gaseous hydrogen storage to include larger cylinder sizes is a prudent step, considering the anticipated increase in demand for hydrogen in various sectors. By accommodating larger cylinder sizes, India can better cater to the evolving needs of industries and applications that require larger volumes of gaseous hydrogen. This expansion would ensure that the standard remains relevant and supportive of the growing hydrogen market while maintaining safety and quality standards for storage.

7.3. Hydrogen transport

Adopting standards for dedicated hydrogen pipelines is essential for facilitating the safe and efficient transport of hydrogen in bulk, supporting the growth of the hydrogen economy in India. Standards such as ASME B31.12-2019 or CGA G-5.6 provide comprehensive guidelines and specifications for the design, construction, operation, and maintenance of hydrogen pipelines, ensuring safety, reliability, and performance. Key considerations for adopting standards for dedicated hydrogen pipelines in India may include these aspects: compatibility with hydrogen, material selection, design and construction specifications, safety and risk management, and interoperability and infrastructure integration, which are elaborated further. These aspects are elaborated further. i) Compatibility with hydrogen: Ensuring that the adopted standard addresses the unique characteristics of hydrogen, such as its high diffusivity and potential for embrittlement, to mitigate risks associated with hydrogen transport. ii) Material selection: Defining requirements for pipeline materials, including steel pipes suitable for hydrogen transport and other alternatives such as advanced composites or polymers, to ensure compatibility with hydrogen and long-term durability. iii) Design and construction specifications: Establish guidelines for pipeline design, construction, and installation to meet safety, integrity, and performance requirements, including considerations for pressure ratings, corrosion protection, and leak detection of hydrogen. Adopting standards for metal hydride storage and the transport of hydrogen is essential for ensuring the safe and effective use of this hydrogen storage technology in India. The ISO 16111:2018 standard provides comprehensive guidelines and specifications for the design, construction, operation, and maintenance of metal hydride storage systems and the transport of hydrogen using this technology. iv) Safety and risk management: Incorporating protocols for risk assessment, hazard mitigation, and emergency response planning to ensure the safe operation of hydrogen pipelines and minimize the potential impact of incidents. v) Interoperability and infrastructure integration: Addressing compatibility and interoperability with existing infrastructure, such as modified natural gas pipelines repurposed for hydrogen transport, to facilitate the efficient integration of hydrogen pipelines into the broader energy infrastructure network. Standards for the maritime transport of hydrogen are essential for ensuring the safe and efficient movement of hydrogen by sea, supporting India's goals for expanding its hydrogen economy and facilitating international trade. The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) and the IMO Resolution MSC.420 provide comprehensive guidelines and regulations for the safe carriage of liquefied gases, including hydrogen, by sea. By adopting the ISO 16111:2018 standard for metal hydride storage and hydrogen transport, India can establish a robust regulatory framework that promotes the safe and effective deployment of these technologies, supporting the growth of the hydrogen economy and contributing to India's sustainable development goals. However, thorough due diligence should be conducted to ensure that the standard is appropriate for India's specific context and regulatory requirements. Additionally, adaptation or customization of the standard may be necessary to address any unique considerations or challenges relevant to India's hydrogen sector [26].

8. CURRENT STATUS OF HYDROGEN-POWERED VEHICLES IN INDIA

Hydrogen (H_2) can be utilized as a fuel in internal combustion engines (ICEs) or fuel cells to power electric motors, offering potential benefits and challenges in both applications. H2 can be used as a direct fuel in ICEs with minor adjustments to the combustion process, by use of H2 injection mechanisms. Due to its high ignition temperature and ability to operate under high compression ratios, H2 can be utilized effectively in ICEs, with additional provisions made in ignition systems and spark plugs. Challenges associated with using H2 as a sole fuel in ICEs include issues like flashback, early ignition, knocking, high compression ratio, high operating temperatures, which are difficult to control, and bulky storage apparatus required for H2, increasing overall vehicle weight by significant amounts. H2 can be added to the existing fuel system of ICEs as a supplement, which can provide an interim solution to reduce emissions and pave the way for a future where H2 may be the primary fuel source. According to data from the Ministry of Road Transport and Highways, there has been a remarkable increase in EV sales in India between 2019 and 2021, which can be attributed to the introduction of new electric car models, increasing consumer awareness about electric vehicles, and government incentives such as subsidies and tax benefits. A similar push for H2 fuel-based vehicles, from the Government of India, is indeed gaining traction. Green hydrogen offers several advantages over electric vehicles (EVs), including higher energy density, lighter weight compared to lithium-ion batteries, longer range, and shorter refueling times. Apart from two or three-wheeler vehicles, multiple original equipment manufacturers (OEMs) in India, like Volvo Eicher Commercial Vehicle (VECV), Ashok Leyland, and Tata Motors are actively working on the development of dedicated hydrogen-powered engines for heavy commercial vehicle applications. Public and private sector companies like National Thermal Power Corporation, Oil India Limited, Daimler Trucks, Bharat Benz, Reliance Industries Limited, through collaborative partnerships, have introduced hydrogen-based fuel cells for both combustion-based and electric powered vehicles. Indian Oil, one of India's largest oil and gas companies, has established demonstration pilot plants for the production of green hydrogen through water electrolysis using solar power, biomass oxy steam gasification, and compressed biogas (CBG) reforming, for refueling hydrogen fuel cell buses. Bosch, a prominent global supplier of automotive components and systems has launched a pilot hydrogen engine testing infrastructure in Bengaluru in 2022, for testing hydrogen engines, components, and systems, enabling Bosch to conduct rigorous performance evaluations, reliability assessments, and optimization studies. The Automotive Research Association of India (ARAI) is set to establish a hydrogen cylinder testing facility at Greenfield Takwe near Pune, with up to 700 bars of hydrogen cylinder pressure and certification services for hydrogen cylinders, for ensuring the safety and reliability of hydrogen storage systems used in vehicles and other applications [27].

