

Cumulative information on the status of H₂ production and subsurface storage in India

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Received 11 March 2026; accepted 17 April 2026; published online 16 June 2026
DOI <https://doi.org/10.21595/getc.2026.26529>



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Abstract. This review article consolidates the status and prospects of hydrogen (H₂) production and underground storage (UHS) in India, emphasizing its role in the energy transition and climate commitments. Studies suggest that H₂ production is currently dominated by carbon-intensive methods such as steam methane reforming and coal gasification, transitioning to renewable-powered electrolysis is critical for sustainability. Reports reveals that India's National Green H₂ Mission targets 5 million metric tons (MMT) of green H₂ production annually by 2030, supported by 125 GW of renewable energy capacity, to decarbonize sectors like transportation, heavy industry, and chemical manufacturing. India's geographical advantages, including high solar irradiance and wind potential, provide a strong foundation for green hydrogen production. Additionally, UHS in geological formations such as salt caverns and depleted reservoirs offer large-scale storage potential, with sedimentary basins like Mumbai Offshore and Krishna-Godavari identified as key regions. However, in India, it is essential to evaluate challenges such as high costs, safety concerns, and the regulatory framework associated with UHS. Work on UHS in India has been negligible; whatever limited progress has been made remains purely conceptual, necessitating experimental and simulation-based studies to translate these concepts into practical reality. Overall, there is a tremendous need for targeted research, pilot projects, and policy cooperation to establish India as a global leader in the production and underground storage of H₂.

Keywords: H₂ production, Underground H₂ storage, Energy transition, India.

1. Introduction

Currently, the entire world is dealing with global climate change. The primary reason is rise in Earth's temperature caused by the increase in atmospheric CO₂. Delving deeper, the emissions from the combustion of fossil fuels, which contain carbon, stand as one of the leading causes. Global energy demand increased by 2.2 % in 2024, faster than the average from 2014 to 2022 [1]. In this context, H₂ energy has emerged as a promising solution due to its potential to act as a clean and versatile energy carrier with zero carbon emissions at the point of use [2-5].

As nations strive to meet climate targets under international agreements, H₂ is increasingly viewed as a critical energy vector capable of decarbonizing sectors that are otherwise difficult to electrify, including heavy industry, long-distance transportation, and chemical manufacturing [6, 7]. H₂ not only serves as a clean fuel but also as an energy carrier that can store surplus renewable energy and facilitate sectoral integration [7]. India, as one of the fastest-growing economies with rapidly increasing energy demand, has recognized H₂ as a strategic priority to ensure energy security, sustainability, and economic competitiveness [8, 9]. Despite the increasing use of renewable energy, fossil fuels, particularly coal and natural gas, continue to dominate the energy sector in India [10]. This dependency has led to rising greenhouse gas emissions, making decarbonization a critical priority. For this, India has pledged to achieve the target of "Net-Zero" emissions by 2070 at the 26th session of the United Nations Framework Convention on Climate Change (COP 26) [8]. India's commitment to achieving net-zero emissions has significantly

accelerated the development of a national H₂ ecosystem. The launch of the National Green H₂ Mission marks a transformative step toward scaling up H₂ production, promoting domestic manufacturing of electrolysers, and establishing India as a global hub for green H₂. Addition to this, India aims to become a global hub for green H₂ production, targeting an annual output of 5 million metric tons (MMT) by 2030, supported by 125 GW of renewable energy capacity [9]. This initiative is expected to reduce dependence on fossil fuel imports, lower greenhouse gas emissions by nearly 50 MMT every year by 2030 and stimulate economic growth through new industrial opportunities [9].

H₂ production in India is currently dominated by fossil fuel-based pathways, particularly steam methane reforming and coal gasification, which contribute to significant carbon emissions [11]. These processes are described as highly carbon-intensive, with SMR responsible for nearly 50 % of global hydrogen yield and emitting approximately 10 kg of CO₂ per kg of H₂ produced [12, 13]. Therefore, to achieve environmental sustainability, it is imperative to transition towards green H₂ production through renewable energy. India's geographical location, characterized by high solar irradiance and substantial wind potential, provides a strong foundation for large-scale renewable energy deployment [14]. As of November 2021, India's installed solar capacity reached 48.556 GW, while wind energy capacity was at 2.07 GW in the financial year 2019-20, marking a 31 % year-over-year growth [14]. Tamil Nadu leads the wind energy sector with a capacity of 7,162.18 MW [15, 16]. Moreover, India has set a target of 450 GW of renewable capacity by 2030 and has achieved 87 GW of on-grid capacity by March 2020. Projects such as Bhadla (2,245 MW), Pavagada (2,050 MW), and Rewa (750 MW) have attracted global investment, addressed land and operational challenges, and driven tariffs down to record lows [17]. These advantageous helps the India to become a global leader in green H₂ production. However, several challenges remain, including high production costs, limited infrastructure, water availability concerns, and the need for technological advancements. Addressing these challenges is crucial for achieving cost competitiveness and scaling up production capacity.

