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Perspective

Leveraging underground hydrogen storage expertise for natural hydrogen exploration: A technical perspective

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Abstract:
Adapting from mature underground hydrogen storage frameworks provides a viable approach for recovering natural hydrogen. While underground hydrogen storage relies on cyclic injection in relatively homogeneous reservoirs, natural hydrogen extraction requires dynamic, unidirectional production from highly heterogeneous fractured matrices. Despite these operational differences, both systems rely on similar physicochemical principles. This perspective shows that multi-physics simulation workflows used in underground hydrogen storage offer transferable algorithms for predicting gas-water distributions. However, numerical models must transition from evaluating cyclic behavior to analyzing long-term breakthrough dynamics under constant, low advective flow rates. Additionally, thermodynamic cushion gas management presents a useful model for handling associated gases in natural hydrogen reservoirs, which requires advanced downhole selective separation to minimize gas-locking risks during production. Successful technology transfer depends on redefining geomechanical and geochemical boundary conditions to couple continuous multi-component phase transitions with hydration-induced bedrock volume expansion. Supported by recent field-scale observations, this recalibration provides an engineering basis for commercial natural hydrogen development.

1. Introduction

Deep geological structures are essential for Underground Hydrogen Storage (UHS), offering a long-term energy storage solution to balance renewable energy intermittency (Yu et al., 2025; Purswani et al., 2026). The recent discovery of high-purity natural hydrogen accumulations requires a detailed understanding of their migration and extraction mechanisms within complex geological settings (Zgonnik, 2020; Han et al., 2025). This paper reviews the latest research progress on UHS and natural hydrogen research, evaluating the feasibility and specific pathways for adapting UHS technology to geological hydrogen production.

Typical hydrogen storage depths range from 500 meters to 2,500 meters. At these depths, reservoir pressure and high-salinity formation waters control the multiphase flow behavior of hydrogen. The low density and dynamic viscosity of hydrogen cause viscous fingering and capillary trapping during injection and production cycles (Yuan et al., 2025). For physical sealing, clay-rich caprocks generally maintain stable, strongly water-wet properties. This generates high capillary breakthrough pressures that prevent the buoyancy-driven ver-

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tical escape of hydrogen (Alanazi et al., 2023). However, the high-frequency injection and production cycles in UHS impose alternating effective stresses on the formation, leading to long-term geomechanical fatigue (Bai and Tahmasebi, 2022).

Natural hydrogen preservation, by contrast, depends on specific in-situ thermobaric and geochemical conditions. Reservoir temperatures are usually below 250 °C to limit physicochemical dissipation (McCollom et al., 2022). For example, the Mali gas field reservoir successfully operates at shallow depths of 100 to 250 meters, with temperatures below 45 °C and low pressures between 0.45 and 1 MPa (Prinzhofer et al., 2018). Expanding field-scale exploration and scientific drilling projects have confirmed the availability of geological hydrogen globally. Examples include hydrogen-rich gas flows in the Songliao Basin continental scientific drilling project (Han et al., 2022), anomalous gas seepages in the Sanshui Basin (Jin et al., 2024), and advective outgassing measured across the Samail ophiolite in Oman (Leong et al., 2023). Unlike the uniform structures used for UHS, natural hydrogen accumulates in highly heterogeneous dual-porosity matrix and fracture networks, which form through multi-stage tectonic activity and localized serpentinization (Wood, 2025; Touré et al., 2026). Understanding how these preferential pathways respond to unidirectional flow is a primary boundary condition for developing natural hydrogen recovery models.

2. Insights from UHS for natural hydrogen exploitation

Conventional UHS sites, including salt caverns, depleted hydrocarbon reservoirs, and saline aquifers, differ geologically from the highly heterogeneous, fractured ultramafic rocks that typically host natural hydrogen. Although the physical sites are not interchangeable, they share similar underlying physical processes. UHS operates within closed, relatively homogeneous reservoirs under periodic alternating stress. In contrast, natural hydrogen systems act as dynamic, unidirectional flow networks controlled by tectonic fractures. Despite these macroscopic geological differences, the physicochemical principles governing both systems, particularly caprock capillary sealing and multiphase flow dynamics, overlap significantly. This overlap provides a methodological basis for natural hydrogen extraction. Fig. 1 illustrates the geological and engineering comparison between the two systems.

