



MULTIDISCIPLINARY *SCIENCE JOURNAL*

VOLUME - 3



WWW.ECOSCIENCEJOURNALS.COM



ISSN
INTERNATIONAL
STANDARD
SERIAL
NUMBER
UNITED STATES
ISSN:3067-1221; CODEN: USA

Subsurface Energy Storage: Opportunities and Challenges for Geological Storage of CO₂ and Hydrogen

Ochuele Dominic Agida¹, Moses Adondua Abah¹, Micheal Oladosu Abimbola¹,

Umunna Christopher Chukwuebuka²,

1. Geology Department, Federal University of Technology, Owerri, Imo State, Nigeria, 2. Research Hub Nexus Institute, Nigeria.

Article Info: Received: 19 Sep 2026, Accepted: 16 Oct 2026, Published: 22 Oct 2026



ABSTRACT:

The transition to low-carbon energy systems requires scalable technologies capable of reducing greenhouse gas emissions while enhancing energy security. Subsurface energy storage has emerged as a strategic solution, with geological carbon dioxide (CO₂) storage supporting carbon capture and storage (CCS) initiatives and underground hydrogen storage enabling large-scale, long-duration energy storage for renewable energy integration. This review examines the opportunities and challenges associated with the geological storage of CO₂ and hydrogen, emphasizing the geological, technical, environmental, and regulatory factors that govern storage performance and long-term security. The suitability of major storage formations, including deep saline aquifers, depleted oil and gas reservoirs, and salt caverns, is discussed in relation to reservoir characteristics, containment mechanisms, and operational requirements. The review further evaluates the contribution of subsurface storage to climate change mitigation, decarbonization of hard-to-abate sectors, and stabilization of future hydrogen-based energy systems. Key challenges, including leakage risks, geomechanical instability, geochemical and microbial interactions, uncertainty in reservoir characterization, monitoring requirements, and regulatory constraints, are critically assessed. Recent advances in reservoir modeling, real-time monitoring technologies, and integrated risk assessment are highlighted as important enablers for improving storage reliability and public confidence. The review also identifies emerging opportunities for integrating CO₂ sequestration and underground hydrogen storage within shared geological infrastructure to enhance resource utilization and accelerate the energy transition. Finally, priority research directions are outlined to address remaining scientific and engineering uncertainties. By providing a concise synthesis of current knowledge and future perspectives, this review offers a comprehensive resource for researchers, industry practitioners, and policymakers working to advance secure and sustainable subsurface energy storage as a cornerstone of global decarbonization strategies.

Keywords: Subsurface energy storage, Carbon dioxide, Hydrogen, Carbon capture and storage (CCS), Energy transition, Reservoir integrity.

CORRESPONDENCE

Moses Adondua Abah

Geology Department, Federal University of Technology, Owerri, Imo State, Nigeria, Email: m.abah@fuwukari.edu.ng.

Citation: Ochuele Dominic Agida et, al. (2026). Subsurface Energy Storage: Opportunities and Challenges for Geological Storage of CO₂ and Hydrogen

Eco Science Journal.2026 3 (12).



Copyrights ©: This article is licensed under the Creative Commons Attribution-NonCommercial-4.0-International-License-(CCBY-NC).

INTRODUCTION:

Subsurface energy storage has become an essential component of the global transition toward low-carbon energy systems by simultaneously addressing greenhouse gas mitigation and long-duration energy storage requirements. As countries intensify efforts to achieve net-zero emissions, technologies capable of permanently storing carbon dioxide (CO₂) and balancing intermittent renewable energy generation have gained increasing strategic importance^[1]. Geological carbon storage has been widely recognized as a cornerstone of carbon capture and storage (CCS), offering a practical solution for reducing emissions from hard-to-abate industrial sectors where direct electrification remains limited^[2]. In parallel, underground hydrogen storage (UHS) has emerged as a promising technology for storing surplus renewable energy at large scales, thereby improving energy security and supporting the development of a hydrogen-based economy^[3]. Recent advances in subsurface energy technologies have further demonstrated that CO₂ sequestration and hydrogen storage should be viewed as complementary rather than competing strategies for achieving climate neutrality and ensuring resilient energy systems^[4,5]. Consequently, the integration of these technologies into future energy infrastructures has attracted growing attention from researchers, industry stakeholders, and policymakers seeking sustainable pathways toward global decarbonization^[6]. The successful deployment of subsurface CO₂ and hydrogen storage depends largely on the suitability of geological formations and the complex interactions between stored fluids and the subsurface environment. Deep saline aquifers provide the largest theoretical storage capacity for permanent CO₂ sequestration because of their extensive distribution and favorable trapping mechanisms^[1]. Depleted oil and gas reservoirs also represent attractive storage sites owing to their well-characterized geology, existing infrastructure, and demonstrated ability to retain fluids over geological timescales^[4]. In contrast, salt caverns are widely considered the preferred option for underground hydrogen storage because of their exceptional sealing capacity, high operational flexibility, and low gas loss during repeated injection and withdrawal cycles^[3]. Nevertheless, hydrogen exhibits distinct physicochemical properties, including high diffusivity and low molecular weight, which introduce unique challenges related to containment, microbial activity, and geochemical reactions that differ substantially from those encountered during CO₂ storage^[7]. These differences highlight the need for storage strategies that are specifically tailored to each energy carrier while leveraging the extensive scientific knowledge gained from decades of geological storage research^[8,9]. Subsurface storage of CO₂ and hydrogen presents significant opportunities for advancing global decarbonization and strengthening energy security. Permanent geological sequestration of CO₂ is increasingly recognized as an indispensable component of climate mitigation strategies, particularly for reducing emissions from carbon-intensive industries that are difficult to decarbonize through conventional approaches¹. The continued expansion of commercial CCS projects worldwide reflects growing confidence in the technical maturity and scalability of geological carbon storage^[2]. Similarly, underground hydrogen storage offers a practical solution for addressing the temporal mismatch between renewable energy generation and energy demand by providing large-scale, long-duration storage that enhances grid reliability and system flexibility^[3]. Existing and prospective hydrogen storage sites across different geological settings further demonstrate the feasibility of integrating hydrogen into future low-carbon energy systems^[9]. Moreover, the potential to repurpose depleted hydrocarbon reservoirs and other subsurface infrastructure for both CO₂ sequestration and hydrogen storage could reduce development costs, improve resource utilization, and accelerate the transition toward sustainable energy systems^[4,6]. Despite these considerable opportunities, several scientific, technical, environmental, and regulatory challenges must be addressed before subsurface energy storage can be deployed at the scale required to achieve global climate goals. The long-term security of stored CO₂ and hydrogen depends on accurate site characterization, reservoir quality, caprock integrity, and the effectiveness of geological trapping mechanisms, all of which influence storage performance and containment reliability^[1].

Compared with CO₂, hydrogen presents additional challenges because of its low molecular weight, high diffusivity, and susceptibility to geochemical and microbial processes that may alter gas composition or reduce storage efficiency^[3,7]. Operational concerns, including cyclic injection and withdrawal, pressure-induced geomechanical responses, induced seismicity, and well integrity, further complicate long-term storage management and require robust monitoring and risk assessment frameworks^[4]. Beyond technical considerations, successful commercialization also depends on supportive regulatory policies, public confidence, and continued investment in research and infrastructure development to ensure that subsurface CO₂ and hydrogen storage can be implemented safely, economically, and sustainably^[2,5].

The purpose of this review is to provide a comprehensive and up-to-date synthesis of the opportunities and challenges associated with subsurface energy storage, with particular emphasis on the geological storage of carbon dioxide (CO₂) and hydrogen as complementary technologies for supporting the global energy transition. The review examines the fundamental geological principles governing subsurface storage, including the characteristics of suitable storage formations, reservoir behavior, containment mechanisms, and the factors that influence storage capacity, injectivity, and long-term integrity. It further evaluates the strategic role of geological CO₂ sequestration in reducing industrial greenhouse gas emissions and the growing importance of underground hydrogen storage in enabling large-scale, long-duration energy storage for renewable energy systems. In addition, the review critically discusses the principal technical, environmental, operational, economic, and regulatory challenges affecting the deployment of these technologies, including storage security, reservoir uncertainty, geomechanical stability, fluid–rock interactions, monitoring requirements, infrastructure readiness, and public acceptance. Emerging technological advances in reservoir characterization, numerical simulation, digital monitoring, and integrated risk assessment are also highlighted to demonstrate their contributions toward improving storage performance and operational reliability. Furthermore, the review explores the potential for integrating CO₂ sequestration and hydrogen storage within shared geological infrastructure to maximize resource utilization and facilitate a cost-effective transition to sustainable energy systems. By consolidating current scientific knowledge and identifying existing research gaps, this review aims to provide researchers, engineers, industry practitioners, and policymakers with a balanced understanding of the scientific, technological, and practical considerations necessary for advancing secure, efficient, and sustainable subsurface energy storage in support of long-term climate and energy objectives.