While H₂ production is a critical component of the H₂ economy, efficient storage is equally important for ensuring reliability and continuity of supply [7]. H₂ storage is inherently challenging due to its low volumetric energy density, high diffusivity, and flammability [18]. Geological formations such as depleted oil and gas reservoirs, deep saline aquifers, and salt caverns offer significant potential for storing H₂ at gigawatt to terawatt-hour scales [3, 4]. These formations provide natural containment due to impermeable caprock layers and have been extensively studied in the context of natural gas and carbon dioxide storage. Conventional surface storage methods, such as compressed gas and liquefied H₂, are currently used but are associated with high energy requirements, safety concerns, and economic limitations [19-21]. UHS has gained increasing attention as a viable large-scale and long-duration storage solution globally [22-25]. For instance, currently, four UHS projects (containing ~95 % H₂) are operational worldwide, one in the United Kingdom and three in the United States. The Teesside facility in the UK, commissioned in 1972, has a storage volume of 210,000 m³ and an energy capacity of about 29.9 GWh, without requiring cushion gas. In the USA, the Clemens site (1983) has a capacity of 580,000 m³ and stores approximately 157.4 GWh, using 2.21×10⁶ kg of cushion gas. The Moss Bluff facility (2007) provides 566,000 m³ of storage with an energy capacity of around 146.7 GWh, requiring 2.30×10⁶ kg of cushion gas, while the Spindletop site (2017) offers the largest capacity at 906,000 m³, storing nearly 274 GWh of energy [24].

Although significant progress has been achieved in H₂ production, large-scale UHS is still in its early stages of development in India, with no operational commercial projects. Geographical and operational considerations would be crucial for the viability of UHS systems in India. Multiple studies have evaluated the potential of salt caverns, depleted hydrocarbon reservoirs, and saline aquifers, indicating substantial theoretical capacity and strong long-term potential in Indian context [26-28]. However, significant gaps remain, including the absence of pilot-scale demonstrations, limited subsurface characterization and site-specific data, lack of a clear regulatory framework, high initial investment requirements, and unresolved technical challenges

such as H₂ leakage, geochemical interactions, and geomechanical compatibility. To enable the large-scale expansion of UHS within India's emerging H₂ economy, it is crucial to address technical, economic, and regulatory challenges through targeted research, pilot projects, and policy collaboration [29-31]. This will also be essential to harness the full potential of H₂ as a clean energy carrier in India.

This article aims to evaluate the current production and UHS status in India based on literature data. Future studies can focus on major environmental risks, including potential impacts on groundwater and subsurface integrity, as well as the techno-economic challenges that could affect its large-scale implementation in India based on practical data.

2. H₂ production status in India

India is actively working on expanding its green H₂ production capacity as part of its National H₂ Mission, launched in 2021, to transition to cleaner energy sources and reduce carbon emissions. A open database of H₂ production projects in India, sourced from the official portal of the MNRE, GoI, India [32], indicates a promising projection of H₂ production. Currently, over 300 projects across India focus on H₂ production at different stages, such as operational, under construction, and planned. The cumulative electrolyser capacity, including both operational and announced projects, is estimated at approximately 111.8 GW. Projects are classified into two categories based on installed capacity, small-scale projects (≤ 10 MW) fall within a range of 0.01 MW to 10 MW, while large-scale projects (> 10 MW) range from 11.57 MW to 7,608.45 MW. Small-scale projects contribute approximately 5 % to the total capacity, while large-scale projects dominate with about 95 %. Importantly, more than 60-70 % of the projects are still in the planned or early development stages, highlighting a strong future pipeline under India's green H₂ mission. Major H₂ production projects in India are listed Table 1.

Table 1. Major H₂ production projects in India [32]

S. No.	Project / organization	Location	Status	Electrolyser capacity (MW)	H ₂ production (Tonnes/Year)
1	IOCL: Mathura Refinery	Mathura, UP	Planned / Ongoing	~5-10	~500-1000
2	IOCL: Panipat Refinery	Panipat, Haryana	Planned / Ongoing	~5-10	~500-1000
3	BPCL: Green H ₂	India	Under Development	~5	~500
4	HPCL: Green H ₂ Plant	India	Under Development	~5	~500
5	GIPCL: 10+5 MW Project	Gujarat	Planned	15	~1500
6	NTPC: H ₂ Projects	Multiple Locations	Pilot / Ongoing	~5-20	~500-2000
7	Adani Group: H ₂	Gujarat / Coastal	Planned	>20	>2000
8	Reliance Industries: H ₂	Gujarat	Planned	>20	>2000

Current H₂ production in India is predominantly based on fossil fuel pathways, including steam methane reforming and coal gasification. Although renewable-based methods such as water electrolysis using solar and wind energy are gaining increasing attention due to their low emissions and sustainability [33, 34]. Furthermore, the integration of H₂ production with power systems through grid-connected electrolyser can enhance energy system flexibility and enable large-scale storage of surplus renewable energy [35]. Alternative production pathways, including nuclear-powered electrolysis, have also been identified as viable options for supplying low-carbon H₂ to support industrial decarbonization in India [36]. Table 2 represents a summary of H₂ production-

based literature from an Indian perspective.

