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Review article

Recent Progress on Salt Cavern Energy Storage: A Review of Underground Salt Storage Technology based on SMRI Spring 2026 Proceedings

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Abstract:

Against the accelerating global energy transition, underground salt cavern energy storage has expanded beyond traditional natural gas strategic reserves to become critical infrastructure for the hydrogen economy and renewable energy integration. This paper aims to systematically sort out cutting-edge progress in core technical fields of salt cavern energy storage, clarify current research characteristics and existing challenges, and point out future development directions. Drawing on the latest research presented at the Spring 2026 Solution Mining Research Institute (SMRI) conference, this systematic review focuses on five core domains: mechanical stability, microbial corrosion, high-frequency cyclic operation, full-lifecycle monitoring, and decommissioning and sealing. Results show that novel salt cavern construction techniques have significantly improved cavern geometric regularity and surrounding rock integrity; microfluidic sensor arrays enable millimeter-level in-situ tracking of microbial corrosion processes; digital twin-based operational optimization extends cyclic lifespan by 37%, and the world's first carbon footprint accounting framework for decommissioning provides quantitative support for defining abandonment-phase environmental liabilities. Current research features multi-scale analysis, multi-physics coupling, and full-lifecycle management. While microbial risks for hydrogen storage are controllable, high-frequency cycling technology is maturing, and probability-based multi-scale creep models offer new theoretical support for cavern abandonment. This review clarifies the development status of global salt cavern energy storage technology, and confirms that future development will rely on digital twins and physics-informed machine learning to achieve full-lifecycle closed-loop safety management, providing a structured reference for subsequent technological innovation and industrial deployment of salt cavern energy storage.

1 Introduction

Against the backdrop of profound shifts in the global energy landscape and the accelerated pursuit of "dual carbon" goals, deep underground energy storage is emerging as a pivotal hub connecting traditional energy with future energy systems, demonstrating unprecedented strategic value. Data from the International Energy Agency (IEA) indicates that to achieve the 2050 global net-zero emissions target, hydrogen and its derivatives will account for 14% of final energy consumption (Gomonov et al., 2025), most hydrogen relying on large-scale, long-duration energy storage technologies. Deep underground energy storage - particularly through the construction of large-scale, high-efficiency underground gas storage systems, such as salt cavern hydrogen storage and underground natural gas storage facilities - represents a critical pathway to addressing the dual challenges of energy security and green transition. Deep underground energy storage serves as an "accelerator" for driving the energy transition and achieving carbon neutrality. Renewable energy sources, such as wind and solar, are char-

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acterized by significant volatility and intermittency, creating an urgent need for large-scale storage systems to ensure grid stability. Deep underground spaces, including salt caverns and abandoned mines, possess natural sealing capabilities, high pressure-bearing capacity, and low permeability, making them ideal "underground vaults" for clean energy sources like hydrogen and compressed air. Therefore, deep underground energy storage is not merely an upgrade to energy infrastructure, but a profound strategic layout for national energy security. It transforms abandoned mines into energy treasure troves, promotes the circular utilization of resources, and drives the development of a "deep earth economy."

As the core form of deep underground energy storage, salt cavern energy storage is becoming a critical infrastructure supporting the construction of new power systems, thanks to its unique geological endowments and exceptional economic viability. Salt cavern energy storage boasts significant technical and economic advantages. Underground salt caverns possess extremely high sealing capacity, pressure-bearing capability, and a natural "self-healing" function, allowing for the safe and stable storage of high-pressure air, natural gas, and hydrogen. Compared to pumped hydro storage, salt caverns offer more flexible site selection, shorter construction cycles, and a smaller ecological footprint. In contrast to electrochemical storage, a single cavern can reach a volume of hundreds of thousands of cubic meters, providing large-scale, long-duration energy storage capabilities. More importantly, salt cavern energy storage offers an exceptionally low levelized cost of electricity. By turning abandoned salt caverns into valuable assets, it not only significantly reduces raw material and land-use costs but also effectively mitigates geological hazards such as ground subsidence that could be triggered by abandoned mines, thereby achieving the safe and circular utilization of resources. From a strategic perspective, salt cavern energy storage serves as a "dual engine" for safeguarding national energy security and driving the green, low-carbon transition. On one hand, acting as a giant "power bank" for the power grid, it stores surplus electricity as compressed air potential energy during off-peak hours and releases it for power generation during peak hours. This efficiently addresses the volatility and intermittency of renewable energy, significantly enhancing the grid's ability to absorb clean energy sources like wind and solar power. On the other hand, salt caverns are ideal carriers for large-scale hydrogen storage, providing a low-cost and highly secure underground guarantee for the future development of the hydrogen economy.

Solution Mining Research Institute, Inc. (SMRI) is a global, non-profit, member-driven organization dedicated to providing specialized education, technical resources, and cutting-edge research for the solution mining and underground storage cavern industries. Its diverse membership includes companies in the salt, potash, and trona sectors, as well as operators, researchers, and government regulators. Since the 1960s, SMRI has continuously advanced industry research, yielding significant achievements such as specialized software, best practices for cavern design, and a comprehensive catalog of global salt deposits. Current research focuses on comparing mineral characteristics, the abandonment of deep underground storage caverns, and the comparative study of hydrogen versus natural gas storage. In response to the green energy transition, SMRI is leveraging over 50 years of experience in oil and gas storage to facilitate the industry's shift toward hydrogen storage. Additionally, SMRI hosts two conferences annually to promote networking, technical training, and field trip opportunities. The organization also maintains a professional library, offering members free access while allowing non-members to purchase relevant research reports https://www.solutionmining.org/.

The SMRI Spring 2026 Conference was held in Edinburgh, UK, from April 26 to 29, 2026. The event brought together over 200 experts and scholars from countries including the United States, Canada, the UK, Germany, France, the Netherlands, Norway, Israel, and China. As the conference gathered representatives from the majority of leading nations in the field of salt cavern energy storage, it provided an authentic reflection of the current state of development in this sector. (https://www.solutionmining.org/spring-2026-conference)

The conference featured a total of 28 technical reports. Based on their content, these reports can be categorized into four main themes: Hydrogen Storage & Energy Transition, Rock Mechanics & Stability, Engineering Practice & Operations, and Survey Technology & Numerical Simulation. The core keywords for each category are presented in Table 1. This conference reveals a global trend, especially across Europe and North America, where the decommissioning pressure on legacy salt cavern infrastructure runs parallel to a surge in the development of new hydrogen storage caverns. To broaden the understanding of the conference discussions and provide a valuable reference for related industrial development and scientific research, the following section presents a comprehensive review based on the conference proceedings.

2 Hydrogen storage & energy transition in salt cavern

Salt caverns are a mature,flexible,and high deliverability option for underground gas storage,and they are now central to Europe's plans for seasonal and intra-seasonal balancing of a future hydrogen system. The advantages are large working volumes,rapid injection/withdrawal,and relatively low OPEX compared to many surface solutions (Dopffel et al., 2026). Compared with natural gas storage in salt cavern, One of the major differences is that H_2 introduces distinct biogeochemical risks not encountered with natural gas because H_2 is a universal electron donor for metabolism of multiple anaerobic microorganisms prevalent in subsurface brines like aquifers and natural gas reservoirs (Gregory et al., 2019).

The following section presents a comprehensive review of salt cavern hydrogen storage technology from three key dimensions: microbiological and geochemical mechanisms, global project practices and applications, and hybrid energy storage simulation.

2.1 Microbiology and geochemistry

Underground hydrogen storage in salt caverns is far more than a simple physical filling process. Microbial activities and the resulting geochemical reactions in the subsurface environment are critical factors influencing hydrogen purity, storage

Tab. 1 SMRI Spring 2026 Report Classification and Core Keywords

Categories	Number	Keywords
Hydrogen Storage & Energy Transition	10	Hydrogen, Microbiology / Microorganisms, Compressed Air, Renewable Energy
Rock Mechanics & Stability	7	Creep, Fracture, Microcracks, Subsidence, Constitutive Model
Engineering Practice & Operations	7	Well Integrity, Decommissioning / Abandonment, Production Optimization, Drilling
Survey Technology & Numerical Simulation	4	Sonar Processing, Seismic and Electromagnetic, Numerical Simulation