2.1 Multiphase flow dynamics

Research on UHS has produced coupled simulation frameworks from pore to reservoir scales. These models describe key processes in hydrogen-brine multiphase flow, including capillary trapping, wettability changes, and relative permeability hysteresis (Bagheri et al., 2024). At the microscopic scale, numerical methods like the lattice Boltzmann approach can capture how molecular interactions control multiphase flow within nanoporous structures (Heinemann et al., 2021; Wang et al., 2026a). These models supply the algorithmic basis for predicting gas-water distributions in natural hydrogen reservoirs.

Although pore-scale simulation techniques from UHS are transferable, adapting these models requires addressing the difference in fluid driving forces. In UHS, multiphase flow is controlled by artificial cyclic pressure gradients. Natural hydrogen transport, however, depends on continuous, buoyancy-driven advection within fractured networks. Existing numerical workflows must therefore transition from analyzing relative permeability hysteresis, which affects cushion gas loss in artificial storage, to evaluating long-term breakthrough dynamics and capillary trapping under constant, low flow rates in highly non-uniform geometries.

2.2 Gas composition management

In terms of gas composition, UHS operations typically require the injection of cushion gases to maintain reservoir pressure and support operational stability (Deng et al., 2025). Unlike artificial storage that incurs additional costs for gas injection, natural hydrogen predominantly exists as a multi-component gas mixture, naturally accompanied by associated gases such as nitrogen and methane (Wang et al., 2026b). This inherent composition implies that the presence of associated gases in natural hydrogen systems naturally mirrors the role of cushion gas in UHS.

This cushion gas parallel creates a dual engineering effect during extraction. The native non-hydrogen components act as a thermodynamic buffer to maintain reservoir energy, but they also introduce spatial gas-locking risks at the production wellbore under continuous drawdown. Gas engineering for natural hydrogen must move beyond the static mass-balance methods used in UHS. Downhole selective extraction strategies should be evaluated to exploit the density and mobility differences of multi-component mixtures, enabling in-situ gas separation during production.

2.3 Fluid-Rock and stress boundaries

Due to differences in geological settings and operational mechanisms, existing fluid and productivity models from UHS require modification. UHS involves physical fluid displacement under periodic alternating stress, leading to fatigue-induced damage in the reservoir matrix. Natural hydrogen recovery operates as a unidirectional, continuous extraction process. Adapting these models requires removing boundary assumptions related to periodic stress.

Media characteristics and water-rock interactions also differ. In UHS, injected hydrogen exists primarily as a free gas phase in macroscopic pores. Its low solubility in formation brine limits chemical interactions with reservoir minerals to strictly localized areas (Moradi et al., 2026). Natural hydrogen, however, occurs as both dissolved and free gas phases within heterogeneous matrix and fracture systems. Its accumulation is coupled with continuous geochemical reactions, such as serpentinization. While core-scale reactive transport simulations for UHS address minor secondary mineral precipitation, natural hydrogen models must account for continuous chemical-mechanical coupling. The volume expansion caused by mineral hydration creates a feedback loop: it induces micro-fracturing that improves localized permeability, but it can also cause throat-clogging along major transport conduits.