9. CONCLUSION

India's current hydrogen consumption, primarily dominated by conventional grey hydrogen derived from fossil fuels, reflects a huge portion of global demand. Despite this reliance on traditional hydrogen sources, the Indian government envisions a transition towards a cleaner hydrogen market. By 2030, the government aims to establish a clean hydrogen market valued at $8 billion, with estimates projecting a substantial growth to $340 billion by 2050. Embracing clean hydrogen presents countless opportunities for India, including significant energy import cost savings. Projections suggest potential savings ranging between $246 billion and $358 billion over the same period. This shift towards clean hydrogen aligns with India's broader goals of reducing carbon emissions, enhancing energy security, and promoting sustainable economic growth. To achieve cost parity and further drive down the cost of green hydrogen, continued advancements in technology, economies of scale, and supportive policy frameworks are essential. Investments in research and development, innovation, and infrastructure are also critical to lowering production costs and accelerating the transition to a hydrogen-based economy. As green hydrogen costs continue to decline and approach parity with grey hydrogen and other players in the market, it will become increasingly attractive for various sectors, leading to broader adoption and significant environmental benefits.

Transitioning to a green hydrogen economy involves various challenges, including technological advancements, infrastructure development, and regulatory frameworks. But by leveraging its renewable energy potential, investing in research and development, and fostering public-private partnerships, India can realize the immense benefits of a clean hydrogen economy. This transition not only contributes to global efforts to combat climate change but also positions India as a leader in the emerging hydrogen market, driving innovation, job creation, and economic prosperity.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] F. Qureshi *et al.*, "Current trends in hydrogen production, storage and applications in India: a review," *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102677, Oct. 2022, doi: 10.1016/j.seta.2022.102677.

[2] S. Kumar, S. Regassa Jufar, S. Kumar, J. Foroozesh, S. Kumari, and A. Bera, "Underground hydrogen storage and its roadmap and feasibility in India toward Net-Zero target for global decarbonization," *Fuel*, vol. 350, p. 128849, Oct. 2023, doi: 10.1016/j.fuel.2023.128849.

[3] M. Aziz, "Liquid hydrogen: a review on liquefaction, storage, transportation, and safety," *Energies*, vol. 14, no. 18, p. 5917, 2021, doi: 10.3390/en14185917.

[4] P. Bakshi, "The green hydrogen economy: insights from India," Florence School of Regulation, European University Institute. [Online]. Available: https://fsr.eui.eu/the-green-hydrogen-economy-insights-from-india/

[5] E. Rivard, M. Trudeau, and K. Zaghib, "Hydrogen storage for mobility: a review," *Materials*, vol. 12, no. 12, p. 1973, Jun. 2019, doi: 10.3390/ma12121973.

[6] R. Moradi and K. M. Groth, "Hydrogen storage and delivery: review of the state of the art technologies and risk and reliability analysis," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 12254–12269, May 2019, doi: 10.1016/j.ijhydene.2019.03.041.

[7] J. O. Abe, A. P. I. Popoola, E. Ajenifuja, and O. M. Popoola, "Hydrogen energy, economy and storage: review and recommendation," *International Journal of Hydrogen Energy*, vol. 44, no. 29, pp. 15072–15086, Jun. 2019, doi: 10.1016/j.ijhydene.2019.04.068.

[8] H. T. Hwang and A. Varma, "Hydrogen storage for fuel cell vehicles," *Current Opinion in Chemical Engineering*, vol. 5, pp. 42–48, Aug. 2014, doi: 10.1016/j.coche.2014.04.004.

[9] M. Reuß, T. Grube, M. Robinius, P. Preuster, P. Wasserscheid, and D. Stolten, "Seasonal storage and alternative carriers: a flexible hydrogen supply chain model," *Applied Energy*, vol. 200, pp. 290–302, Aug. 2017, doi: 10.1016/j.apenergy.2017.05.050.

[10] A. Lys *et al.*, "Enhancing the hydrogen storage properties of AxBy intermetallic compounds by partial substitution: a short review," *Hydrogen*, vol. 1, no. 1, pp. 38–63, Dec. 2020, doi: 10.3390/hydrogen1010004.

