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Editorial

Underground energy storage: Key scientific challenges and frontier directions in the energy transition

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Abstract:
The intermittency and volatility of renewable energy sources critically constrain their large-scale grid integration, positioning underground energy storage as an indispensable solution for the energy transition. This editorial provides a comprehensive overview of major underground energy storage technologies-including salt cavern compressed air energy storage, depleted gas reservoir storage, underground hydrogen storage, geological CO_2 sequestration, and underground thermal energy storage. For each modality, we identify key challenges such as multi-physics coupling, caprock integrity, geochemical reactivity, and long-term reservoir stability. We further highlight cross-cutting frontiers including digital rock physics, artificial intelligence-driven characterization, and digital twin technologies. Finally, we issue a formal call for contributions that bridge fundamental mechanisms with field-scale engineering practice, reaffirming the commitment of *Advances in Geo-Energy Research* to advancing geo-energy science for a sustainable future.

The global energy landscape is undergoing a profound transformation. Driven by the goals of carbon peaking and carbon neutrality, the large-scale integration of renewable energy sources such as wind and solar into power grids has become an irreversible trend. However, the inherent intermittency, volatility, and randomness of renewable energy pose serious challenges to grid stability and reliable energy supply. Large-scale energy storage technologies are thus regarded as the "last mile" of the energy transition, and underground energy storage—which employs deep geological formations including salt caverns, artificial chambers, depleted oil and gas reservoirs, deep saline aquifers, and abandoned mines—is widely recognized as one of the most promising solutions. Recent comprehensive work has systematically outlined the integration of large-scale underground energy storage technologies with renewable energy sources, highlighting both opportunities and systemic requirements (Geweda et al., 2025).

Salt cavern construction and evaluation technologies form the foundation for underground energy storage, owing to the sealing capacity, mechanical stability, and operational flexibility of salt formations. However, critical scientific challenges remain, including long-term creep, permeability evolution, and thermal-hydraulic-mechanical coupled responses. Site selection, leaching design, shape control, and stability assessment have been addressed, yet guidelines for safe utilization still need refinement (Wan et al., 2023a). Although these investigations have established criteria for geometry and pressure, long-term integrity under cyclic loading remains uncertain. The development of compressed air energy storage (CAES) in China has been reviewed by Wan et al. (2023b), yet challenges

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persist in site selection and uncertainty quantification. The review covers potential, maturity, and economics, but the roadmap still needs to address unresolved mechanical issues. Wellbore design also affects performance, serving as the cavern-surface interface, and integrity under cyclic conditions raises concerns. Optimization of injection-production systems has targeted erosion and energy loss, with large-diameter wells mitigating damage, but erosion and thermal effects require further study. Optimized configurations can improve efficiency and feasibility, yet field complexity still needs to be addressed (Sun et al., 2026).

Depleted gas reservoirs represent another important avenue for underground energy storage. Given abundant geological data and existing surface facilities and wellbores, these reservoirs can significantly reduce capital expenditure and project lead time compared to salt caverns, making them particularly attractive for repurposing projects in mature hydrocarbon basins (Shi et al., 2025). However, several critical scientific challenges persist. The development status and technology roadmap for energy storage in depleted gas reservoirs have been comprehensively assessed, yet fundamental questions remain regarding caprock sealing capacity under cyclic loading, the coupled mechanical response of reservoir rocks during repeated pressurization and depletion, and the long-term evolution of storage capacity (Wan et al., 2024). Key challenges include understanding caprock failure mechanisms under pressure and temperature fluctuations, quantifying reservoir compaction and surface subsidence, evaluating chemical reactions between injected fluids and formation minerals, and determining optimal cushion gas composition to prevent water encroachment. Addressing these scientific questions is essential for converting depleted gas fields into large-scale, long-duration storage hubs that help to balance seasonal fluctuations in renewable energy supply and demand, thereby enhancing the flexibility and resilience of the overall energy system.

Beyond naturally occurring or leached salt caverns, artificial underground chambers purpose-built for CAES systems present unique engineering challenges. Unlike salt caverns constrained by salt bed distribution, artificial chambers can be constructed in a wider range of geological settings, offering greater flexibility in site selection, particularly closer to renewable energy hubs. However, this flexibility demands more rigorous engineering design, and key scientific questions remain regarding rock mass behavior under cyclic loading. Critical construction technologies—including excavation methods, sealing materials, reinforcement strategies, and monitoring systems—have been systematically examined to ensure long-term integrity under cyclic high-pressure operation (Jiang et al., 2024). Nevertheless, the long-term performance of concrete linings and steel-reinforced seals under repeated loading, the mechanisms of micro-crack initiation and propagation, and the coupled effects of thermal-mechanical-hydraulic processes on chamber stability remain poorly understood. High capital costs and geological uncertainties—including fault zones, groundwater inflow, and rock mass behavior—remain significant barriers to widespread adoption beyond a handful of demonstration projects.