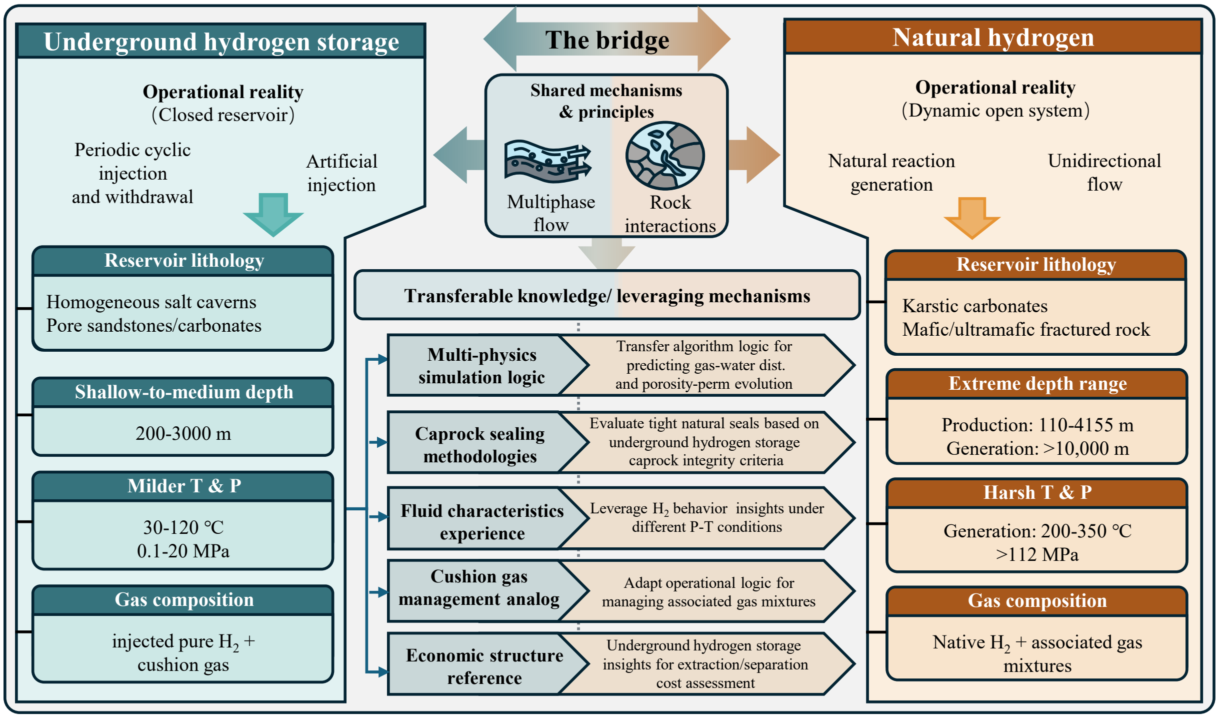

Fig. 1. Geological and engineering comparison between UHS and natural hydrogen (Purswani et al., 2026; Sekar et al., 2026).

Accurate technology transfer requires redefining these geomechanical and chemical boundary conditions. It needs unified algorithms that balance multi-component gas phase transitions, hydration-induced bedrock structural changes, and fracture-dominated flow under steady, non-cyclic stress fields.

3. Conclusions and prospects

This perspective evaluates the technical viability of transferring UHS and natural hydrogen exploitation. The specific conclusions are drawn as follows:

- Despite macroscopic geological differences between engineered UHS sites and highly heterogeneous fractured ultramafic matrices, both systems rely on similar physicochemical principles for caprock capillary sealing and multiphase fluid migration.
- Mature multi-physics simulation workflows from UHS provide transferable algorithms for predicting reservoir gas-water distributions. However, these numerical models must be recalibrated to focus on long-term breakthrough dynamics under constant, ultra-low advective flow rates, rather than relative permeability hysteresis.
- The thermodynamic cushion gas management in UHS serves as an engineering analog for handling natural multi-component associated gases. This highlights the need to transition from static mass-balance approaches to downhole selective extraction strategies to reduce localized wellbore gas-locking risks.

3.1 Future prospects

To address the complexity of geological conditions, future research should expand beyond theoretical modeling to include physical and engineering technologies. The focal directions for future research are outlined as follows:

- There is a need to develop novel sensing tools capable of operating under complex thermobaric and geochemical conditions to capture real-time fluid evolution and phase transitions within fractured networks.
- To reduce spatial gas-locking risks caused by associated natural gases during continuous drawdown, downhole selective extraction strategies, such as in-situ membrane or gravity separation tools, should be developed to utilize density and mobility differences.
- Given the continuous fluid-rock reactions, including mineral hydration and bedrock expansion, research must address hydrogen embrittlement and corrosion risks by developing hydrogen-resistant casing materials and specialized cements to ensure long-term production safety.

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Conflicts of interest

The authors declare no competing interest.

References

Alanazi, A., Al-Yaseri, A., Mowafi, M., et al. First assessment of hydrogen/brine/saudi basalt wettability: Implications for hydrogen geological storage. Frontiers in Earth Science, 2023, 11: 1225131.

