Cumulative information on the status of H_2 production and subsurface storage in India

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

Abstract. This review article consolidates the status and prospects of hydrogen (H_2) production and underground storage (UHS) in India, emphasizing its role in the energy transition and climate commitments. Studies suggest that H_2 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 H_2 Mission targets 5 million metric tons (MMT) of green H_2 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 H_2.

Keywords: H_2 production, Underground H_2 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 CO_2. 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, H_2 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, H_2 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]. H_2 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 H_2 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 H_2 ecosystem. The launch of the National Green H_2 Mission marks a transformative step toward scaling up H_2 production, promoting domestic manufacturing of electrolysers, and establishing India as a global hub for green H_2. Addition to this, India aims to become a global hub for green H_2 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].

H_2 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 CO_2 per kg of H_2 produced [12, 13]. Therefore, to achieve environmental sustainability, it is imperative to transition towards green H_2 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 H_2 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 H_2 production is a critical component of the H_2 economy, efficient storage is equally important for ensuring reliability and continuity of supply [7]. H_2 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 H_2 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 H_2, 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 % H_2) 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 m^3 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 m^3 and stores approximately 157.4 GWh, using 2.21×10^6 kg of cushion gas. The Moss Bluff facility (2007) provides 566,000 m^3 of storage with an energy capacity of around 146.7 GWh, requiring 2.30×10^6 kg of cushion gas, while the Spindletop site (2017) offers the largest capacity at 906,000 m^3, storing nearly 274 GWh of energy [24].

Although significant progress has been achieved in H_2 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 H_2 leakage, geochemical interactions, and geomechanical compatibility. To enable the large-scale expansion of UHS within India's emerging H_2 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 H_2 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. H_2 production status in India

India is actively working on expanding its green H_2 production capacity as part of its National H_2 Mission, launched in 2021, to transition to cleaner energy sources and reduce carbon emissions. A open database of H_2 production projects in India, sourced from the official portal of the MNRE, GoI, India [32], indicates a promising projection of H_2 production. Currently, over 300 projects across India focus on H_2 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 H_2 mission. Major H_2 production projects in India are listed Table 1.

Table 1. Major H_2 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: H2 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 H_2 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 H_2 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 H_2 to support industrial decarbonization in India [36]. Table 2 represents a summary of H_2 production-based literature from an Indian perspective.

Table 2. Summary of some H_2 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 H_2 storage potential in India

In India, H_2 storage is primarily focused on three techniques: compressed H_2, liquefied H_2, and metal hydrides [20]. Compressed H_2 is the most utilized method, however, in this method, safety concerns arise due to high pressure requirements [41]. Liquid H_2 storage involves cooling H_2 to -253°C, but it faces challenges like boil-off losses and high energy consumption during liquefaction. India has established H_2 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 H_2 storage remains challenging due to high costs, safety concerns, and energy inefficiencies.

As India targets 5 MMT of green H_2 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 H_2 storage potential, with deep saline aquifers alone capable of storing up to 22,610 TWh of H_2. 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 H_2 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 H_2 storage capacity of 592,869 million cubic meters at standard conditions [28]. Fig. 1 shows categorized H_2 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].

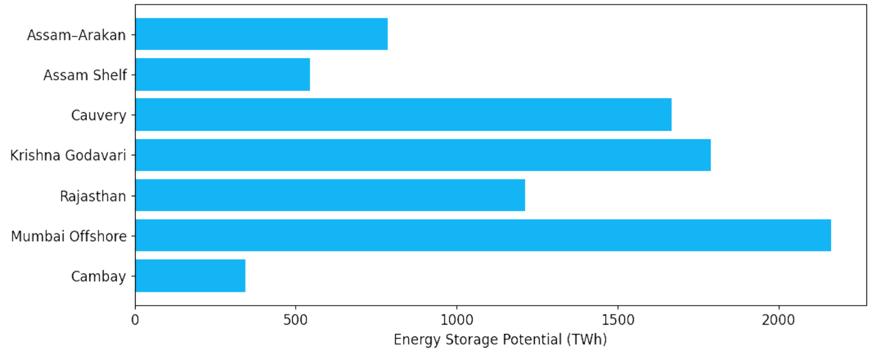
Furthermore, experimental and simulation-based studies indicate that H_2 storage in porous media is generally stable, with minimal geochemical losses (< 1 %) and relatively low diffusion losses (~4 %) [28, 45] However, key challenges include H_2 mobility, microbial activity, and reservoir heterogeneity, 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 H_2 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 H_2 economy