Table 2. Summary of some H₂ production-based studies in Indian prospective

Reference	Production pathway	Key findings	Challenges	India perspective / potential
[19]	Multi-source (biomass, renewables)	H ₂ versatile energy carrier	Storage, safety, cost barriers	Integration with renewables essential for India
[29]	Fossil + renewable mix	Current H ₂ is mainly fossil-based	Policy gaps, infrastructure, cost	National H ₂ Mission to boost production
[30]	Biomass, electrolysis	Biomass contributes significantly (~40 % potential globally)	High production cost	India rich in biomass → strong production potential
[31]	Electrolysis, methane reforming, coal gasification	H ₂ key for decarbonizing transport and power sectors	High cost, technology maturity	Supports Atmanirbhar Bharat and future energy demand
[33]	Renewable (solar, wind), fossil (SMR, coal gasification)	Multiple pathways available; electrolysis gaining importance	Low efficiency, integration with storage, feedstock dependency	Strong potential due to abundant solar & wind resources
[34]	Solar photocatalysis (wastewater)	H ₂ from industrial waste streams possible	Technology scalability	Solar + wastewater offers sustainable pathway
[35]	Electrolysis (grid-integrated)	H ₂ can balance grid and utilize excess renewable power	Infrastructure and system optimization required	H ₂ can support grid stability and industrial decarbonization
[36]	Nuclear-powered electrolysis	Can produce 1.8-4.0 MMT/year H ₂	High cost, economic viability	Nuclear can supply 6-15 % H ₂ demand in India
[37]	Solar (photoelectrochemical)	Solar H ₂ is viable with advanced materials (TiO ₂)	Low efficiency, material limitations	Good solar potential for decentralized production
[38]	Solar-based electrolysis (PV + PEM)	Developed deep learning model (CEEMDAN-BiDLSTM) for solar forecasting; created atlas for H ₂ potential	Intermittency of solar irradiance, forecasting uncertainty	High solar potential in Rajasthan; supports large-scale green H ₂ planning
[39]	Multi-feedstock (waste, biomass, fossil, electrolysis)	Integrated approach: feedstock, circular economy, emissions	Economic constraints, lack of awareness, H ₂ emissions	Strong feedstock diversity (waste, biomass); policy-driven growth under Green H ₂ Mission
[40]	Renewable-based electrolysis (solar, wind, biomass, hydro)	Solar ranked as best renewable source; multi-criteria analysis (AHP, TOPSIS)	Cost, policy support, social acceptance	India has ~748 GW solar potential; ideal for green H ₂ hub

3. Underground H₂ storage potential in India

In India, H₂ storage is primarily focused on three techniques: compressed H₂, liquefied H₂, and metal hydrides [20]. Compressed H₂ is the most utilized method, however, in this method, safety concerns arise due to high pressure requirements [41]. Liquid H₂ storage involves cooling H₂ to -253°C, but it faces challenges like boil-off losses and high energy consumption during liquefaction. India has established H₂ liquefaction plants in Mahendragiri and Saggonda, primarily

for oil refineries and fertilizer factories [21]. Moreover, metal hydrides offer a safer storage option due to their stability across a wide temperature range, but they require high temperatures and pressures, which limit their efficiency and practicality [42-44]. Despite these techniques, large-scale H₂ storage remains challenging due to high costs, safety concerns, and energy inefficiencies.

As India targets 5 MMT of green H₂ production annually, large-scale storage becomes essential. Surface storage methods are insufficient at this scale; therefore, underground storage in geological formations including salt caverns, depleted reservoirs, and saline aquifers seems practical and scalable solution. Multiple studies suggests that India possesses promising geological potential [26-28] for UHS. For instance, Vishal et al. [26] reported that India possesses substantial H₂ storage potential, with deep saline aquifers alone capable of storing up to 22,610 TWh of H₂. According to this study, major sedimentary basins, including the Mumbai Offshore, Krishna-Godavari, Rajasthan, Cauvery, and Cambay basins, have been identified as key regions with significant storage capacities. Roy et al. [27] demonstrated about UHS in hydrocarbon basins across South Asia, focusing on India. They estimated a total pure H₂ storage capacity of 29,799.43 TWh, with India contributing over 75 %. Moreover, the South Tapti gas field in the Mumbai Offshore Basin is identified as a potential site for UHS. It has a reservoir pressure of 3582 psi (24.7 MPa), a temperature of 186.8 °F (86 °C), and an estimated H₂ storage capacity of 592,869 million cubic meters at standard conditions [28]. Fig. 1 shows categorized H₂ storage potential (TWh) of Indian sedimentary basins. Category I basins show significant storage potential dominated by the Mumbai offshore and Krishna-Godavari basins. Category II basins exhibit strong contributions from the Vindhyan and Andaman-Nicobar regions. Category III basins display highly variable storage potential, with the Kerala-Konkan-Lakshadweep basin having the highest estimated capacity [26].

Furthermore, experimental and simulation-based studies indicate that H₂ storage in porous media is generally stable, with minimal geochemical losses (< 1 %) and relatively low diffusion losses (~4 %) [28, 45] However, key challenges include H₂ mobility, microbial activity, and reservoir heterogeneity, which can affect storage efficiency and recovery [46-50]. Advanced approaches, such as foam-assisted storage, have shown improvement in storage performance by enhancing mobility control in porous media [49]. Furthermore, regional assessments suggest that basins like Krishna-Godavari and Cauvery can support long-term H₂ storage for several years, contributing to industrial decarbonization [51]. Although some literature on UHS is available in India, it remains limited and is continually evolving, indicating that the field has not yet reached maturity. Table 3 presents a summary of existing studies on UHS from an Indian perspective; it outlines the methodologies, key findings, and identified limitations to provide an understanding of current research gaps. Overall, while UHS in India demonstrates strong technical feasibility and large-scale potential, more extensive and site-specific investigations, long-term field validation, and development of regulatory frameworks are required for its safe and efficient implementation.