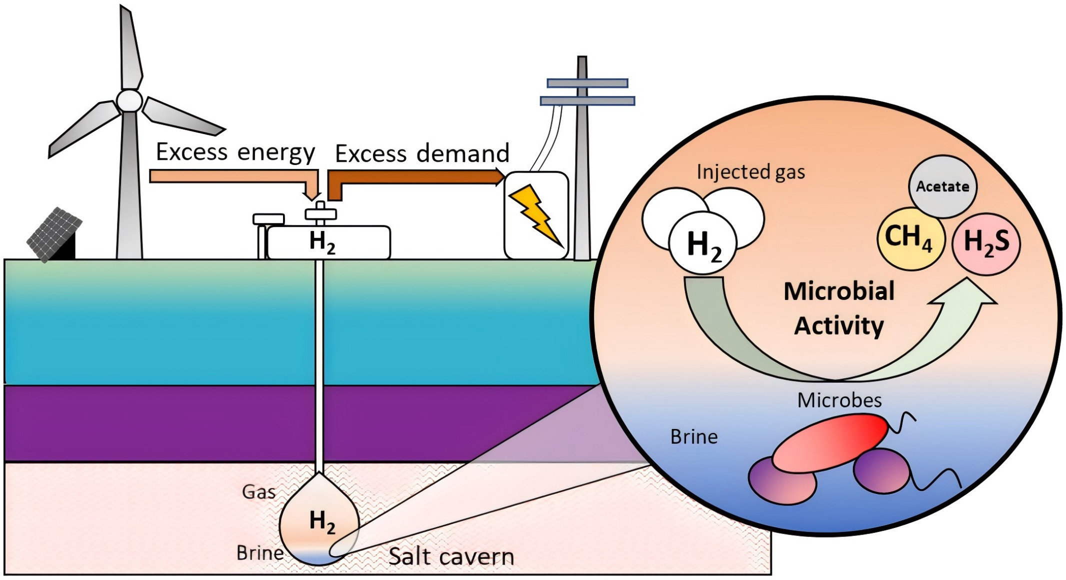

Fig. 1 Schematic overview of a H_2 underground storage concept in salt caverns using excess energy for producing hydrogen and withdrawal when needed (Dopffel et al., 2026). Right details: microbes present in the brine and sump can use injected H_2 gas as energy source and produce different products including H_2S, CH_4 or acetate.

safety, and wellbore integrity. Recent studies have not only unveiled the evolutionary patterns of microbial communities but have also proposed novel risk mitigation strategies based on the chemical properties of brine.

2.1.1 Microbial succession and hydrogen consumption risk

Research indicates that salt caverns are not sterile environments; in fact, halophiles are widely present in cavern brines. Halophiles are a highly specialized group of microorganisms that, as their name suggests, not only survive in high-salinity conditions but actually require a specific salt concentration to grow and reproduce. Cavern brine represents a typical high-salinity extreme environment, naturally hosting a vast array of these halophiles, particularly halophilic archaea and bacteria. When hydrogen is injected into underground salt caverns, these microorganisms can metabolize it as an energy source. This process not only consumes valuable hydrogen but can also generate hydrogen sulfide (H_2S), leading to wellbore corrosion.

HyPSTER (Hydrogen Pilot STorage for large Ecosystem Replication) is a project funded by the EU Clean Hydrogen Partnership Initiative, officially launched in January 2021. Recognized as the first demonstration project for green hydrogen storage, HyPSTER utilizes the EZ53 salt cavern in the greater Lyon area of France to store hydrogen, effectively buffering demand fluctuations for local industrial and mobility sectors. The HyPSTER site and site photo is shown in Fig.2 and Fig.3 respectively (Beeder et al., 2026).

In the HyPSTER demonstration project (the EZ53 salt cavern in Étrez), Beeder et al. observed that the structure of the microbial community in the cavern brine underwent significant changes following hydrogen injection (Beeder et al., 2026). Fig.4 shows the average result of DNA analysis in the original samples from before (2023)and after (2025) H_2 injection.In the sample before H_2 injection the diversity is relatively high, containing different types of microbes. The community encountered after H_2 injection is more homogenous than the community in the sample prior to H_2 injection. Prior to hydrogen injection, the brine exhibited high microbial diversity but low hydrogen consumption rates. In contrast, after five months of hydrogen injection and cyclic operation, the community structure became less diverse, showing a significant enrichment of hydrogen-utilizing microorganisms, such as the sulfate-reducing bacteria Desulfovibrionales. Experimental data revealed that in samples exposed to hydrogen, the onset of sulfide (H_2S) generation occurred much earlier (shortened from 152 days to 35 days), accompanied by a marked increase in hydrogen consumption rates. These findings indicate that hydrogen injection exerted a selective pressure on the micro-

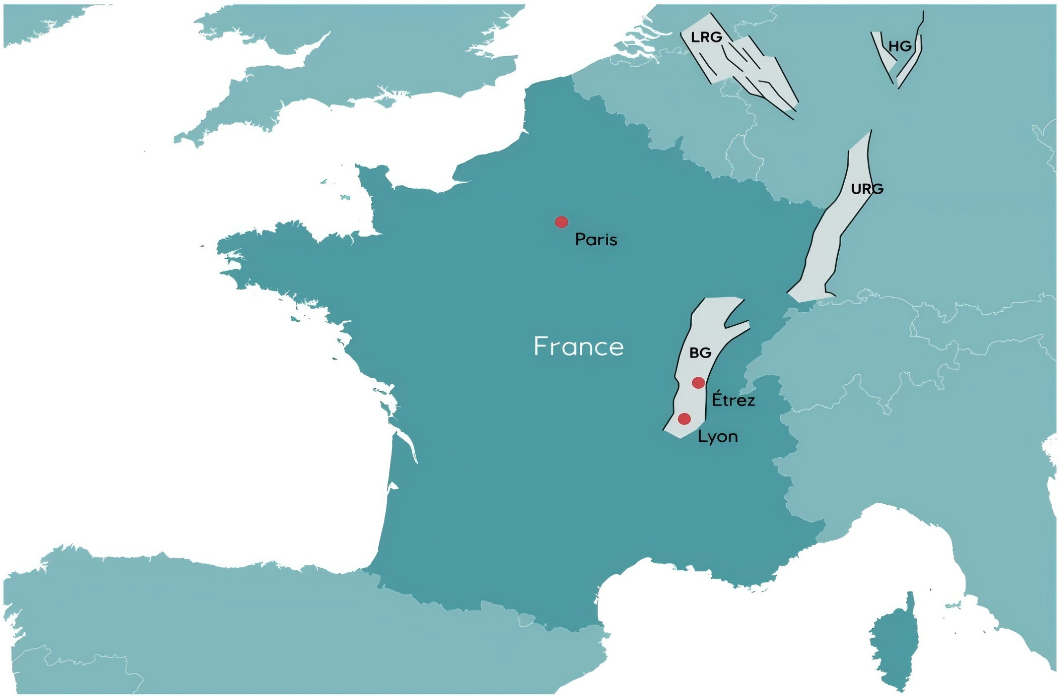

Fig. 2 Location of salt cavern EZ53 close to Étrez within the Bresse Graben (BG) as part of the Cenozoic rift system including the Upper Rhine Graben (URG),the Lower Rhine Graben (LRG)and the Hesse Graben (HG) (Beeder et al., 2026)

Fig. 3 HyPSTER site photo (https://www.h2-mobile.fr/actus/hypster-premier-site-francais-cavite-saline-devient-realite/)

bial community, favoring specific populations adapted to the hydrogen-rich environment.

Similar conclusions have been corroborated in studies on hydrogen storage projects in Pingdingshan, China, and at Jingshen in Jiangsu. Song et al. noted that China's salt cavern hydrogen storage projects face similar risks of microbial hydrogen consumption and hydrogen sulfide generation, which require focused attention (Song et al., 2026).

In the CETP co-funded HyLife project, Nicole Dopffel et al. investigated multiple potential gas storage sites across Europe, covering 21 brine samples from 14 different salt caverns. All brines were collected following a standardized protocol and