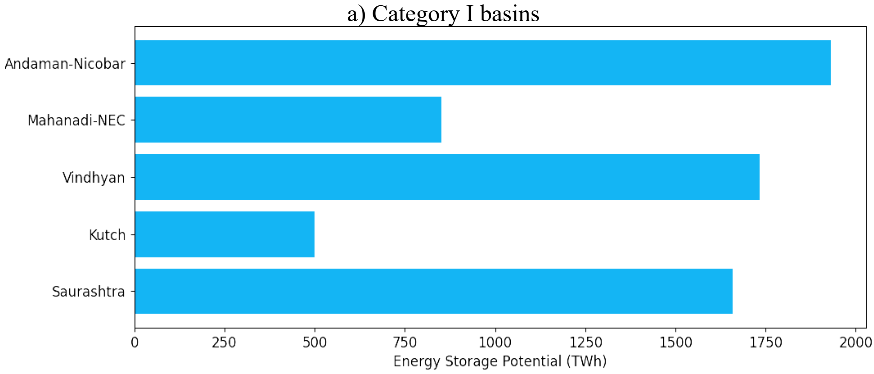
India has undertaken various policy measures and strategic initiatives to foster the development of a hydrogen-based energy ecosystem, with a particular emphasis on “Green Hydrogen” as a pathway toward decarbonization and energy security. The information presented in this section has been compiled and 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 H_2 is being adopted to replace fossil-based feedstocks in fertilizers, petroleum refining, and steel production. In the refining sector, green H_2 is being integrated to reduce carbon emissions. Pilot projects in the steel industry are evaluating H_2-based iron reduction under Indian operating conditions. In the mobility sector, pilot projects involving 37 H_2-powered vehicles and nine refueling stations have been initiated with financial support of approximately ≈ \$25.1 million. In the maritime sector, green H_2 production and bunkering facilities have been established at major ports to support cleaner shipping operations. The commissioning of a high-altitude H_2 mobility project in Leh demonstrates the operational feasibility of H_2 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 H_2 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

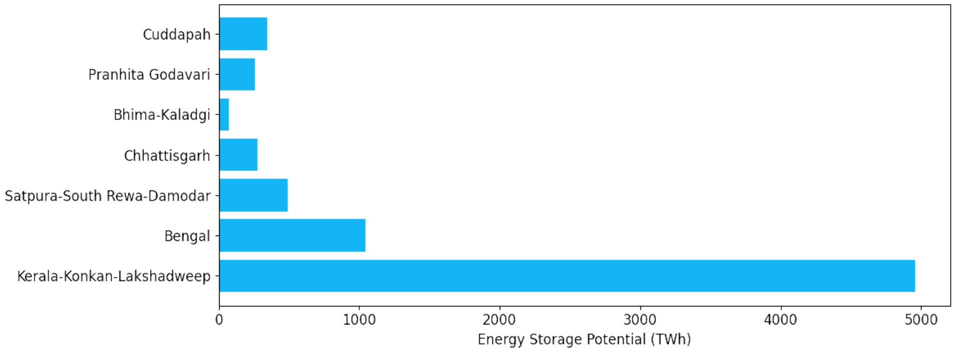
H_2 production in India can face several challenges that hinder its large-scale adoption and commercialization. The high cost of renewable-powered electrolysis, coupled with limited infrastructure and water availability concerns, makes green H_2 production expensive and less accessible. Additionally, the technological maturity of electrolysers, including their efficiency and durability, requires further improvement to achieve cost competitiveness. While the National Green H_2 Mission provides a framework, gaps in policy and regulatory support slow the transition to a H_2 economy. The dominance of fossil fuel-based H_2 production (grey H_2) continues to contribute to carbon emissions, while slow commercialization and the early development stage of most planned projects further delay progress.



a) Category I basins



b) Category II basins



c) Category III basins

Fig. 1. H_2 storage potential (TWh) of major Indian sedimentary basins (data sourced from [26])

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 H_2 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 H_2 production and storage.

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 H_2 economy, driven by ambitious climate goals, increasing energy demand, and strong policy support under the National Green H_2 Mission. Although significant progress has been made in advancing green H_2 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

 ISSN ONLINE 3030-2951

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 H_2 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.

Author contributions

Apoorv Verma: writing-original draft, conceptualization of the study, data curation. Mayur Pal: writing, review, editing, resources, and supervision.

Conflict of interest

Prof. Mayur Pal is an editor in chief for Geo-Energy Transition and Carbon Management and was not involved in the editorial review and/or the decision to publish this article.

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