4. Government policies, guidelines, initiatives in India for H₂ economy

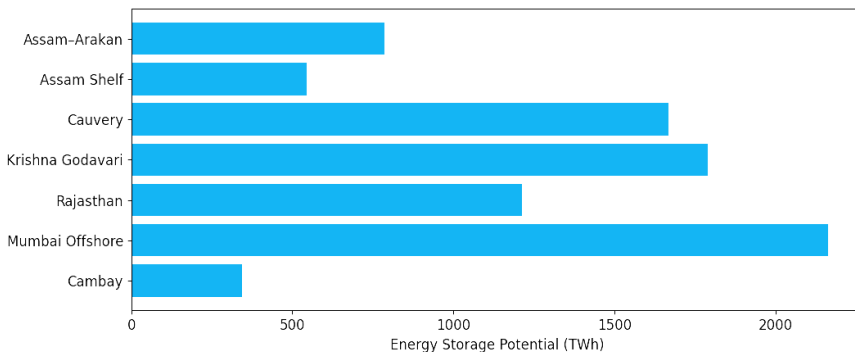
India has undertaken various policy measures and strategic initiatives to foster the development of a hydrogen-based energy ecosystem, with a particular emphasis on “Green Hydrogen” as a pathway toward decarbonization and energy security. The information presented in this section has been compiled and synthesized from credible sources, including official reports and communications from the Press Information Bureau (PIB), the Ministry of New and Renewable Energy (MNRE), and other relevant government agencies [32], the Press Information Bureau [54-70], and other official communications. In the industrial domain, green H₂ is being adopted to replace fossil-based feedstocks in fertilizers, petroleum refining, and steel production. In the refining sector, green H₂ is being integrated to reduce carbon emissions. Pilot projects in the steel industry are evaluating H₂-based iron reduction under Indian operating conditions. In the mobility sector, pilot projects involving 37 H₂-powered vehicles and nine refueling stations have

been initiated with financial support of approximately \approx \$25.1 million. In the maritime sector, green H₂ production and bunkering facilities have been established at major ports to support cleaner shipping operations. The commissioning of a high-altitude H₂ mobility project in Leh demonstrates the operational feasibility of H₂ in extreme environments. The mission is further supported by policy measures such as waivers on interstate transmission charges and streamlined access to renewable energy. Skill development initiatives have resulted in the certification of over 5,600 professionals in H₂ technologies. India is also strengthening its global engagement through collaborations with the European Union, the United Kingdom, Germany, and Singapore, focusing on technology development, standardization, and market expansion.

5. Research gaps and future directions

H₂ production in India can face several challenges that hinder its large-scale adoption and commercialization. The high cost of renewable-powered electrolysis, coupled with limited infrastructure and water availability concerns, makes green H₂ production expensive and less accessible. Additionally, the technological maturity of electrolyzers, including their efficiency and durability, requires further improvement to achieve cost competitiveness. While the National Green H₂ Mission provides a framework, gaps in policy and regulatory support slow the transition to a H₂ economy. The dominance of fossil fuel-based H₂ production (grey H₂) continues to contribute to carbon emissions, while slow commercialization and the early development stage of most planned projects further delay progress.

UHS in India also faces significant limitations. Large-scale storage in geological formations involves high costs and safety concerns, including risks associated with high pressure, flammability, and boil-off losses. While India has promising geological potential, detailed site-specific assessments and field-scale validations could be essential to confirm the feasibility of identified storage sites. Challenges such as microbial activity, reservoir heterogeneity, and H₂ losses due to diffusion and geochemical reactions further complicate storage efficiency. Additionally, the lack of a comprehensive regulatory framework and the dependence on intermittent renewable energy sources for hydrogen production and storage integration remain critical barriers to large-scale implementation. Addressing these challenges is vital for India to realize its vision of becoming a global hub for green H₂ production and storage.