Geological Basis of Subsurface Energy Storage: Subsurface energy storage utilizes naturally occurring geological formations to safely store energy carriers over extended timescales, thereby supporting decarbonization and enhancing energy system flexibility. The concept relies on injecting fluids into deep subsurface reservoirs where geological and geophysical conditions promote secure containment while allowing efficient injection and recovery. For carbon dioxide (CO₂), storage is intended to provide permanent isolation from the atmosphere through structural, residual, solubility, and mineral trapping mechanisms, thereby contributing to long-term greenhouse gas mitigation^[1,10]. In contrast, underground hydrogen storage (UHS) is designed to enable cyclic injection and withdrawal, allowing excess renewable energy to be stored and retrieved according to seasonal or operational demand^[3]. The effectiveness of both storage systems depends on reservoir properties, caprock integrity, in situ stress conditions, and well integrity, all of which determine storage capacity, injectivity, containment security, and operational performance^[4,6]. Consequently, detailed geological characterization and reservoir assessment remain fundamental prerequisites for the successful implementation of subsurface energy storage^[10]. Several geological formations have been identified as suitable for subsurface storage because of their favorable petrophysical and structural characteristics.

Deep saline aquifers possess the largest theoretical storage capacity for CO₂ owing to their widespread distribution, high pore volume, and effective trapping mechanisms, making them the preferred option for large-scale carbon sequestration^[1,10]. Depleted oil and gas reservoirs also represent attractive storage sites because their geological behavior has been extensively characterized through hydrocarbon production, while existing wells and infrastructure may reduce development costs^[4]. Salt caverns are considered the most mature and technically reliable option for underground hydrogen storage because of their exceptional impermeability, high deliverability, and excellent sealing capacity during repeated injection and withdrawal cycles^[11,3]. Other formations, including depleted gas fields and selected saline aquifers, have also demonstrated considerable potential for hydrogen storage, although their suitability depends on reservoir mineralogy, microbial activity, and geomechanical stability^[12,8]. Appropriate site selection therefore requires integrated geological, geophysical, hydrogeological, and geochemical evaluations to ensure safe and efficient long-term operation^[7,10]. Although CO₂ and hydrogen can be stored within similar geological formations, their storage objectives, fluid properties, and operational requirements differ substantially. Geological CO₂ storage focuses on permanent containment, with injected CO₂ progressively immobilized through multiple trapping mechanisms that enhance storage security over time^[1]. Conversely, hydrogen storage prioritizes repeated recovery with minimal gas loss, requiring reservoirs that preserve gas purity while maintaining injectivity throughout multiple storage cycles^[12,3]. Compared with CO₂, hydrogen has a much lower molecular weight, higher diffusivity, and greater susceptibility to microbial consumption and geochemical reactions, creating additional challenges related to containment, reservoir integrity, and storage efficiency^[5,7]. Furthermore, the increasing production of low-carbon hydrogen through renewable-powered electrolysis and emerging biohydrogen technologies is expected to drive demand for large-scale underground storage infrastructure capable of balancing future energy supply and demand^[13]. Despite these differences, both technologies rely on robust reservoir characterization, continuous monitoring, and comprehensive risk assessment to ensure safe, reliable, and economically sustainable deployment, underscoring their complementary roles in achieving global climate and energy transition goals^[1,6].

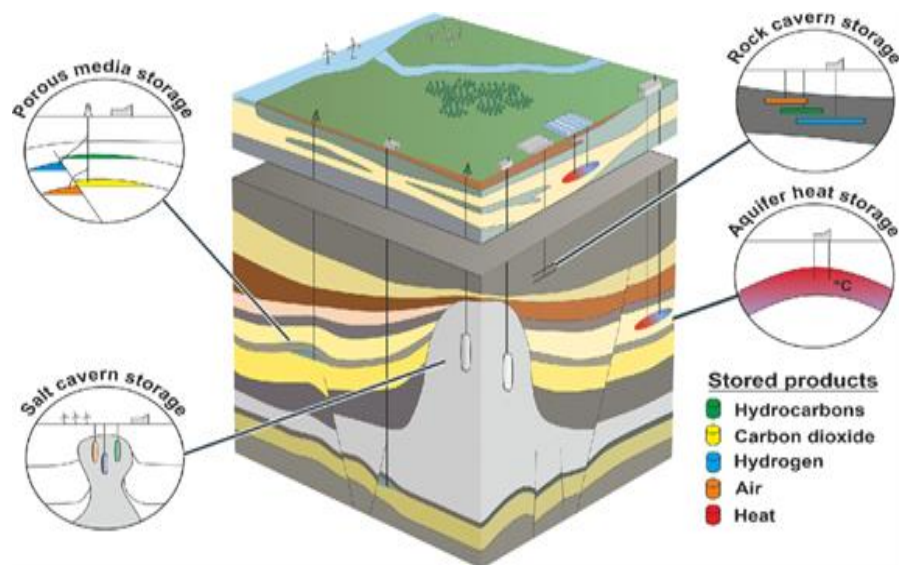


FIG-1. Overview of subsurface storage options illustrating major geological storage formations and the range of stored products, including carbon dioxide (CO₂), hydrogen (H₂), natural gas, and compressed air. The figure highlights the principal geological reservoirs used for subsurface energy storage, emphasizing their suitability for permanent CO₂ sequestration and cyclic hydrogen storage while providing context for other underground energy storage applications ^[20].