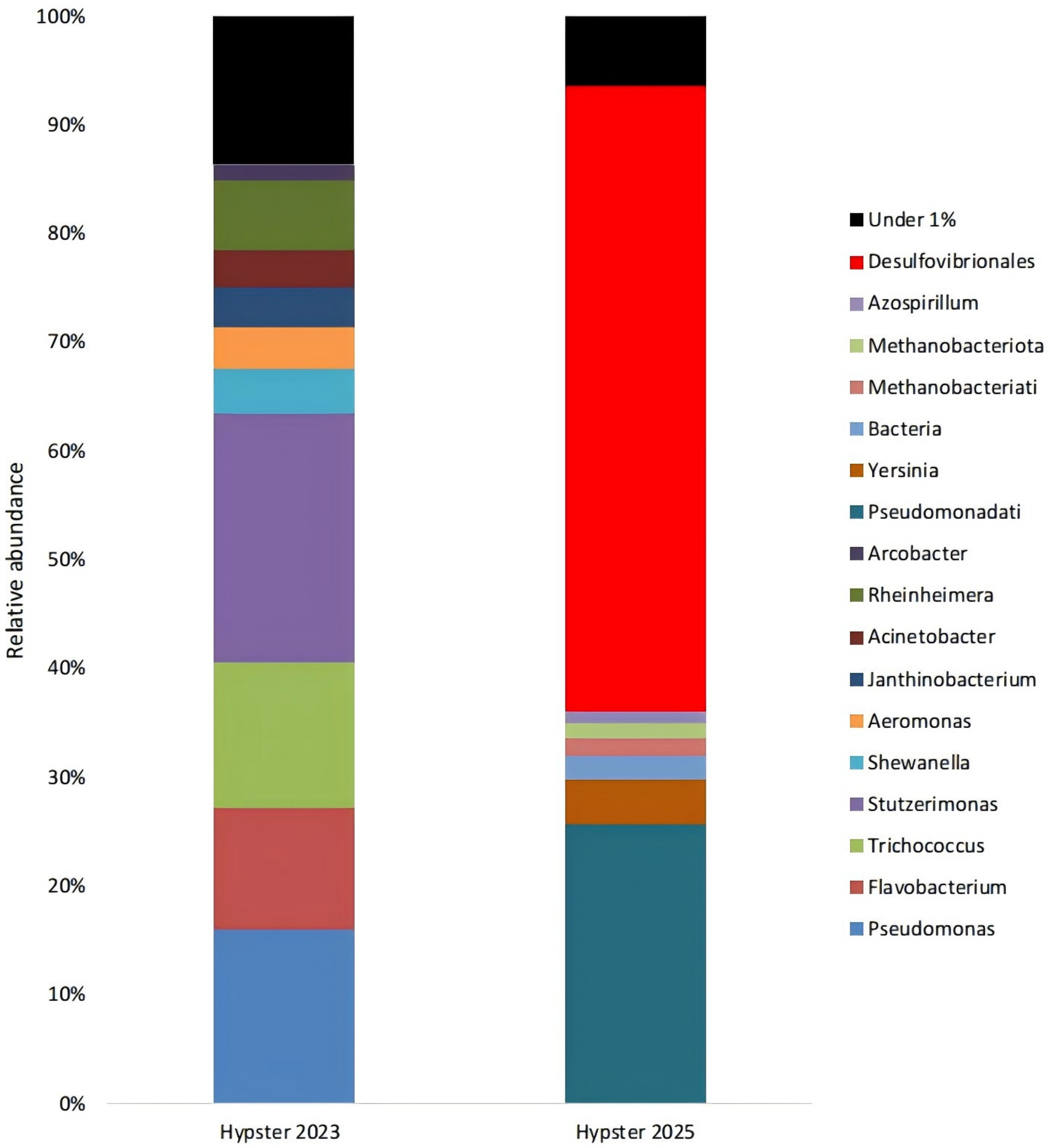

Fig. 4 Average results from different parallel DNA analysis,using v4 primer,of original brine from samples prior to (left) and after (right) H_2 injection respectively (Beeder et al., 2026)

were uniformly subjected to hydrochemical and DNA-based analyses by four different laboratories within the HyLife consortium. Hydrochemical analysis revealed varying concentrations of sulfate, potassium, iron, and calcium across the samples due to differing geological conditions. Detectable microbial populations were found in all investigated salt caverns, with significant differences in community composition across the various sites, as shown in Fig.5 (Dopffel et al., 2026). On the other hand, the researchers observed a special case where neighboring caverns within the same field exhibited similar microbial communities as a result of a specific chemical treatment. Metabolic predictions indicated that the microbes in these caverns are dominated by halophilic generalists. Many of these microorganisms demonstrated the potential to utilize hydrogen through nitrate and sulfate reduction, as well as acetate oxidation. In the laboratory, the team incubated 12 salt cavern brine samples under a hydrogen atmosphere for up to one year. Approximately 25% of the samples exhibited microbial activity, evidenced by the formation of H_2S and the consumption of hydrogen. Among the 12 enrichment cultures tested, microbial H_2 consumption was detected in three replicates, with a representative result presented in Fig. 6a. All three active enrichments produced H_2S, the primary product of microbial sulfate reduction, with headspace concentrations ranging from 0 to 1840 ppm (as shown in Fig. 6b). They also observed a measurable increase in pH during incubation (Fig. 6b), which serves as a clear indicator of microbial hydrogen oxidation: this metabolic process consumes protons, and is well-documented to drive a significant pH increase in the system. Microbial activity initiated after 60 days of incubation in two of the three enrichments, while the third replicate did not show detectable activity until approximately 400 days. Beyond these three enrichments, additional enrichment cultures from other caverns also exhibited microbial activity (detected as CO_2 production or pH shifts), but did not show measurable H_2 consumption. This indicates that active microbial communities in these samples do not universally rely on direct H_2 utilization as an energy source. Based on these observations, sulfate-reducing microorganisms appear to be the dominant active microbial group in the investigated samples. Since H_2S is a toxic and highly corrosive gas, it requires appropriate management and handling. Two natural geochemical reactions are thermodynamically favorable for H_2S removal: first, elevated pH promotes increased dissolution of gaseous H_2S into the aqueous phase; second, dissolved iron in brine can chemically scavenge dissolved H_2S via precipitation. Only after the available iron is fully consumed, or the system pH decreases, will H_2S accumulate and enter the gaseous phase.

2.1.2 Chaotropicity and risk mitigation

To address microbial risks, recent studies have proposed an innovative control strategy: leveraging the “chaotropicity” of brine to mitigate these risks. Research by Kedir et al. and Dopffel et al. indicate that microbial activity in high-salinity environments is not only influenced by osmotic pressure but is also restricted by the membrane-disrupting effects of salt ions—known as chaotropicity (Kedir et al., 2026; Dopffel et al., 2026). Studies have found that certain salt cavern brines exhibit “kosmotropic” (order-promoting) characteristics, which favor microbial stability, while others display “chaotropic” (order-disrupting) properties. When the concentration of magnesium (Mg^{2+}) or calcium (Ca^{2+}) ions in the brine reaches a specific threshold (e.g., 55% $MgCl_2$ at over 3 mol/L), a strong chaotropic effect is triggered. This effect disrupts microbial cell membranes, thereby inhibiting their growth, as illustrated in Fig.7 (Kedir et al., 2026).

Based on this finding, the research team proposed a novel risk assessment strategy: prioritize selecting salt formations with high chaotropic potential during the site selection phase, or introduce specific chaotropic agents into the salt cavern brine during the operational phase to suppress microbial activity. This strategy has been validated in the EZ53 salt cavern of the HyPSTER project, demonstrating that microbial risks can be effectively mitigated by regulating the brine’s chemical properties.

2.1.3 Hydrogen sulfide generation and wellbore corrosion

The study by Andrea Böllmann et al. found that microbial activity and community composition can vary significantly between different salt caverns—and even within the same cavern field (Böllmann et al., 2026). This variation can be attributed to differing physicochemical conditions, cavern histories, and the introduction of various materials or chemicals into the caverns. The researchers investigated microbiological hydrogen consumption in brine from three distinct types of salt caverns: a gas cavern, a diesel cavern, and an unused cavern. Samples from the gas and unused caverns did not contain sufficient microorganisms to quantify cell numbers or perform molecular biology analyses. Only the diesel cavern (designated as sample Heide H108) contained enough microbial cells to allow for both cell quantification and the extraction of sufficient DNA for microbial community assessment. The researchers utilized experimental data from pure cultures of sulfate-reducing bacteria to develop and validate a lab-scale simulation model. This validated model was subsequently upscaled to the dimensions of actual salt caverns. Based on cavern geometry and operating pressure ranges, the model predicted temperature deviations of up to 12°C within the caverns. By combining the simulated microbial activity in the cavern sump with the mass transfer of gas components, the study estimated H_2S concentrations in the withdrawn gas. Depending on the specific cavern, predicted H_2S concentrations ranged from single-digit to low double-digit ppm levels . Furthermore, subsurface findings cannot be directly extrapolated to surface infrastructure. The introduction of hydrogen into surface facilities may accelerate microbiologically influenced corrosion (MIC). Therefore, these material effects should be considered at an early stage to develop appropriate MIC mitigation and management strategies, and to incorporate them into the asset management systems of future hydrogen infrastructures.

2.2 Projects and applications

Worldwide, salt cavern hydrogen storage projects are transitioning from theoretical research to large-scale engineering practice. This section focuses on a comprehensive review of representative engineering cases in China, France, and the UK.

2.2.1 China: transition from natural gas storage to multi-energy storage

China is currently dedicated to developing an integrated technical system for salt cavern hydrogen storage (HS), compressed air energy storage (CAES), and carbon dioxide storage (CS). China has launched a batch of pioneering underground salt cavern gas storage (USCS) projects, including:

(1)Jintan, Jiangsu: A mature natural gas storage project;

(2)Pingdingshan, Henan: An ongoing pilot project for hydrogen storage;

(3)Jingshen, Jiangsu: A newly developed underground hydrogen storage (UHS) project;

(4)Yingcheng, Hubei: A compressed air energy storage project;

(5)Huaian, Jiangsu: A pilot carbon sequestration project.

Research teams are focusing on overcoming key challenges, such as gas migration characteristics in layered salt rock, the collapse mechanism and prediction monitoring methods for thick interlayers, and have developed fiber optic sensors for underground gas storage. These engineering practices demonstrate that China is rapidly expanding into the fields of hydrogen energy and multi-energy complementarity by leveraging its mature salt cavern leaching technology.