a) Category I basins

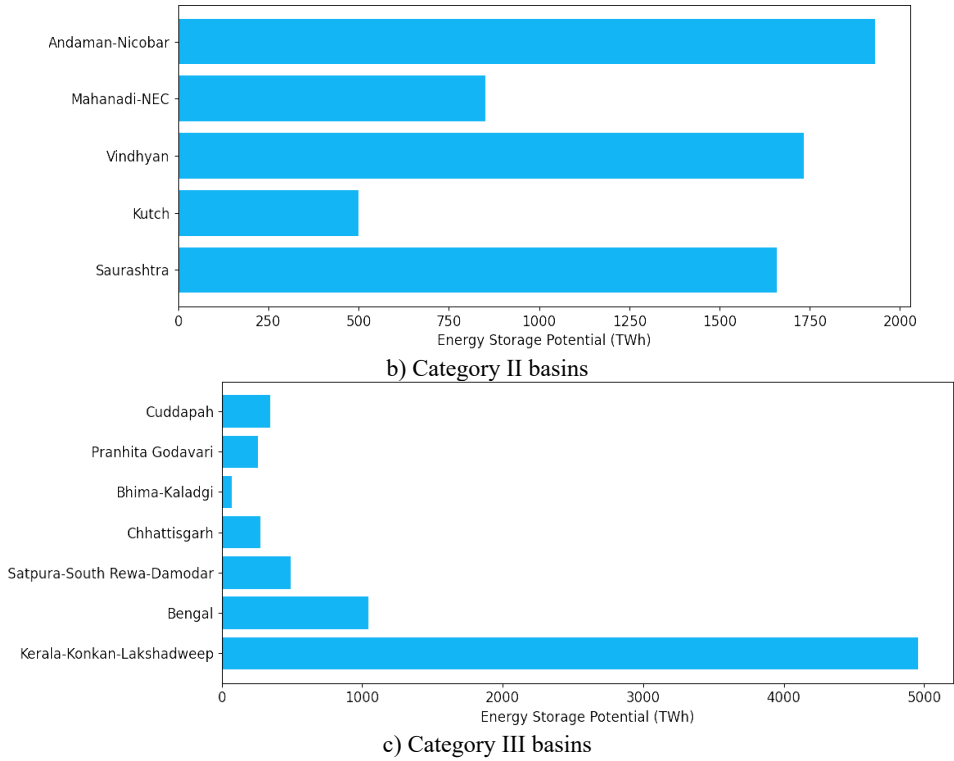


Fig. 1. H₂ storage potential (TWh) of major Indian sedimentary basins (data sourced from [26])

Table 3. Summary of available studies on UHS in Indian prospective with their limitations

References	Focus area	Methodology	Key findings	Storage type / medium	Limitations
[26]	UHS potential in India	Basin-scale geological assessment	India has a storage potential of up to 22,610 TWh in deep saline aquifers; major basins identified include Mumbai Offshore, Krishna-Godavari, Rajasthan, Cauvery, and Cambay	Deep saline aquifers, depleted reservoirs	Preliminary estimation requires detailed site-specific validation
[28]	Offshore H ₂ storage in depleted gas fields (Tapti field)	Geological, geochemical, and reservoir simulation study	Estimated storage capacity of 592,869 million m ³ ; H ₂ loss <1% due to geochemical reactions; ~3.85% loss due to diffusion; anticline structure ensures good seal ability; 80-day production cycle identified as optimal	Depleted offshore gas reservoir	Requires optimized injection–production strategy; limited caprock data

[45]	Reservoir integrity during H ₂ injection	Experimental cyclic H ₂ injection in sandstone	No significant mechanical degradation observed; permeability and geochemical interactions require monitoring	Sandstone reservoirs	Long-term behavior and scale-up uncertainties
[48]	Role of UHS in energy transition	Review of energy systems and storage technologies	UHS is suitable for large-scale (GW-TWh) seasonal storage, supporting renewable energy integration	Aquifers, salt caverns, depleted reservoirs	Limited field-scale implementation and regulatory framework
[49]	Feasibility and challenges of UHS	Conceptual and technical review	Seasonal H ₂ storage is feasible; challenges include microbial activity, H ₂ mobility, and permeability changes	Aquifers, depleted oil and gas fields	Limited experimental and field validation
[50]	Enhancement of H ₂ storage efficiency	Experimental study using foam-assisted injection	Storage efficiency improves by 1.5-2.7 times due to mobility control	Porous media (sandstone)	Foam stability affected by hydrocarbons
[51]	Regional H ₂ storage for decarbonization	Energy demand and storage modeling	Krishna-Godavari and Cauvery basins can support H ₂ supply for 6-7 years	Aquifers and reservoirs	Region-specific study; dependent on renewable energy availability
[52]	Underground energy storage potential (CAES analogy applicable to UHS) in India and UK	Review + geological assessment + spatial analysis	Identified suitable geological formations (salt caverns, aquifers, depleted reservoirs); ~1.05% of India's land suitable; underground storage essential for large-scale energy storage	Salt caverns, aquifers, depleted reservoirs, lined rock caverns	Limited salt cavern availability in India; high cost and uncertainty in aquifer storage; lack of field-scale demonstration
[53]	Hydrogen storage in lined rock caverns (LRC) and material challenges	Review + experimental insights + numerical modeling of hydrogen embrittlement	LRC offers flexible site selection and high-pressure storage; hydrogen embrittlement is a critical risk affecting structural integrity	Lined rock caverns (hard rock storage)	Limited experimental data: hydrogen embrittlement not fully understood; lack of large-scale deployment; technology still in developmental stage

6. Conclusions

India is at a pivotal stage in its transition toward a H₂ economy, driven by ambitious climate goals, increasing energy demand, and strong policy support under the National Green H₂ Mission. Although significant progress has been made in advancing green H₂ production, several challenges, such as high costs, limited infrastructure, water availability, and technological advancements, still need to be addressed to enable its large-scale commercialization. The dominance of fossil fuel-based hydrogen production further underscores the need for accelerated

efforts to transition to renewable-powered methods.

Similarly, UHS presents a promising solution for large-scale and long-duration storage, essential for ensuring supply reliability and industrial utilization. India's geological formations, including salt caverns, depleted reservoirs, and deep saline aquifers, offer substantial storage potential. However, technical, economic, and regulatory challenges, such as high costs, safety concerns, and limited field validation, must be addressed to unlock this potential. By fostering technological advancements, strengthening policy frameworks, and conducting site-specific research, India can overcome these barriers and establish itself as a global leader in green H₂ production and storage, contributing significantly to a sustainable and low-carbon energy future.