Opportunities for Geological Storage: Geological storage has emerged as a key enabler of global decarbonization by providing long-term solutions for carbon management and energy storage. Beyond its conventional role in subsurface resource management, geological storage supports climate mitigation through permanent carbon dioxide (CO₂) sequestration and enhances energy security through underground hydrogen storage (UHS). As energy systems increasingly integrate renewable resources, these technologies are becoming indispensable for reducing greenhouse gas emissions, improving energy system flexibility, and facilitating the transition toward sustainable, low-carbon economies^[16,17].

Opportunity	CO ₂ Storage	Hydrogen storage
Climate mitigation	Permanent carbon sequestration	Indirect emission reduction through clean energy
Energy security	Supports low-carbon industrial operations	Seasonal and long-duration energy storage
Renewable integration	Enables negative-emission pathways	Balances intermittent wind and solar power
Infrastructure utilization	Uses existing pipelines and reservoirs	Repurposes depleted reservoirs and salt caverns
Economic benefits	Supports CCS industries and carbon markets	Facilitates hydrogen economy development

Table 1. Key opportunities of geological CO₂ and hydrogen storage in low-carbon energy systems.

CO₂ Sequestration for Climate Mitigation: Geological CO₂ sequestration is one of the most effective strategies for reducing emissions from hard-to-abate sectors where alternative decarbonization options remain limited. By capturing CO₂ from industrial processes and permanently injecting it into deep geological formations, carbon capture and storage (CCS) significantly lowers atmospheric carbon emissions while supporting compliance with national and international climate targets^[18]. Recent years have witnessed substantial growth in commercial CCS deployment, reflecting increasing confidence in geological storage as a technically mature and economically viable climate mitigation technology^[19]. Improvements in reservoir characterization, injection management, and monitoring technologies have enhanced storage security, minimized leakage risks, and strengthened long-term containment performance^[20]. Furthermore, integrating CCS with industrial clusters and negative-emission technologies offers additional opportunities for achieving net-zero emissions while sustaining industrial productivity, thereby reinforcing the strategic importance of geological CO₂ storage in future climate action^[18].

Hydrogen Storage for Energy Security: Underground hydrogen storage provides a practical solution for addressing the intermittency of renewable energy and ensuring reliable energy supply during periods of fluctuating demand. Excess electricity generated from wind and solar resources can be converted into hydrogen through electrolysis and stored in suitable geological formations for subsequent recovery, thereby enabling long-duration and seasonal energy storage^[21]. This capability improves grid stability, reduces renewable energy curtailment, and strengthens energy security by ensuring continuous energy availability^[22]. Salt caverns remain the preferred storage option because of their excellent sealing properties and operational flexibility, although depleted hydrocarbon reservoirs and selected saline aquifers also offer considerable storage potential^[21].

As hydrogen demand expands across electricity generation, transportation, and industrial sectors, underground storage will play an increasingly important role in developing resilient hydrogen supply chains and supporting the commercialization of hydrogen-based energy systems^[23].

Integration with the Low-Carbon Energy Transition: The greatest advantage of geological storage lies in its ability to integrate multiple low-carbon technologies within a unified energy system. Geological CO₂ sequestration complements renewable energy deployment by mitigating emissions from sectors that cannot be fully electrified while underground hydrogen addresses the variability of renewable electricity through large-scale energy balancing^[20]. Together, these technologies create opportunities for flexible, resilient, and low-emission energy networks capable of supporting increasing renewable energy penetration^[24]. The utilization of existing subsurface infrastructure, including depleted hydrocarbon reservoirs and associated transport networks, further reduces capital investment and accelerates technology deployment^[19]. Moreover, integrating CCS, hydrogen production, renewable electricity, and underground storage promotes resource efficiency and strengthens long-term energy resilience, positioning geological storage as a fundamental component of sustainable energy transitions and future net-zero energy systems^[18,25].