2.2.2 France: HyPSTER green hydrogen storage demonstration

The HyPSTER project is recognized as Europe’s first large-

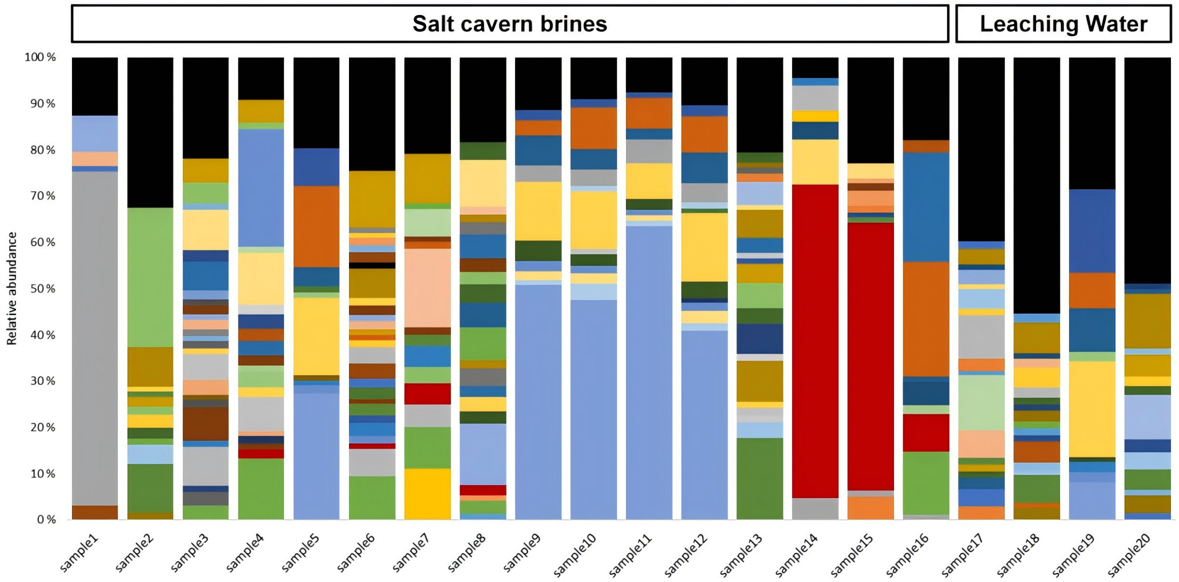

Fig. 5 Microbial community fingerprint of the samples 1-20. Each color represents a different microbial group identified by DNA.Only the groups with over 1% abundance are shown in color, while black shows less abundant groups.Leaching water marked with red box (Dopffel et al., 2026)

scale green hydrogen storage demonstration project. Located in the Etrez salt mine near Lyon, France, the project aims to investigate the interaction between hydrogen and the subsurface environment using the EZ53 salt cavern as a "natural laboratory."

Recent progress reported by Schlichtenmayer et al. (2026) reveals that over 100 hydrogen pressure cycling tests were successfully completed between December 2024 and April 2025 (Schlichtenmayer et al., 2026). The study found that the thermal coupling effect between hydrogen and the surrounding rock is stronger than that of natural gas. A thermodynamic model (KAVPOOL software) calibrated with field test data indicates that under identical geological conditions, hydrogen storage exhibits more significant temperature fluctuations than natural gas; however, existing geological barrier integrity standards remain applicable.

Furthermore, the project validated that by applying parameter modifications to existing natural gas storage models, the behavior of hydrogen storage can be accurately predicted. This provides strong data support for repurposing existing natural gas salt cavern facilities into hydrogen storage reservoirs across Europe.

2.2.3 UK: Rapid cycling validation at salinae and stublach

The UK is advancing multiple large-scale hydrogen storage projects, with the Salinae Hydrogen Storage Project and the Stublach Underground Gas Storage representing distinct technological pathways. The Salinae project (located in Warmingham, Cheshire) is a pure hydrogen storage initiative developed through a partnership between Uniper and British Salt. Leveraging British Salt's existing mining rights, the project aims to construct some of the UK's first salt caverns dedicated to large-scale hydrogen storage. As described by Schmüth et al., the project employs a double-barrier, fully monitored wellbore design to meet the integrity requirements for hydrogen storage. Currently, drilling and logging for the first two wells have been completed, confirming the presence of thick, pure salt layers within the Northwich Halite formation suitable for cavern development Schmüth et al. (2026).

Meanwhile, Storengy has conducted long-term rapid cycling tests at its Stublach Underground Gas Storage facility in the UK (Kidd et al., 2026). Stublach is one of Europe's most active rapid-cycle gas storage facilities, designed for up to 12 cycles per year. Research indicates that after more than a decade of high-frequency injection and withdrawal cycles, the cavern geometry remains stable with minimal creep. More importantly, the study suggests that hydrogen imposes a smaller thermodynamic load on salt caverns compared to natural gas. This implies that existing natural gas salt cavern facilities, following proper assessment, are fully capable of adapting to future rapid-cycle hydrogen storage demands.

2.3 Simulation & numerical modeling of hybrid energy storage

As energy systems become increasingly complex, single storage media can no longer fully meet grid demands, making hybrid energy storage simulation a prominent research hotspot.

2.3.1 Simulation of hydrogen-natural gas blended storage

Fabig et al. utilized FLAC3D software to conduct an in-depth study on the mechanical behavior of salt cavern fields under blended storage and non-parallel cycling modes (Fabig et al., 2026).

Traditional salt cavern design assumes that all adjacent caverns operate under identical pressure conditions (parallel operation mode). However, future scenarios may involve one cavern storing hydrogen (high-frequency cycling) while an adjacent cavern stores natural gas (seasonal cycling). Simulation results indicate that under this non-parallel operation mode, the stress

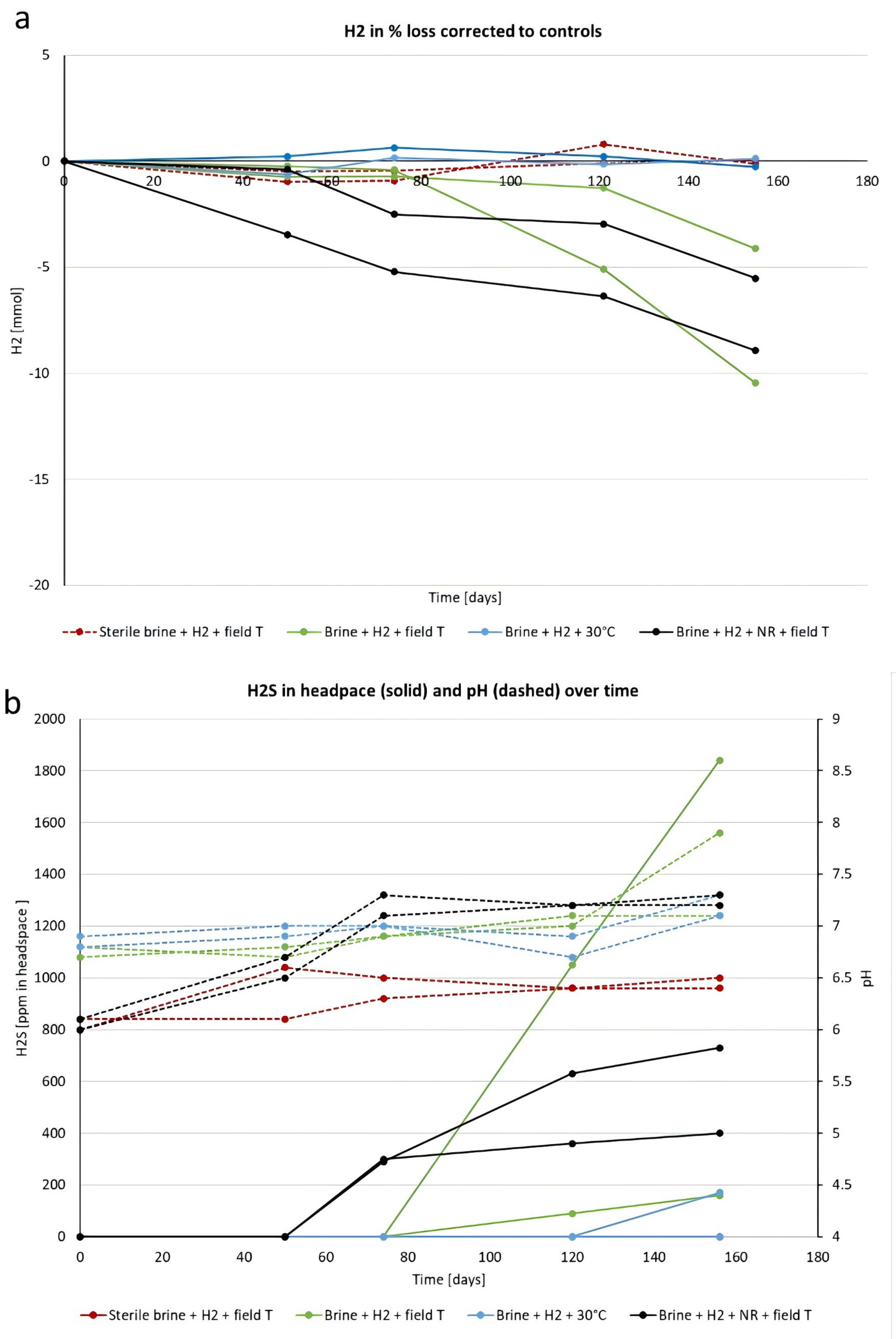

Fig. 6 a)Evolution of H_2 loss over time shown in % loss corrected to distilled water controls in one exemplary cavern sample. b) gaseous H_2S in ppm (solid lines) and pH development (dashed lines) over time of the same sample. The following set-ups are shown red =three times auto claved brine as sterile control incubated with 100% H_2 at field temperature, green =brine incubated with 100% H_2 at field temperature, blue =brine incubated with 100% H_2 at 30 °C/86 °F,black =brine with added nutrients with 100% H_2 at field temperature (Dopffel et al., 2026)