Acknowledgements

During the writing and drafting of this article, the authors express his gratitude to the Research Council of Lithuania for providing financial support under Grant No. P-PD-23-090.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

- [1] "Global energy review 2025," IEA, Paris, 2025.
- [2] M. Pal, A. Verma, and S. Malik, "In-situ microbial hydrogen production under reservoir conditions: lessons from coreflood experiments," *Next Research*, Vol. 6, p. 101401, Apr. 2026, <https://doi.org/10.1016/j.nexres.2026.101401>
- [3] A. Verma, M. Pal, V. R. S., M. Kurkuri, and K. Upendranath, "Microbial hydrogen production from depleted hydrocarbon reservoirs: evidence from field investigations and lab experiments," *Energy Reports*, Vol. 14, pp. 5616–5627, Dec. 2025, <https://doi.org/10.1016/j.egy.2025.11.103>
- [4] A. Verma, S. Malik, and M. Pal, "Evaluating the potential for underground hydrogen storage (UHS) in Lithuania: a review of geological viability and storage integrity," *Applied Sciences*, Vol. 15, No. 3, p. 1614, 2025, <https://doi.org/10.3390/app15031614>
- [5] A. Verma, M. Pal, and S. Malik, "Unlocking hydrogen potential from depleted hydrocarbon reservoirs in Lithuania: a sustainable approach," in *ECMOR 2024*, Vol. 2024, No. 1, pp. 1–11, 2024, <https://doi.org/10.3997/2214-4609.202437038>
- [6] D. Kundu et al., "Green hydrogen pathways for a net-zero future: technologies, circular economy integration, life-cycle performance and safety dimensions," *RSC Advances*, Vol. 16, No. 15, pp. 13471–13514, 2026, <https://doi.org/10.1039/d5ra09599a>
- [7] S. Sikiru, J. O. Olutoki, T. Alomayri, and H. Soleimani, "Integrating hydrogen into modern power grids: infrastructure requirements and techno-economic perspectives," *International Journal of Hydrogen Energy*, Vol. 228, p. 154511, 2026, <https://doi.org/10.1016/j.ijhydene.2026.154511>
- [8] "Press release." Press Information Bureau, Government of India, 2023, <https://www.pib.gov.in/pressreleaseiframepage.aspx?prid=1945472>.
- [9] "Press note." Press Information Bureau, Government of India, 2025 <https://www.pib.gov.in/pressnotedetails.aspx?id=155990>
- [10] M. K. Singh, J. Malek, H. K. Sharma, and R. Kumar, "Converting the threats of fossil fuel-based energy generation into opportunities for renewable energy development in India," *Renewable Energy*, Vol. 224, p. 120153, 2024, <https://doi.org/10.1016/j.renene.2024.120153>
- [11] P. Phogat, B. Chand, and Shreya, "Hydrogen economy: pathways, production methods, and applications for a sustainable energy future," *Sustainable Materials and Technologies*, Vol. 45, p. e01550, 2025, <https://doi.org/10.1016/j.susmat.2025.e01550>
- [12] S. M. Soltani et al., "Sorption-enhanced steam methane reforming," *Carbon Capture Science and Technology*, Vol. 1, p. 100003, 2021.
- [13] W. Ma, W. Han, Q. Liu, J. Li, Y. Xin, and G. Xu, "Hydrogen production system with near-zero carbon dioxide emissions enabled by complementary utilization of natural gas and electricity," *Journal of Cleaner Production*, Vol. 447, p. 141395, 2024, <https://doi.org/10.1016/j.jclepro.2024.141395>