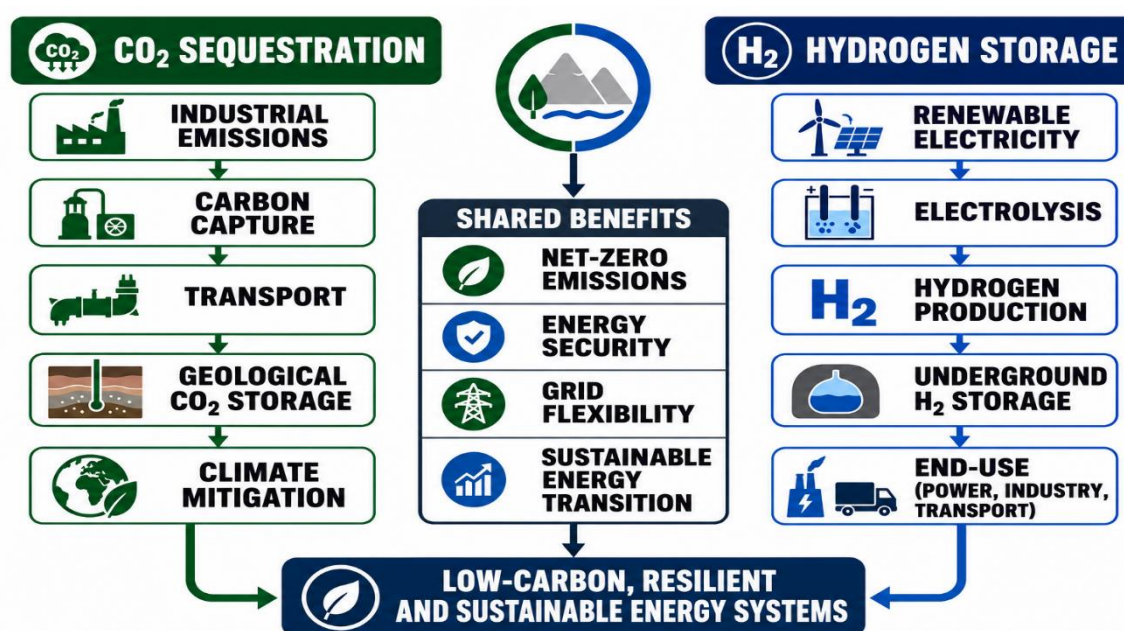


FIG-2. Integrated roles of geological CO₂ sequestration and underground hydrogen storage in the low-carbon energy transition. CO₂ sequestration enables long-term carbon storage, while underground hydrogen storage supports large-scale energy storage and grid flexibility. Together, they contribute to climate mitigation, energy security, and sustainable energy systems^[1,18,25].

Challenges and Risk Considerations: Despite the growing potential of geological storage for supporting climate mitigation and energy security, its large-scale deployment remains constrained by several geological, technical, environmental, and regulatory challenges. The long-term success of both geological carbon dioxide (CO₂) sequestration and underground hydrogen storage (UHS) depends on reliable site selection, effective containment, continuous monitoring, and robust governance frameworks. Addressing these challenges is essential for ensuring operational safety, environmental protection, and public confidence while facilitating the sustainable expansion of subsurface energy storage technologies^{20, 21}.

Geological and Technical Challenges: Geological heterogeneity remains one of the principal challenges affecting storage performance and long-term containment. Variations in reservoir porosity, permeability, caprock integrity, fault distribution, and in situ stress conditions significantly influence injectivity, storage capacity, and fluid migration²². For underground hydrogen storage, additional uncertainties arise from hydrogen's low molecular weight, high diffusivity, and potential interactions with reservoir minerals and indigenous microorganisms, which may reduce storage efficiency and compromise gas quality^[23, 24]. Maintaining wellbore integrity during repeated injection and withdrawal cycles further presents operational challenges, particularly under changing pressure and temperature conditions²¹. Consequently, comprehensive geological characterization, geomechanical modelling, and reservoir simulation are indispensable for minimizing technical risks and ensuring reliable long-term storage performance^[22, 25].

Environmental and Safety Concerns: Environmental protection and operational safety are central to the successful deployment of subsurface storage systems. Although geological formations are selected for their containment capability, leakage through faults, fractures, abandoned wells, or compromised caprocks remains a potential concern if storage sites are inadequately characterized or managed^[20]. Pressure perturbations associated with fluid injection may also induce geomechanical deformation or seismic events capable of affecting reservoir stability and public acceptance^[26]. In hydrogen storage systems, gas migration, microbial activity, and possible contamination by reactive gases may reduce storage efficiency and introduce additional operational risks^[23, 24]. These challenges underscore the importance of rigorous environmental risk assessment, site-specific hazard evaluation, and preventive engineering measures to ensure safe and sustainable storage operations^[21].

Monitoring and Regulatory Issues: Effective monitoring and supportive regulatory frameworks are fundamental for maintaining storage integrity throughout project lifecycles. Modern monitoring strategies increasingly integrate seismic imaging, well logging, pressure and temperature surveillance, satellite remote sensing, fibre-optic sensing, and geochemical monitoring to detect fluid migration and verify long-term containment^[27]. Remote sensing technologies further enhance environmental surveillance by enabling continuous assessment of surface deformation, vegetation stress, and other indicators associated with subsurface storage activities^[28]. Nevertheless, regulatory requirements for underground hydrogen storage remain less mature than those governing geological CO₂ sequestration, creating uncertainties regarding licensing, operational standards, long-term liability, and site closure^[21]. Harmonized international regulations, standardized monitoring protocols, and transparent risk communication will therefore be essential for promoting stakeholder confidence and enabling the safe, responsible, and large-scale deployment of geological storage technologies^[27, 29].