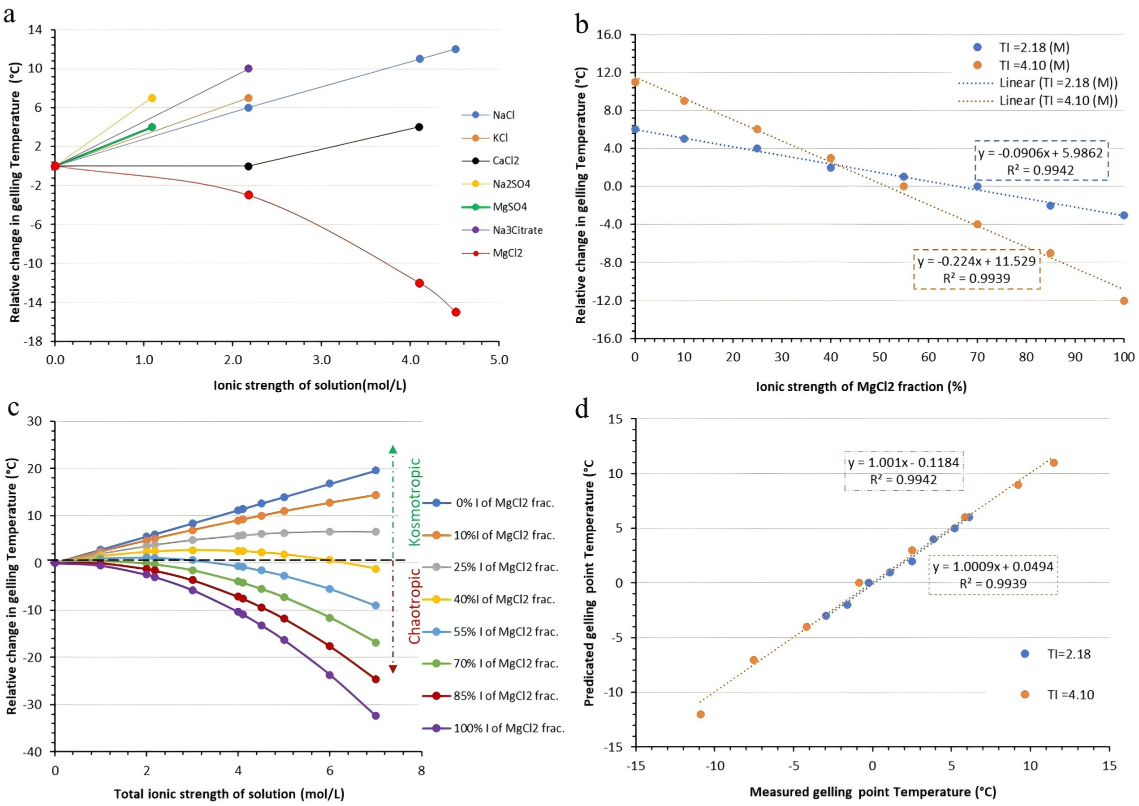

Fig. 7 Detailed investigation of change in gelling temperature of kosmotropic and chaotropic salt: a). The relative change in agar gelling point temperature of 1.5wt % agar in NaCl, KCl, $CaCl_2$, $MgCl_2$, Na_2SO_4, $MgSO_4$, and Na_3Cit as a function of their ionic strength of solution. (b) The measured (M) relative change in gelling point temperature of 1.5wt % agar as a function of ionic strength fraction of $MgCl_2$ while maintaining the total ionic strength of the solution at 2.18 and 4.10 mol/L. (c). Predicted relative change in gelling point temperature of 1.5wt % agar in a mixture of $MgCl_2$ and NaCl as a function of the total ionic strength of the solution while varying the ionic strength fraction of $MgCl_2$. (d). A comparison between measured (M) and predicted (P) relative change in gelling point temperature of 1.5wt % agar in a mixture of $MgCl_2$ and NaCl as a function of the total ionic strength of solution at 2.18 and 4.10 mol/L while varying the ionic strength fraction of $MgCl_2$ (Kedir et al., 2026)

field between adjacent caverns undergoes significant changes, the results were shown in Fig.8 and Fig.9.

Through calculation, Fabig et al. found that the prevailing pressure differences lead to locally reduced stresses within the pillar, indicating that safe operation in accordance with the criteria may no longer be ensured. Consequently, adjustments to the cavern design are required from a rock-mechanical point of view. Based on the results, the following aspects were identified and formulated as recommendations: (1) when new caverns are planned within existing fields, or when a completely new field is developed, non-parallel operating modes must be considered in the design of pillar dimensions; (2) if caverns in an existing field are to be repurposed, the existing pillars must be checked for sufficient thickness, and the maximum storage pressures must be reduced if necessary (Fabig et al., 2026).

In conclusion, it should be noted that, if the aspect of non-parallel operation comes into play, whether in a new facility or a repurposed cavern, additional rock mechanical considerations must be taken into account to ensure safe operation. These findings are also relevant for maintenance and other technical operations, where single gas caverns may to be operated at a significantly reduced pressure relative to their neighboring caverns.

2.3.2 Hybrid energy storage of compressed air and hydrogen

Beyond the blending of hydrogen and natural gas, the integration of hydrogen with Compressed Air Energy Storage (CAES) has also garnered significant attention. Tapiero et al. explored the site selection and repurposing of underground Compressed Air Power Plants (CAPP) (Tapiero et al., 2026). Meanwhile, Fabig et al. also conducted numerical research on the behavior of salt cavern fields under “hybrid and non-parallel storage cycling.” The study points out that future energy storage facilities will face high-frequency and counter-cycling operational modes, presenting new challenges for predicting rock salt creep characteristics and surface subsidence (Fabig et al., 2026).

Through numerical simulation, researchers are developing generalized models capable of adapting to multiple gas media (hydrogen, natural gas, and compressed air). The goal is to optimize the operational strategies of underground reservoirs, ensuring that underground facilities maintain long-term stability and tightness within complex multi-energy complementary

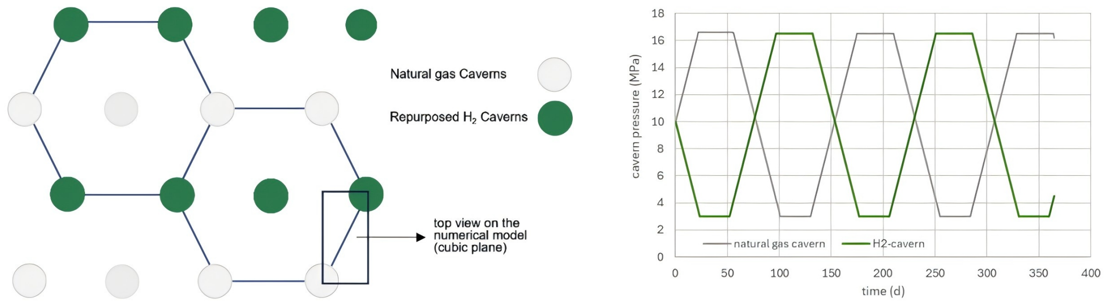

Fig. 8 Schematic representation of a cavern field in the closest hexagonal pattern (left). Natural gas caverns (gray) and a repurposed hydrogen caverns (green) are shown. On the right, a counter-rotating (non-parallel) storage operation is illustrated. The green curve represents hydrogen operation, while the gray curve represents natural gas operation. It can be observed that when one cavern is at p_{MAX}, the pressure in the other cavern is at p_{MIN} (Fabig et al., 2026)

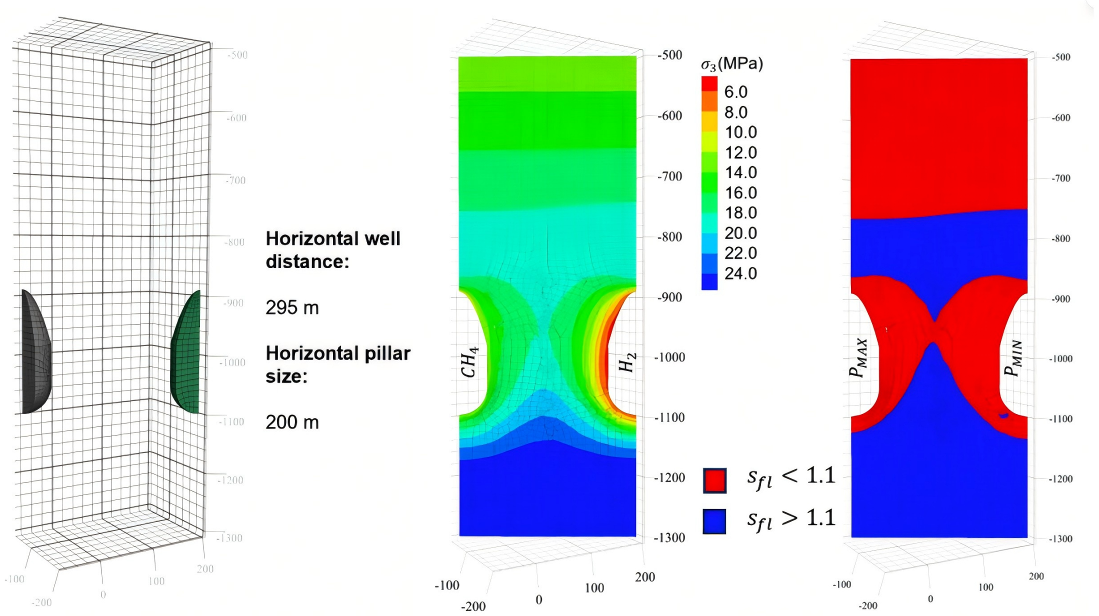

Fig. 9 Calculated distribution of minimum principal stress when natural gas cavern (CH_4) is at p_{MAX} and hydrogen cavern (H_2) is at p_{MIN}. Zones in which the minimum stress criterion is fulfilled (blue) as well as those in which it is not fulfilled (red) are on the right (Fabig et al., 2026)

systems..