- [14] S. Dey, A. Sreenivasulu, G. T. N. Veerendra, K. V. Rao, and P. S. S. A. Babu, "Renewable energy present status and future potentials in India: an overview," *Innovation and Green Development*, Vol. 1, No. 1, p. 100006, 2022, <https://doi.org/10.1016/j.igd.2022.100006>
- [15] C. R. Monroy and A. S. Hernandez, "Financial innovation in energy projects," *International Journal of Sustainable Development and World Ecology*, Vol. 15, No. 5, pp. 471–483, 2008.
- [16] R. Cynthia Neudoerffer, P. Malhotra, and P. Venkata Ramana, "Participatory rural energy planning in India – a policy context," *Energy Policy*, Vol. 29, No. 5, pp. 371–381, 2001, [https://doi.org/10.1016/s0301-4215\(00\)00132-4](https://doi.org/10.1016/s0301-4215(00)00132-4)
- [17] K. Shah, "India's utility-scale solar parks," IEEFA report, 2020.
- [18] I. M. Anekwe et al., "Hydrogen storage challenges and safety," *International Journal of Hydrogen Energy*, Vol. 167, p. 150952, 2025.
- [19] L. Mulky et al., "An overview of hydrogen storage technologies – key challenges and opportunities," *Materials Chemistry and Physics*, Vol. 325, p. 129710, 2024, <https://doi.org/10.1016/j.matchemphys.2024.129710>
- [20] 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, 2022, <https://doi.org/10.1016/j.seta.2022.102677>
- [21] T. Zhang, J. Uratani, Y. Huang, L. Xu, S. Griffiths, and Y. Ding, "Hydrogen liquefaction and storage: recent progress and perspectives," *Renewable and Sustainable Energy Reviews*, Vol. 176, p. 113204, 2023, <https://doi.org/10.1016/j.rser.2023.113204>
- [22] D. Zivar, S. Kumar, and J. Foroozesh, "Underground hydrogen storage: a comprehensive review," *International Journal of Hydrogen Energy*, Vol. 46, No. 45, pp. 23436–23462, 2021, <https://doi.org/10.1016/j.ijhydene.2020.08.138>
- [23] R. Gholami, "Hydrogen storage in porous media," *Journal of Energy Storage*, Vol. 59, p. 106576, 2023.
- [24] C. Sambo et al., "Global UHS review," *International Journal of Hydrogen Energy*, Vol. 47, No. 54, pp. 22840–22880, 2022.
- [25] L. Borghini et al., "UHS suitability index," *International Journal of Hydrogen Energy*, Vol. 149, p. 150110, 2025.
- [26] V. Vishal, Y. Verma, K. Sulekh, T. N. Singh, and A. Dutta, "A first-order estimation of underground hydrogen storage potential in Indian sedimentary basins," *Geological Society, London, Special Publications*, Vol. 528, No. 1, pp. 123–137, 2023, <https://doi.org/10.1144/sp528-2022-24>
- [27] D. Guha Roy, J. Goyal, and M. Talukdar, "Capacity assessment and economic analysis of geologic storage of hydrogen in hydrocarbon basins: A South Asian perspective," *International Journal of Hydrogen Energy*, Vol. 92, pp. 917–929, 2024, <https://doi.org/10.1016/j.ijhydene.2024.10.282>
- [28] R. Kiran, R. Upadhyay, V. K. Rajak, S. D. Gupta, and H. Pama, "Comprehensive study of the underground hydrogen storage potential in the depleted offshore Tapti-gas field," *International Journal of Hydrogen Energy*, Vol. 48, No. 33, pp. 12396–12409, 2023, <https://doi.org/10.1016/j.ijhydene.2022.12.172>
- [29] S. K. Kar, A. S. K. Sinha, S. Harichandan, R. Bansal, and M. S. Balathanigaimani, "Hydrogen economy in India: A status review," *WIREs Energy and Environment*, Vol. 12, No. 1, p. e459, 2022, <https://doi.org/10.1002/wene.459>
- [30] V. M. Medisetty, R. Kumar, M. H. Ahmadi, D.-V. N. Vo, A. A. V. Ochoa, and R. Solanki, "Overview on the current status of hydrogen energy research and development in India," *Chemical Engineering and Technology*, Vol. 43, No. 4, pp. 613–624, 2020, <https://doi.org/10.1002/ceat.201900496>
- [31] R. Kumar Singh and D. N. Priyadarshini Nayak, "DIVE method integration for techno-economic analysis of hydrogen production techniques in India," *Materials Today: Proceedings*, Vol. 102, pp. 226–235, 2024, <https://doi.org/10.1016/j.matpr.2023.05.088>
- [32] "National Green Hydrogen Mission: Project Database," ministry of new renewable energy, Government of India, 2023.
- [33] S. K. Dash, S. Chakraborty, and D. Elangovan, "A brief review of hydrogen production methods and their challenges," *Energies*, Vol. 16, No. 3, p. 1141, 2023, <https://doi.org/10.3390/en16031141>
- [34] V. Preethi, "Solar hydrogen production in India," *Environment, Development and Sustainability*, Vol. 25, No. 3, pp. 2105–2135, Feb. 2022, <https://doi.org/10.1007/s10668-022-02157-1>
- [35] R. Bhattacharyya et al., "Hydrogen for grid balancing in India," *Energy and Climate Change*, Vol. 5, p. 100131, 2024.