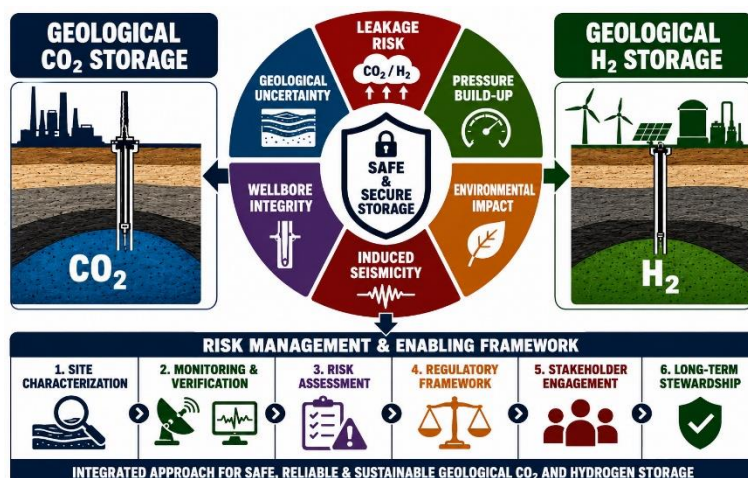


FIG-3. Major challenges and risk management framework for geological CO₂ and hydrogen storage. The figure summarizes the principal geological, technical, environmental, and regulatory challenges affecting subsurface CO₂ and hydrogen storage, together with the key risk management measures required to ensure safe, secure, and long-term storage. [3,11,26].

Emerging Developments and Future Perspectives: Rapid advances in subsurface science, digital technologies, and integrated energy systems are reshaping the future of geological CO₂ and hydrogen storage. Emerging characterization techniques, intelligent monitoring systems, and data-driven reservoir management are improving the accuracy of site selection, operational efficiency, and long-term storage security^[15]. Recent developments in high-resolution seismic imaging, fibre-optic sensing, geochemical monitoring, and artificial intelligence (AI)-assisted reservoir modelling have enhanced the early detection of fluid migration and geomechanical changes, enabling more reliable prediction of storage performance and risk mitigation¹⁶. These innovations are expected to strengthen confidence in large-scale deployment while reducing operational uncertainties associated with long-term subsurface storage^[17]. An important emerging direction is the integration of geological CO₂ sequestration with underground hydrogen storage within interconnected low-carbon energy systems. Rather than operating as independent technologies, both storage approaches can complement renewable energy generation, carbon capture, and hydrogen production to improve system flexibility, optimize infrastructure utilization, and reduce overall decarbonization costs^[18]. Existing subsurface assets, including depleted hydrocarbon reservoirs and associated transport infrastructure, provide opportunities for integrated storage networks capable of supporting industrial decarbonization and seasonal energy balancing^[1]. Continued evaluation of alternative storage formations, including depleted shale gas reservoirs, is also expanding the range of geological options available for future hydrogen storage applications^[19].

Future research should prioritize improving the fundamental understanding of coupled geological, geochemical, geomechanical, and microbial processes that govern long-term storage performance under diverse subsurface conditions. Greater emphasis is also needed on standardized monitoring protocols, predictive digital twins, AI-driven decision support, uncertainty quantification, and harmonized international regulatory frameworks to facilitate safe commercial deployment^{15, 18}. Furthermore, multidisciplinary collaboration among geoscientists, engineers, policymakers, and industry stakeholders will be essential for translating laboratory-scale innovations into field-scale applications and accelerating technology commercialization²⁰.

Collectively, these advances position geological CO₂ and hydrogen storage as complementary technologies that will play an increasingly important role in achieving resilient, secure, and net-zero energy systems.

Focus area	Emerging development	Expected Outcomes
Characterization	AI, digital twins, advanced imaging	Improved site selection
Monitoring	Fibre-optic, seismic, geochemical sensing	Enhanced storage integrity
Integrated systems	Coupled CO ₂ –H ₂ storage with renewables	Greater energy flexibility
Research priorities	Standardization, predictive modelling, regulatory harmonization	Safe, scalable deployment

Table 2. Emerging developments and future priorities in geological CO₂ and hydrogen storage.