Bagheri, M., Mahani, H., Ayatollahi, S., et al. Direct numerical approach for determination of h2-water flow functions applicable to underground hydrogen storage and production. Journal of Energy Storage, 2024, 96: 112573.

Bai, T., Tahmasebi, P. Coupled hydro-mechanical analysis of seasonal underground hydrogen storage in a saline aquifer. Journal of Energy Storage, 2022, 50: 104308.

Deng, P., Ma, H., Song, J., et al. Carbon dioxide as cushion gas for large-scale underground hydrogen storage: Mechanisms and implications. Applied Energy, 2025, 388: 125622.

Han, S., Huang, J., Prinzhofer, A., et al. Advances in global natural hydrogen research and exploration. Advances in Geo-Energy Research, 2025, 15(2): 91-94.

Han, S., Tang, Z., Wang, C., et al. Hydrogen-rich gas discovery in continental scientific drilling project of songliao basin, northeast china: New insights into deep earth exploration. Science Bulletin, 2022, 67(10): 1003-1006.

Heinemann, N., Alcalde, J., Miocic, J. M., et al. Enabling large-scale hydrogen storage in porous media-the scientific challenges. Energy & Environmental Science, 2021, 14(2): 853-864.

Jin, Z., Zhang, P., Liu, R., et al. Discovery of anomalous hydrogen leakage sites in the sanshui basin, south china. Science Bulletin, 2024, 69(9): 1217-1220.

Leong, J. A., Nielsen, M., McQueen, N., et al. H2 and ch4 outgassing rates in the samail ophiolite, oman: Implications for low-temperature, continental serpentinization rates. Geochimica et Cosmochimica Acta, 2023, 347: 1-15.

McCollom, T. M., Klein, F., Ramba, M. Hydrogen generation from serpentinization of iron-rich olivine on mars, icy moons, and other planetary bodies. Icarus, 2022, 372: 114754.

Moradi, R., Didari, H., Jha, B., et al. Computer simulation of reaction and transport of core-scale serpentinization of fe-bearing olivine and evolution of geological hydrogen. International Journal of Hydrogen Energy, 2026, 232: 154997.

Prinzhofer, A., Tahara Cissé, C. S., Diallo, A. B. Discovery of a large accumulation of natural hydrogen in bourakebougou (mali). International Journal of Hydrogen Energy, 2018, 43(42): 19315-19326.

Purswani, P., Bijay, K. C., Lee, H., et al. Integrated geological, economic, and risk assessment of underground hydrogen storage. Fuel, 2026, 420: 138930.

Sekar, L. K., Indro, A. P., Matey-Korley, V. G., et al. Advancing underground hydrogen storage: Geological insights from natural hydrogen occurrences in porous media. Geoenergy Science and Engineering, 2026, 257: 214208.

Touré, K., Loisy, C., Cerepi, A., et al. Natural hydrogen migration and trapping in the bulqizë ophiolitic massif (albania). Fuel, 2026, 426: 139595.

Wang, H., Xia, X., Zhao, W., et al. Lattice boltzmann modelling of molecular interaction governing multiphase flow in nanoporous media. Journal of Fluid Mechanics, 2026a, 1036: A15.

Wang, K., Zhou, Y., Zhao, W., et al. Hydrogen storage in subsurface porous media: Mechanisms, challenges, and safety. Renewable and Sustainable Energy Reviews, 2026b, 226: 116351.

Wood, D. A. Natural hydrogen resource exploitation must confront the issue that certain gas compositions are undesirable in terms of environmental sustainability. Advances in Geo-Energy Research, 2025, 15(3): 185-189.

Yu, X., Dong, H., Li, Y., et al. Microscopic insights into co2-shale oil miscibility via interaction energy coupled with pore confinement: Implications for co2-enhanced oil recovery. Advances in Geo-Energy Research, 2025, 17(2): 107-120.

Yuan, C., Yu, X., Li, P., et al. From micro to macro: A comprehensive review for underground hydrogen storage technologies and challenges. Renewable and Sustainable Energy Reviews, 2025, 224: 116090.

Zgonnik, V. The occurrence and geoscience of natural hydrogen: A comprehensive review. Earth-Science Reviews, 2020, 203: 103140.