3 Salt rock mechanics and cavity stability

Salt cavern gas storage has become a critical infrastructure for underground energy storage thanks to its low permeability, high ductility and self-healing capacity. However, as its application scenarios shift from traditional seasonal natural gas peak shaving to high-frequency, asynchronous hydrogen storage, and a large number of aging storage facilities enter the decommissioning phase, existing mechanical theories and engineering practices are facing severe challenges. Traditional design is usually based on synchronous injection-production mode, assuming that the pressure of cavity groups changes synchronously. But in future mixed storage scenarios (for example, adjacent cavities store hydrogen and natural gas respectively), the differential stress field caused by asynchronous cycles may trigger new stability risks. Meanwhile, the long-term safety of geological storage after decommissioning, especially the prediction of fracture initiation and propagation, has become a key bottleneck for regulatory decision-making (de Ruiter et al., 2026; Gouveia et al., 2026; Habbani et al., 2026; Harrington et al., 2026).

3.1 Multi-scale creep characteristics and long-term settlement prediction

The long-term creep behavior of salt rock is the core factor controlling cavity convergence and surface subsidence. In traditional high deviatoric stress regions, dislocation creep dominates; while in the low deviatoric stress environment of decommissioned caverns or shallow storage cavities, the role of pressure-solution creep cannot be ignored (Walega et al., 2026; Weber et al., 2026).

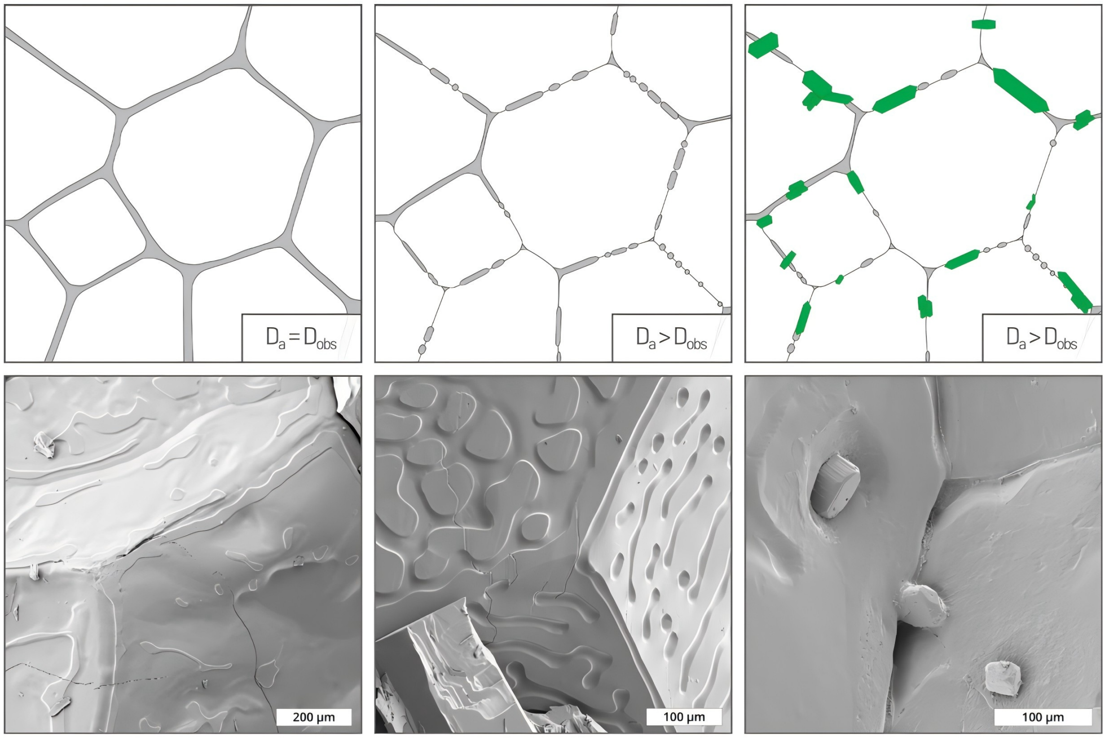

Fig. 10 Conceptual basis of apparent grain size. Top row: idealized sketches of grain-boundary networks for three end-members of pressure-solution activity. Left: fully wetted and well-connected grain boundaries, for which the apparent grain size equals the observed grain size (D_a=D_{obs}). Middle: partly disintegrated or poorly connected fluid films along grain boundaries, reducing the efficiency of pressure-solution creep and leading to an increased apparent grain size (D_a>D_{obs}). Right: heterogeneous rock salt with second-phase impurities along grain boundaries, which further hinder grain-boundary mass transfer and can likewise be represented by a larger apparent grain size. Bottom row: Corresponding SEM micrographs of halite grain surfaces illustrating the three end-member situations in natural salt microstructures. For the first end-member (fully wetted), it should be noted that this state is unlikely to be captured in sample material under non-subsurface conditions. Accordingly, the displayed halite grain surface exhibits several solid–solid contact plateaus (Baumann et al., 2026)

Baumann et al. pointed out that due to the heterogeneity of natural salt rock (impurities, discontinuous grain boundary fluid films), the directly measured matrix grain size cannot accurately reflect its creep behavior. Their study introduced the concept of “Apparent Grain Size” (Fig.10), which refers to the grain size of equivalent pure halite aggregate, to revise the pressure solution creep model (Baumann et al., 2026). The study found that impurity-enriched samples exhibit larger apparent grain size, indicating lower pressure solution efficiency. Meanwhile, combining microstructural observations and laboratory data, a probabilistic multi-scale framework was constructed, and the accuracy of the model was verified by the laboratory data (Fig.11) and measured settlement data in the Barradeel region of the Netherlands (Fig.12).

TerHeege et al. further noted that for shallow cavities in horizontally layered salt formations, pressure solution creep plays a dominant role, and there is a threshold stress of approximately 0.2 MPa—creep stops when the stress is below this value (Fig.13). This finding is crucial for predicting residual settlement after decommissioning. Numerical simulations show that if this threshold is ignored, the model will overestimate the long-term Rebound effect, leading to incorrect prediction of surface uplift (TerHeege et al., 2026).

3.2 Evolution of micro-fractures and multi-physical field characterization

The development of fracture networks directly affects the permeability evolution of salt rock. Although intact salt rock has extremely low permeability, beyond the dilatancy boundary, the initiation and connection of microcracks can increase permeability by several orders of magnitude.

Jiménez-Camargo et al. developed a comprehensive workflow combining mechanical testing, X-ray micro-CT and machine learning-based image segmentation (Fig.14). The study compared creep experiments under unconfined and confined conditions (Jiménez-Camargo et al., 2026).

Unconfined loading: It showed higher deformation rate and more micro-fractures (aperture > 5μm). Grain boundary sliding and opening are significant, indicating that uniaxial experiments may overestimate the damage degree under actual in-situ underground working conditions.

Confined loading: Confining pressure effectively inhibits the propagation of microcracks, resulting in a lower fracture volume fraction. This emphasizes the importance of simulating the in-situ stress state in laboratory research.

In his study, the pre-trained U-Net convolutional neural network based on the MicroNet dataset was used to successfully