CONCLUSION:

Geological storage of carbon dioxide and hydrogen has emerged as a critical component of the global transition toward low-carbon and sustainable energy systems. While geological CO₂ sequestration provides an effective pathway for long-term greenhouse gas mitigation, underground hydrogen storage offers the large-scale and long-duration energy storage required to support increasing renewable energy penetration and strengthen energy security. Despite significant progress, challenges related to reservoir characterization, storage integrity, environmental safety, monitoring, and regulatory frameworks must be addressed to enable widespread commercial deployment. Continued advances in subsurface characterization, digital monitoring, predictive modelling, and integrated storage strategies are expected to improve storage performance, operational reliability, and public confidence. Strengthening multidisciplinary collaboration, supportive policy frameworks, and sustained research investment will be essential for overcoming existing barriers and accelerating implementation. Collectively, geological CO₂ sequestration and hydrogen storage represent complementary technologies with substantial potential to support resilient, secure, and net-zero energy systems.

ACKNOWLEDGEMENT: We thank all the researchers who contributed to the success of this research work.

CONFLICT OF INTEREST: The authors declared that there are no conflicts of interest.

FUNDING: The authors declared that there are no conflicts of interest.

BIBLIOGRAPHY:

1.

Ali, M., Isah, A., Yekeen, N., Hassanpouryouzband, A., Sarmadivaleh, M., Okoroafor, E. R. et al. (2025). Recent progress in underground hydrogen storage. *Energy & Environmental Science*, 18(12): 5740–5810. <https://doi.org/10.1039/D4EE04564E>.

2.

Alsubaih, A., Sepehrnoori, K., Mojdeh, D. and Lopez, M. A. (2025). A comprehensive review of CO₂ subsurface storage: Integrity, safety, and economic viability. *Energy Geoscience*, 6(3):100441. <https://doi.org/10.1016/j.engeos.2025.100441>.

3. Azizi, A., Abdul Aziz, N. H., Kadri, A., Kamalul Aripin, N. F. et al. (2024). Exploring the prospects and challenges of underground hydrogen storage for a sustainable energy future. *Malaysian Journal of Chemical Engineering & Technology*, 7(1). <https://doi.org/10.24191/mjcet.v7i1.1363>.
4. Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A. and Stolten, D. (2020). Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*, 45(11):6793–6805. <https://doi.org/10.1016/j.ijhydene.2019.12.161>.
5. Dai, K., Xia, Y., Yuan, G. and Liu, T. (2025). Experimental procedures, influencing parameters, and future prospects of geological sequestration of carbon dioxide. *Frontiers in Earth Science*, 13: 1442518. <https://doi.org/10.3389/feart.2025.1442518>.
6. Dodangoda, C., Ranjith, P.G. and Haque, A. (2024). Unlocking the potential of underground hydrogen storage for clean energy solutions. *Geomech. Geophys. Geo-energ. Geo-resour.*, 10:130. <https://doi.org/10.1007/s40948-024-00782-w>.
7. Edlmann, K. (2024). Challenging perceptions of underground hydrogen storage. *Nature Reviews Earth & Environment*, 5(7): 478–480. <https://doi.org/10.1038/s43017-024-00572-8>
8. Ghaboulia Zare, S., Amirmoeini, K., Bahn, O., Baker, R. C., Mousseau, N., Neshat, N. et al. (2025). The role of hydrogen in integrated assessment models: A review of recent developments. *Renewable and Sustainable Energy Reviews*, 215:115635.
9. Global CCS Institute. (2024). Global Status of CCS 2024. Melbourne, Australia: Global CCS Institute.
10. Hassanpouryouzband, A., Joonaki, E., Edlmann, K. and Haszeldine, R. (2021). Offshore Geological Storage of Hydrogen: Is This Our Best Option to Achieve Net-Zero? *ACS Energy Letters*, 6(3):2181–2186. DOI:10.1021/acsenergylett.1c00845
11. Hawez, H. K., Omar, S. R. and Alwan, L. L. (2026). Underground Hydrogen Storage: A Comprehensive Review of Technologies, Geological Formations, and Future Prospects. *Energies*, 19(12): 2760. <https://doi.org/10.3390/en19122760>
12. Hofmann, F., Tries, C., Neumann, F., Zeyen, E. and Brown, T. (2025). H₂ and CO₂ network strategies for the European energy system. *Nature Energy*, 10: 715–724. <https://doi.org/10.1038/s41560-025-01752-6>
13. Igwe, G. and Diepiriye, C. (2025). Geological Carbon Storage: Advances and Challenges in Site Selection, Characterization, and Monitoring – A Review. *Nigerian Journal of Pure and Applied Sciences*. DOI:10.48198/NJPAS/25.B11
14. Johnson, N., Liebreich, M., Kammen, D. M., Ekins, P., McKenna, R. and Staffell, I. (2025). Realistic roles for hydrogen in the future energy transition. *Nature Reviews Clean Technology*, 1:351–371. <https://doi.org/10.1038/s44359-025-00050-4>
15. Kaczmarek, A. and Blachowski, J. (2025). Remote Sensing Perspective on Monitoring and Predicting Underground Energy Sources Storage Environmental Impacts: Literature Review. *Remote Sensing*, 17(15): 2628. <https://doi.org/10.3390/rs17152628>
16. Khalili, Y., Yasemi, S., Abdi, M., Ghasemi Ertian, M., Mohammadi, M. and Bagheri, M. (2025). A Review of Integrated Carbon Capture and Hydrogen Storage: AI-Driven Optimization for Efficiency and Scalability. *Sustainability*, 17(13): 5754. <https://doi.org/10.3390/su17135754>
17. Kianoush, P. and Jamshidi, E. (2026). Geomechanical insights for enhanced wellbore stability in the Sarvak Formation: A comprehensive analysis of pore pressure and fracture gradient. *Journal of Rock Mechanics and Geotechnical Engineering*. Advance online publication. <https://doi.org/10.1016/j.jrmge.2025.11.015>
18. Krevor, S., de Coninck, H., Gasda, S. E., Ghaleigh, N. S., de Gooyert, V., Hajibeygi, H. et al. (2023). Subsurface carbon dioxide and hydrogen storage for a sustainable energy future. *Nature Reviews Earth & Environment*, 4(2): 102–118. <https://doi.org/10.1038/s43017-022-00376-8>