[11] N. S. Muhammed, B. Haq, D. Al Shehri, A. Al-Ahmed, M. M. Rahman, and E. Zaman, "A review on underground hydrogen storage: insight into geological sites, influencing factors and future outlook," *Energy Reports*, vol. 8, pp. 461–499, Nov. 2022, doi: 10.1016/j.egyr.2021.12.002.

[12] M. Bai, K. Song, Y. Sun, M. He, Y. Li, and J. Sun, "An overview of hydrogen underground storage technology and prospects in China," *Journal of Petroleum Science and Engineering*, vol. 124, pp. 132–136, Dec. 2014, doi: 10.1016/j.petrol.2014.09.037.

[13] S. Iglauer, "Optimum geological storage depths for structural H2 geo-storage," *Journal of Petroleum Science and Engineering*, vol. 212, p. 109498, May 2022, doi: 10.1016/j.petrol.2021.109498.

[14] J. Andersson and S. Grönkvist, "Large-scale storage of hydrogen," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 11901–11919, May 2019, doi: 10.1016/j.ijhydene.2019.03.063.

[15] A. G. Rao, F. Yin, and H. Werij, "Energy transition in aviation: the role of cryogenic fuels," *Aerospace*, vol. 7, no. 12, p. 181, Dec. 2020, doi: 10.3390/aerospace7120181.

[16] D. E. Demirocak, *Hydrogen storage technologies in nanostructured materials for nextgeneration energy storage and conversion*. Springer Berlin Heidelberg, 2017. [Online]. Available: https://hdl.handle.net/10657.1/1611.

[17] R. Dickson, M. S. Akhtar, A. Abbas, E. D. Park, and J. Liu, “Global transportation of green hydrogen via liquid carriers: economic and environmental sustainability analysis, policy implications, and future directions,” *Green Chemistry*, vol. 24, no. 21, pp. 8484–8493, 2022, doi: 10.1039/D2GC02079C.

[18] I. Staffell *et al.*, “The role of hydrogen and fuel cells in the global energy system,” *Energy & Environmental Science*, vol. 12, no. 2, pp. 463–491, 2019, doi: 10.1039/C8EE01157E.

[19] A. Ibrahim, M. Paskevicius, and C. E. Buckley, “Chemical compression and transport of hydrogen using sodium borohydride,” *Sustainable Energy & Fuels*, vol. 7, no. 5, pp. 1196–1203, 2023, doi: 10.1039/D2SE01334G.

[20] L. Lin, Y. Tian, W. Su, Y. Luo, C. Chen, and L. Jiang, “Techno-economic analysis and comprehensive optimization of an on-site hydrogen refuelling station system using ammonia: hybrid hydrogen purification with both high H 2 purity and high recovery,” *Sustainable Energy & Fuels*, vol. 4, no. 6, pp. 3006–3017, 2020, doi: 10.1039/C9SE01111K.

[21] L. Zhai, S. Liu, and Z. Xiang, “Ammonia as a carbon-free hydrogen carrier for fuel cells: a perspective,” *Industrial Chemistry & Materials*, vol. 1, no. 3, pp. 332–342, 2023, doi: 10.1039/D3IM00036B.

[22] G. Jeerh, M. Zhang, and S. Tao, “Recent progress in ammonia fuel cells and their potential applications,” *Journal of Materials Chemistry A*, vol. 9, no. 2, pp. 727–752, 2021, doi: 10.1039/D0TA08810B.

[23] C. Chu, K. Wu, B. Luo, Q. Cao, and H. Zhang, “Hydrogen storage by liquid organic hydrogen carriers: catalyst, renewable carrier, and technology – a review,” *Carbon Resources Conversion*, vol. 6, no. 4, pp. 334–351, Dec. 2023, doi: 10.1016/j.crcon.2023.03.007.

[24] M. Niermann, S. Drünert, M. Kaltschmitt, and K. Bonhoff, “Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain,” *Energy & Environmental Science*, vol. 12, no. 1, pp. 290–307, 2019, doi: 10.1039/C8EE02700E.

[25] Steering Committee on Hydrogen Energy & Fuel Cells, Ministry of New and Renewable Energy, Government of India, *Hydrogen energy and fuel cells in India — a way forward*, Government of India, 2016. [Online]. Available: https://studylib.net/doc/18212088/hydrogen-energy-and-fuel-cells-in-india%E2%80%94a-way-forward.

[26] W. Alsaba, S. A. Al-Sobhi, and M. A. Qyyum, “Recent advancements in the hydrogen value chain: opportunities, challenges, and the way forward–Middle East perspectives,” *International Journal of Hydrogen Energy*, vol. 48, no. 68, pp. 26408–26435, Aug. 2023, doi: 10.1016/j.ijhydene.2023.05.160.

[27] S. V. Thakur *et al.*, “Effective energy saving techniques for the system of pneumatic gauges,” *Materials Today: Proceedings*, vol. 72, pp. 1153–1157, 2023, doi: 10.1016/j.matpr.2022.09.188.

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