- [36] R. Bhattacharyya et al., “Nuclear-to-hydrogen production potential,” *International Journal of Energy Research*, Vol. 46, No. 13, pp. 18901–18918, 2022.
- [37] M. S. Leo Hudson et al., “Hydrogen energy in changing environmental scenario: Indian context,” *International Journal of Hydrogen Energy*, Vol. 34, No. 17, pp. 7358–7367, 2009, <https://doi.org/10.1016/j.ijhydene.2009.05.107>
- [38] K. Sareen, B. K. Panigrahi, T. Shikhola, and R. Nagdeve, “Deep learning solar forecasting for green hydrogen production in India: A case study,” *International Journal of Hydrogen Energy*, Vol. 50, pp. 334–351, 2024, <https://doi.org/10.1016/j.ijhydene.2023.08.323>
- [39] A. P. Singh, “Assessment of India’s green hydrogen mission and environmental impact,” *Renewable and Sustainable Energy Reviews*, Vol. 203, p. 114758, 2024, <https://doi.org/10.1016/j.rser.2024.114758>
- [40] S. Gupta, R. Kumar, and A. Kumar, “Green hydrogen in India: Prioritization of its potential and viable renewable source,” *International Journal of Hydrogen Energy*, Vol. 50, pp. 226–238, 2024, <https://doi.org/10.1016/j.ijhydene.2023.08.166>
- [41] V. P. Utgikar and T. Thiesen, “Safety of compressed hydrogen fuel tanks: Leakage from stationary vehicles,” *Technology in Society*, Vol. 27, No. 3, pp. 315–320, 2005, <https://doi.org/10.1016/j.techsoc.2005.04.005>
- [42] N. Klopčič, I. Grimmer, F. Winkler, M. Sartory, and A. Trattner, “A review on metal hydride materials for hydrogen storage,” *Journal of Energy Storage*, Vol. 72, p. 108456, Nov. 2023, <https://doi.org/10.1016/j.est.2023.108456>
- [43] A. Alobaid, M. Kamil, and K. Abdelrazek Khalil, “Metal hydrides for solid hydrogen storage: Experimental insights, suitability evaluation, and innovative technical considerations for stationary and mobile applications,” *International Journal of Hydrogen Energy*, Vol. 128, pp. 432–456, 2025, <https://doi.org/10.1016/j.ijhydene.2025.04.232>
- [44] K. S. Nivedhitha et al., “Advances in hydrogen storage with metal hydrides: Mechanisms, materials, and challenges,” *International Journal of Hydrogen Energy*, Vol. 61, pp. 1259–1273, 2024, <https://doi.org/10.1016/j.ijhydene.2024.02.335>
- [45] S. Joshi, A. D. Panchakarla, and K. R. Chaturvedi, “Investigating the impact of cyclical hydrogen injection and extraction on subsurface reservoir formation rocks for underground hydrogen storage,” in *SPWLA 66th Annual Symposium Transactions*, p. D041S018R008, 2025, <https://doi.org/10.30632/spwla-2025-0087>
- [46] A. Shojaee, S. Ghanbari, G. Wang, and E. Mackay, “Impact of reservoir heterogeneity on microbial and geochemical reactions during underground hydrogen storage,” in *86th EAGE Annual Conference and Exhibition*, Vol. 2025, No. 1, pp. 1–5, 2025, <https://doi.org/10.3997/2214-4609.202510773>
- [47] A. B. Dohrmann and M. Krüger, “Microbial H₂ consumption under high-pressure conditions,” *Environmental Science and Technology*, Vol. 57, No. 2, pp. 1092–1102, 2023.
- [48] 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, 2023, <https://doi.org/10.1016/j.fuel.2023.128849>
- [49] S. Joshi and K. R. Chaturvedi, “Exploring the feasibility of geological storage of hydrogen in Indian porous media: Challenges, opportunities and the way ahead,” in *International Petroleum Technology Conference*, p. D021S024R002, 2022, <https://doi.org/10.2523/iptc-22320-ms>
- [50] K. R. Chaturvedi, S. Bajpai, J. Trivedi, and T. Sharma, “Air foams for mobility control and subsurface storage of hydrogen in porous media: An experimental study,” *Energy and Fuels*, Vol. 36, No. 9, pp. 5036–5046, 2022, <https://doi.org/10.1021/acs.energyfuels.1c04246>
- [51] P. Nikhil et al., “CO₂ emissions and hydrogen geo-storage potential in India,” *International Journal of Hydrogen Energy*, Vol. 52, pp. 1507–1521, 2024.
- [52] M. King, A. Jain, R. Bhakar, J. Mathur, and J. Wang, “Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK,” *Renewable and Sustainable Energy Reviews*, Vol. 139, p. 110705, 2021, <https://doi.org/10.1016/j.rser.2021.110705>
- [53] Y. K. Patanwar, H.-M. Kim, D. Deb, and Y. K. Gujjala, “Underground storage of hydrogen in lined rock caverns: an overview of key components and hydrogen embrittlement challenges,” *International Journal of Hydrogen Energy*, Vol. 50, pp. 116–133, 2024, <https://doi.org/10.1016/j.ijhydene.2023.08.342>

- [54] “India poised to emerge as global hub for green hydrogen innovation: Union minister of state Shri Shripad Yesso Naik.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2166110>
- [55] “Ministry of new and renewable energy participates in world hydrogen summit 2025, highlights India’s vision and capabilities in renewable energy and green hydrogen.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2129952>
- [56] “India accelerates green hydrogen mission with new R&D push, start-up innovation fund and global collaborations.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2165811>
- [57] “National green hydrogen mission.” Ministry of New and Renewable Energy, Government of India, 2024, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2039091>
- [58] “Three major ports recognized as green hydrogen hubs under national green hydrogen mission.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2177591>
- [59] “MNRE organizes workshop on opportunities for MSMEs in green hydrogen supply chain.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2125231>
- [60] “Centre issues scheme guidelines for funding of testing facilities, infrastructure, and institutional support under the national green hydrogen mission.” Ministry of New and Renewable Energy, Government of India, 2024, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2030686>
- [61] “SECI conducts first-ever auction for procurement of green ammonia under national green hydrogen mission.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2153006>
- [62] “Pilot projects on hydrogen-fuelled buses and trucks launched under the national green hydrogen mission.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2107795>
- [63] “Shri Sarbananda Sonowal unveils green hydrogen pilot project at VOC port in Tamil Nadu.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2164314>
- [64] “Green hydrogen mobility project at Leh comprises in-situ 1.7 MW solar plant, green hydrogen filling station of capacity 80 kg/day and 5 hydrogen intra-city buses.” Ministry of New and Renewable Energy, Government of India, 2024, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2076327>
- [65] “New and renewable energy secretary addresses world hydrogen summit 2024, highlights India’s vision and capabilities in renewable energy and green hydrogen.” Ministry of New and Renewable Energy, Government of India, 2024, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2020773>
- [66] “Maiden India pavilion at world hydrogen summit 2024, Netherlands showcases national green hydrogen mission.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2020510>
- [67] “Workshop on green hydrogen aims at strengthening India-UK cooperation.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2100208>
- [68] “SECI signs MoU to promote green hydrogen initiatives.” Ministry of New and Renewable Energy, Government of India, 2024, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2075049>
- [69] “Solar Energy Corporation of India issues RfS for selection of green ammonia producers under SIGHT programme of the national green hydrogen mission (NGHM).” Ministry of New and Renewable Energy, Government of India, 2024, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2023625>
- [70] “India’s solar leap to produce green hydrogen by splitting water molecules using only solar energy.” Ministry of New and Renewable Energy, Government of India, 2025, <https://www.pib.gov.in/pressreleasedetail.aspx?prid=2138051>



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