19. Liu, N., Liu, D., Zhan, Y., Chen, Q., Qiao, Y. and Tan, R. (2025). From innovation to integration: The evolving role of carbon capture and storage in global decarbonization. *cScience*, 1(1): e70008. <https://doi.org/10.1002/csc3.70008>.
20. Miocic, J. M., Heinemann, N., Alcalde, J., Edlmann, K. and Schultz, R. A. (2023). Enabling secure subsurface storage in future energy systems: An introduction. *Geological Society, London, Special Publications*, 528(1): 1–14. <https://doi.org/10.1144/SP528-2023-5>.
21. Mwakipunda, G. C., Kouassi, A. K. F., Ayimadu, E. T., Komba, N. A., Nadege, M. N., Mgimba, M. M. et al. (2025). Underground hydrogen storage in geological formations: A review. *Journal of Rock Mechanics and Geotechnical Engineering*, 17(10): 6704–6741. <https://doi.org/10.1016/j.jrmge.2025.02.014>
22. Opoku Duarte, K., Ampomah, W., Rahnema, H. and Mehana, M. (2025). Underground Hydrogen Storage: Transforming Subsurface Science into Sustainable Energy Solutions. *Energies*, 18(3):748. <https://doi.org/10.3390/en18030748>
23. Roces, S., Caicedo-Potosí, J., Kovács, T., Ordóñez-Casado, B., Llana-Fúnez, S. and Berrezueta, E. (2026). Geological storage of CO₂ and H₂: A bibliometric synthesis of general and laboratory-scale research evolution. *Greenhouse Gases: Science and Technology*, 16(1):111–124. <https://doi.org/10.1002/ghg.2380>
24. Sambo, C., Dudun, A., Samuel, S. A., Esenenjor, P., Muhammed, N. S. and Haq, B. (2022). A review on worldwide underground hydrogen storage operating and potential fields. *International Journal of Hydrogen Energy*, 47(54):22840–22880.
25. Schultz, R. A., Heinemann, N., Horváth, B., Wickens, J., Miocic, J. M., Babarinde, O. O. et al. (2023). An overview of underground energy-related product storage and sequestration. In *Enabling Secure Subsurface Storage in Future Energy Systems*. Geological Society, London. 528:15–35. <https://doi.org/10.1144/SP528-2022-160>
26. Wang Y, Shi M, Wei N, et al. (2026). Advances in monitoring technologies for CO₂ geological storage: A review from the laboratory to field-scale applications. *Advances in Geo-Energy Research*, 19(2): 146-165. <https://doi.org/10.46690/ager.2026.02.04>
27. Wu, L., Luo, Z., Cheng, L., Yang, L., Lüddeke, C. T., Mao, J. and Yao, Z. (2025). A review of underground hydrogen storage in depleted shale gas reservoirs: Advances, challenges, and outlook. *Carbon Neutral Systems*, 1:14. <https://doi.org/10.1007/s44438-025-00016-w>
28. Xu, X., Zhou, Q. and Yu, D. (2022). The future of hydrogen energy: Bio-hydrogen production technology. *International Journal of Hydrogen Energy*, 47(79): 33677-33698. <https://doi.org/10.1016/j.ijhydene.2022.07.261>
29. Zhao, A. P., Li, S., Xie, D., Wang, Y., Li, Z., Hu, P. J.-H. and Zhang, Q. (2025). Hydrogen as the nexus of future sustainable transport and energy systems. *Nature Reviews Electrical Engineering*, 2:447–466. <https://doi.org/10.1038/s44287-025-00178-2>



Save Me I will Save you