Underground hydrogen storage is a prominent emerging direction in the energy storage landscape, driven by the global push toward a hydrogen-based economy. Hydrogen is regarded as a vital energy carrier, and large-scale, safe underground hydrogen storage bridges the gap between intermittent renewable generation and continuous industrial demand. Comprehensive reviews have outlined key challenges, yet significant scientific questions remain regarding geochemical reactivity with reservoir minerals, microbial activity triggers and impacts, and mixing behavior with cushion gases—which governs pressure maintenance and withdrawal efficiency (Hematpur et al., 2023). Pore-scale modelling has revealed hydrogen transport behavior in porous media, but the effects of wettability, diffusion, and capillary forces on displacement efficiency remain poorly understood, particularly given hydrogen's lower density and higher diffusivity compared to natural gas (Wang et al., 2023). The coupled mechanisms of multiphase flow, geochemical reactions, and microbial processes under reservoir conditions remain a critical knowledge gap. Answering these scientific questions is essential for de-risking field projects and designing safe, economically viable injection and withdrawal strategies.

Geological CO_2 storage remains a strategic technology for climate change mitigation, with the potential to permanently sequester billions of tons of anthropogenic CO_2 in deep formations. Broad reviews have established the overarching framework for carbon capture and storage, yet fundamental questions remain regarding the long-term evolution of trapping mechanisms and the coupled chemical-mechanical responses of reservoir rocks (Liu et al., 2024). More focused studies have examined subsurface multiphase reactive flow, identifying mineral dissolution, precipitation, and capillary trapping as key factors, but the rates and spatial distribution of these processes under varying reservoir conditions remain poorly constrained (Zhang et al., 2022). The transition from structural and residual trapping to mineralization trapping over centennial to millennial scales introduces significant uncertainties in storage security predictions. The synergistic optimization of CO_2-enhanced oil recovery and storage offers a viable pathway, yet the complex interactions between CO_2, formation fluids, and rock matrix under dynamic injection conditions require further mechanistic understanding (Ampomah et al., 2017). Field demonstrations show promise, but the predictability of long-term containment and the potential for fault reactivation remain open scientific questions.

Underground thermal energy storage (UTES) expands subsurface space use, offering a versatile and scalable solution for growing thermal energy demands. It encompasses variants like aquifer storage, borehole storage, and pit/cavern storage, with varied heat transfer and temperature ranges-from low temperature aquifer thermal energy storage (10-30 °C) to high temperature cavern storage exceeding 90 °C. However, several critical scientific questions remain unresolved. Key challenges include understanding the mechanisms of thermal breakthrough and efficiency degradation, quantifying geochemical reactions such as mineral precipitation and scaling induced by temperature fluctuations, and characterizing reservoir mechanical stability under cyclic thermal loading that may induce fatigue damage. Advanced numerical modeling, combined with site specific thermal response tests, is essential for optimizing well spacing, injection and extraction rates, and seasonal storage strategies, yet the predictive accuracy of these models under complex field conditions remains uncertain. Coupling enhanced geothermal systems with underground thermal energy storage offers flexible solutions for district heating, cooling, and grid peak shaving (Vallese et al., 2026). Through cyclic injection and recovery operations, this integration reduces seasonal mismatches, but the long term performance of cyclic thermal loading on reservoir integrity and the evolution of storage efficiency over time remain open scientific questions.

Across these diverse storage modalities, several common scientific questions remain. Digital rock physics and pore-scale simulation techniques offer unprecedented resolution in revealing microscopic fluid-rock interaction mechanisms (Reinhardt et al., 2022). The application of artificial intelligence and deep learning methods is reshaping the research paradigm, enabling reservoir property prediction, intelligent production profile interpretation, and early risk warning (Zhou et al., 2024). Moreover, the emerging concept of digital twins offers the potential for dynamic management and risk warning over the entire life cycle of underground storage systems.

Notably, the editorial team of *Advances in Geo-Energy Research (AGER)* particularly values research contributions supported by microscopic mechanistic experiments or field application validation, rather than purely theoretical derivations. This editorial orientation reflects the disciplinary trend in underground energy storage research, moving from the laboratory to the field, and from mechanism to engineering. By prioritizing studies that combine rigorous fundamental investigation with practical validation, *AGER* aims to foster research that is not only scientifically sound but also directly relevant to industrial deployment and real-world energy challenges.

Looking ahead, several strategic directions are clear. First, fine-scale characterization of deep subsurface space, combined with multi-source data fusion integrating geological, geophysical, and production data, will enhance site selection and evaluation accuracy, reducing uncertainty in storage capacity and long-term performance. Second, multi-energy co-storage-e.g., hydrogen with CO_2, or compressed air with natural gas—optimizes subsurface resource allocation and space use. Third, intelligent monitoring with digital twins enables real-time risk management, providing early warnings and proactive decisions over the facility life.

Conflicts of interest

The authors declare no competing interest.

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