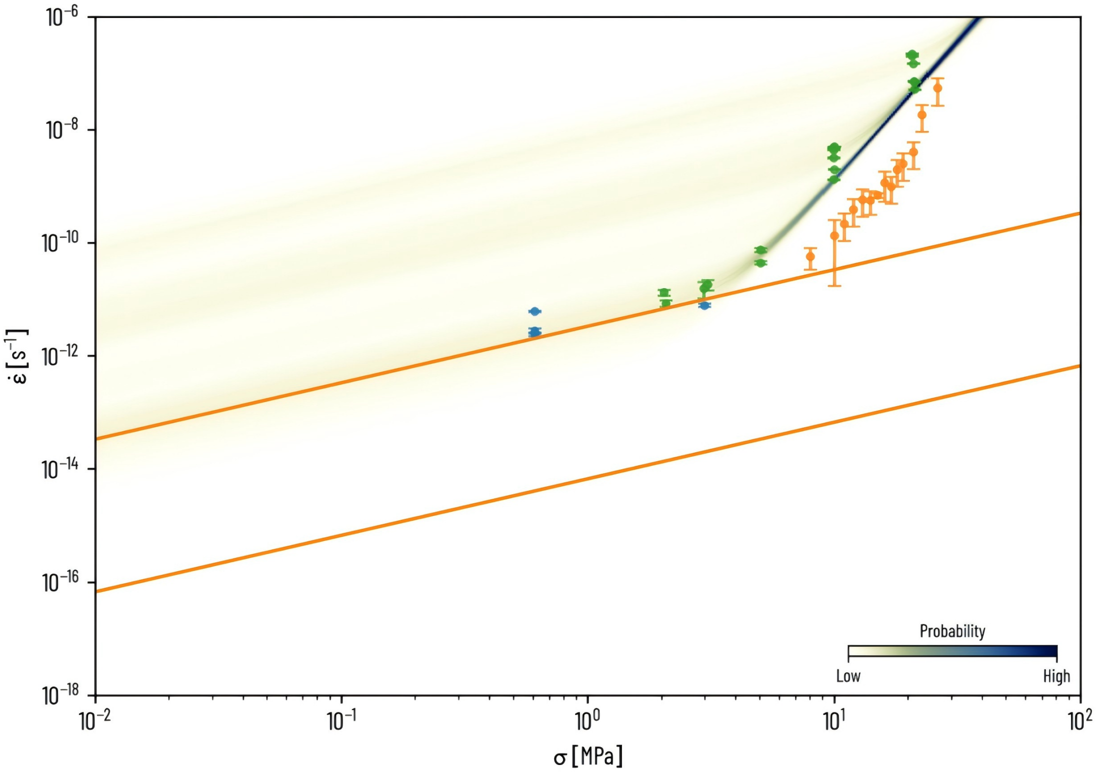

Fig. 11 Posterior creep-model response evaluated for the 100 °C laboratory test conditions (green markers). The model predictions use the posterior apparent grain sizes inferred for the individual samples. Orange symbols denote observed steady-state creep data from an earlier laboratory series at about 40 °C, while blue symbols represent low-stress creep tests at about 8 °C. Orange lines indicate the dome-scale feasibility bounds for orientation (see following section). The result demonstrates that the inferred model captures the stress-dependent creep behavior over the evaluated temperature range (Baumann et al., 2026)

achieve high-precision segmentation of halite matrix, associated mineral phases and micro-fractures. This method overcomes the limitation of traditional threshold segmentation in low-contrast fracture identification, and provides a new approach for establishing the quantitative relationship between macroscopic mechanical response and microstructure evolution.

3.3 Numerical simulation of fracture propagation during the abandoned period

After a salt cavern is abondened, the internal pressure will gradually recover to lithostatic pressure, and stress redistribution may cause tensile stress concentration around the roof or wellbore, inducing fractures. Djizanne et al. reviewed three mainstream numerical simulation strategies to address this complex multi-physics coupling problem (Djizanne et al., 2026).

Current research gaps lie in the lack of chemo-mechanical coupling formulations specifically for brine-saturated conditions, as well as the absence of systematic benchmark protocols among different models. Future regulatory frameworks will rely on these high-precision models to set safety limits for fracture propagation.

3.4 Complex injection-production conditions and wellbore integrity

The wellbore is the weakest link in underground gas storage. Yfantis et al. compared the performance of two cement sheath constitutive models in numerical simulation: the Mohr-Coulomb (MC) model and the Concrete Damage Plasticity (CDP) model (Yfantis et al., 2026). The study found that although the classic MC model is easy to implement, it cannot simulate the elastic stiffness degradation of cement under cyclic loading. In contrast, the CDP model can capture the damage evolution of cement under both tension and compression conditions, and predicts the formation and development of micro-annuli more accurately. Especially when simulating the pseudo 2D section and the full 3D cavity-wellbore coupling model, the CDP model reveals the nonlinear failure mechanism of the cement sheath under alternating thermo-mechanical loading, providing a more reliable basis for optimizing completion design.

3.5 Fluid-induced string vibration during cavity construction

During the process of solution cavity construction and gas injection-production, the stability of the suspended brine string is directly related to operational safety. Paidoussis com-

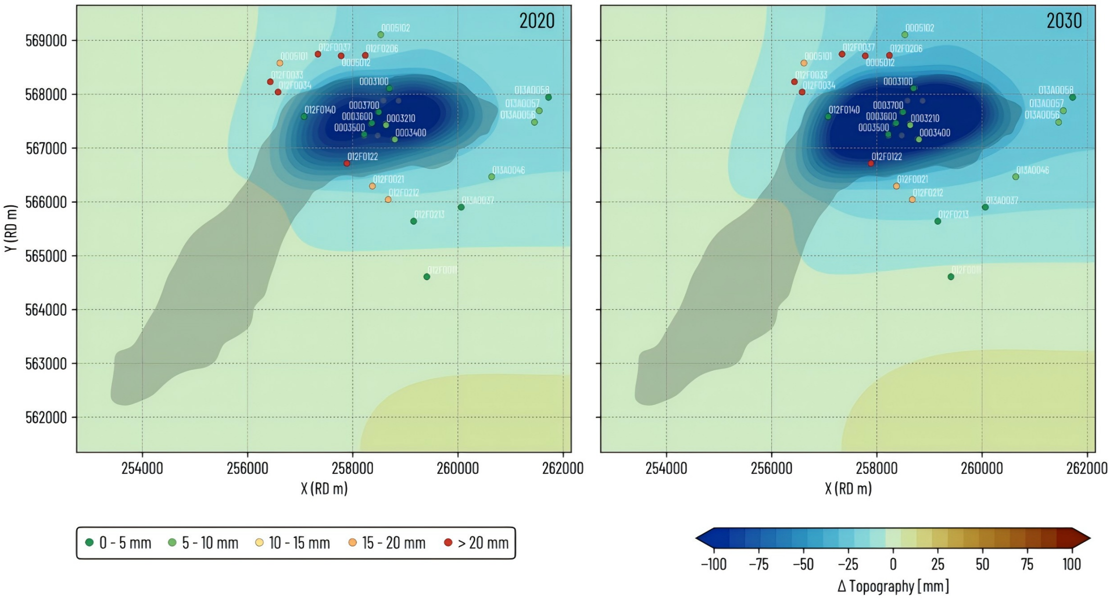

Fig. 12 Modelled cavern-induced surface displacement relative to 1986 for two selected time slices. Values are obtained by subtracting the dome-only reference simulation from the full dome-scale simulation including the Nobian brine caverns. Negative values indicate subsidence. Monitoring stations are overlain, and their colors represent the RMS misfit between simulated and measured time series. The spatial pattern shows a gradually deepening and widening subsidence bowl centered above the cavern cluster, with the smallest misfits in the central dome area and larger discrepancies toward the margins (Baumann et al., 2026)

Tab. 2 Comparative synthesis of fracture modeling strategies for salt cavern abandonment (Djizanne et al., 2026)

Criterion	Phase-field / Gradient Damage	Cohesive Zone Model (CZM)	XFEM	Hybrid CZM–Gradient Damage
Framework	Continuum; damage field regularized over ℓ	Discrete interface; traction-separation law	Enriched FE; level-set front tracking	Coupled continuum + interface
Crack topology	Implicit – branching, coalescence, nucleation	Predefined or inserted path	Arbitrary 3D path, no remeshing	Distributed + localized zones
Healing modelling	Natural: healing term reverses damage variable	Re-bonding under compression via law modification	Requires recontact closure algorithm	Combines both mechanisms
THM coupling	Straightforward (shared variational structure)	Via leak-off and pressure-dependent cohesion	Via level-set propagation and fluid-filled enrichment	Inherits from both
3D efficiency	Good; HPC-intensive for fine ℓ	Moderate; mesh dependency on interface placement	Excellent – no remeshing	Moderate–high
TRL for salt geomechanics	TRL 4–5 (research codes validated on benchmarks)	TRL 5–6 (commercial codes; cavern-scale studies)	TRL 4–5 (3D implementations advancing)	TRL 3–4 (GeoResources prototype)
Key limitation for abandonment	Regularisation length ℓ difficult to identify for rock salt	Crack path must be known a priori or inserted heuristically	Healing and viscoplastic coupling are still under development	Computational cost and coupling complexity

pleted the fifth phase of research on fluid-induced vibration and developed an executable software package applicable to Configuration 3 (brine injection through tubing, production through annulus) and Configuration 4 (brine production through tubing, injection through annulus) (Païdoussis et al., 2026).

This study determined the critical flow velocity that induces flutter or buckling of the string. The mathematical model, verified by bench tests, can accept wellbore structure, string properties and fluid parameters as inputs, and output the critical flow velocity and instability mode. This achievement provides a quantitative engineering design tool for solving the long-standing problem of vibration failure of injection-production strings in the industry, and helps maximize the injection-

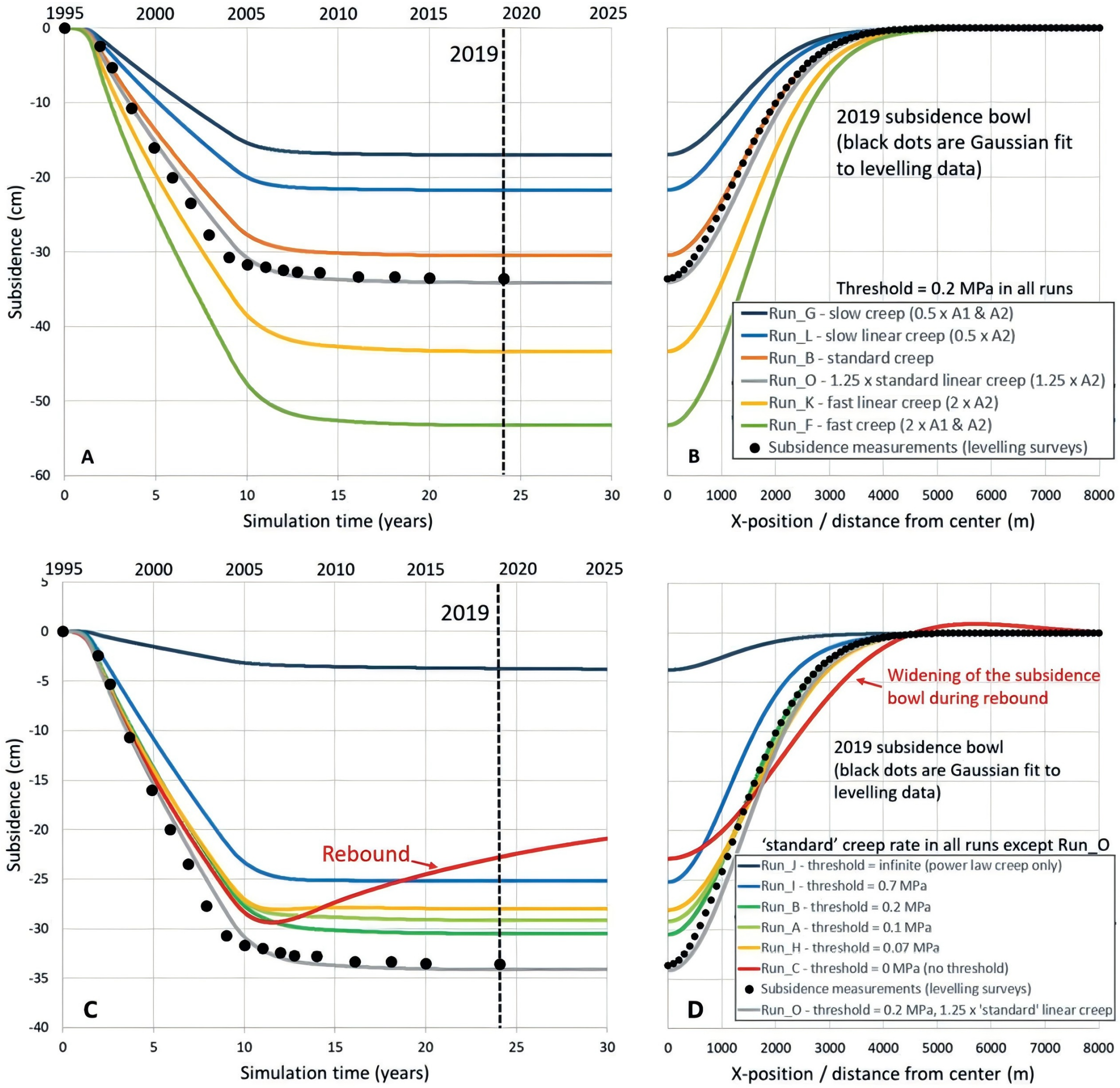

Fig. 13 Comparison of DIANA FEA model simulations of land subsidence for different creep models with subsidence measurements from levelling surveys at the Barradeel salt solution mining location in the Netherlands (cavern model at 2570-2940 m depth) (TerHeege et al., 2026)

production rate while ensuring operational safety (Braun et al., 2026).

3.6 Summary

In summary, research on salt rock mechanics and cavity stability is developing rapidly toward the directions of multi-scale integration, multi-physics field coupling, and intelligent characterization.

Micro-macro cross-scale correlation: The proposal of the concept of "apparent grain size" has successfully bridged the gap between microstructure and macroscopic creep prediction, significantly improving the reliability of long-term subsidence assessment.

Advanced characterization technology: Machine learning-assisted micro-CT technology provides a "perspective" for revealing the evolution of microcracks under complex stress paths, and corrects the deviation of traditional uniaxial experiments.

Innovation in numerical simulation paradigms: The application of phase-field method, cohesive zone model (CZM) and CDP model makes the prediction of fracture propagation during the abandonment period and wellbore damage more refined and physically consistent.

Adaptation to new working conditions: New design specifications and evaluation tools have been formed for the high-frequency non-parallel cycling in hydrogen energy storage and the fluid vibration problem during cavity construction.

Future research should focus on the role of chemo-mechanical coupling mechanism in fracture healing, establish a multi-code verification framework to unify the prediction results of different numerical methods, and further explore the in-depth application of artificial intelligence in real-time monitoring and risk early warning. With the maturation of these technologies, salt cavern gas storage will play a more solid role in global energy security and the process of carbon neutrality (Carver et al., 2026).

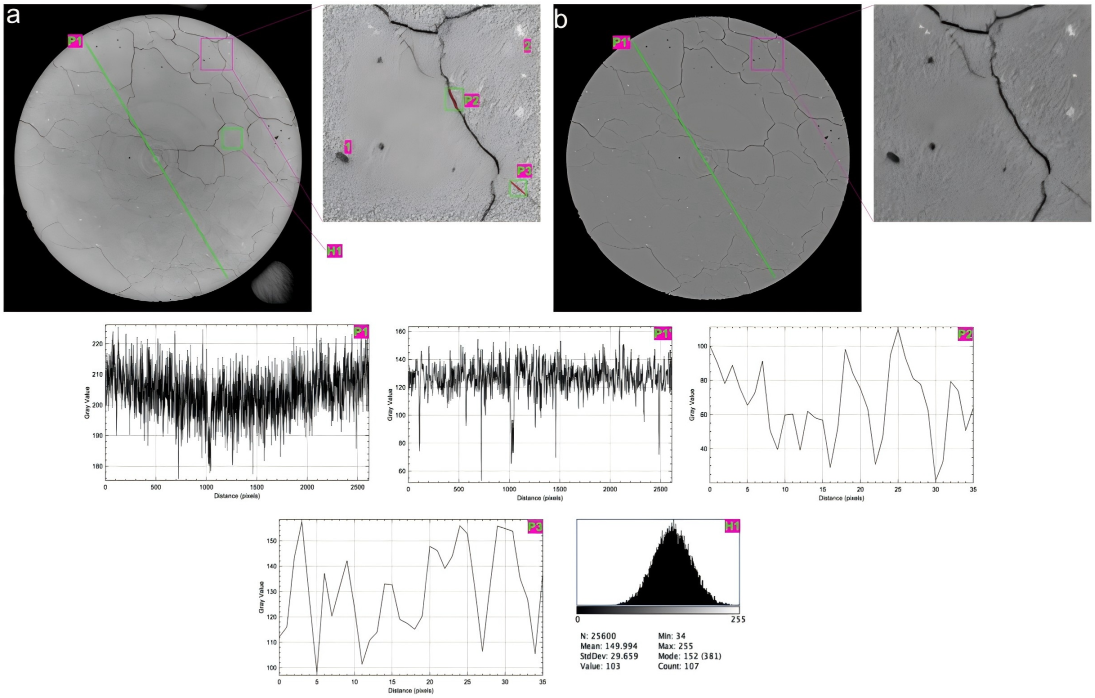

Fig. 14 Pre-processing workflow for microcrack characterization in micro-CT datasets of natural rock salt (2900×2900 pixels). a) Raw reconstructed slice with enhanced brightness and contrast for visualization. The green ROI corresponds to the gray-level histogram (H1) of the noisy matrix. The inset shows inclusions (1), accessory minerals (2), gray level profile for wider cracks (P2), and gray level profile for thin cracks (P3). The image illustrates representative acquisition noise and pervasive ring artifacts, with the associated intensity profile (P1) revealing a non-linear background gradient resulting from X-ray attenuation, which obscures low-aperture features. b) Processed slice following an initial denoising via BM3D (σ=0.02) that effectively reduced noise while maintaining edge sharpness at crack-matrix interfaces, followed by a frequency-domain bandpass filtering that mitigated long-wavelength background artifacts and selectively amplified target frequencies. The flattened intensity profile (P1') demonstrates the successful homogenization of the matrix background, enabling a better resolution of the microcrack network before segmentation (Jiménez-Camargo et al., 2026)

4 Conclusions

The SMRI 2026 conference report mainly presents the following characteristics: Research driven by energy transition: The conference content highly responds to the green energy transformation. More than 40% of the reports directly involve hydrogen storage, and research on microbial reactions (such as the HyPSTER project) has become the biggest highlight, indicating that the industry is actively addressing the biochemical stability issues of hydrogen in underground storage.

(1)Leap from "gas storage" to "hydrogen storage": Many reports discuss how to transfer and adapt the traditional experience of natural gas storage (including rapid cycling and compressed air storage) to hydrogen storage, which is the core pain point of the current industry.

(2)Digitalization and open-source tools: The industry has attached increasing importance to digitalization, and there have been reports on tool development such as SaltPy (open-source sonar processing) (Bauer et al., 2026), which aims to lower technical barriers and improve the transparency of data processing.

(3)Full life cycle management: From drilling technologies for newly built caverns (large-inclination wells) to decommissioning of old facilities (creep, settlement, decommissioning guidelines), the conference covers the full life cycle management of underground storage.

Future research should further pay attention to the adaptive evolution of microorganisms under long-period operation, the thermal-hydro-mechanical coupling mechanism under the coexistence of multi-energy media, and artificial intelligence-based full life cycle health management of salt caverns. With the maturation of related technologies, salt cavern hydrogen storage will play an irreplaceable cornerstone role in the global energy transition.

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Conflict of interest

The authors declare no competing interest.

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