Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P9331-cd

A preliminary review of risks in underground hydrogen storage

Nadezhda Gotcheva

Human Factors and System Safety, VTT Technical Research Centre of Finland, Tampere, Finland. E-mail: nadezhda.gotcheva@vtt.fi

Tero Välisalo

Human Factors and System Safety, VTT Technical Research Centre of Finland, Tampere, Finland. E-mail: tero.valisalo@vtt.fi

Sami Karadeniz

Human Factors and System Safety, VTT Technical Research Centre of Finland, Espoo, Finland. E-mail: sami.karadeniz@vtt.fi

Nina Wessberg

Ethics and Responsibility of Innovations, VTT Technical Research Centre of Finland, Tampere, Finland. E-mail: nina.wessberg@vtt.fi

Underground hydrogen storage (UHS) is a promising solution for integrating hydrogen into the energy mix and ensuring a reliable and flexible energy supply. This work is part of ongoing research project Hydrogen UnderGround (HUG), funded by Business Finland, which aims at building the basis for large-scale hydrogen storage concept for the Finnish hydrogen business and technology ecosystem. The objective of this preliminary review is to gain a better understanding on the risks and uncertainties associated with UHS, especially concerning applicability to lined rock caverns (LRC). A lined rock cavern is a constructed underground storage facility, characterized by steel, polymer or concrete impermeable lining, designed to hold gases like hydrogen at high pressures. LRC is considered a feasible option for the Finnish conditions, due to lack of suitable natural geological formations. Other types of underground hydrogen storages may vary significantly in their geological and storage set-up, including aquifer, depleted oil/gas reservoir, rock/mining caves and salt caverns. The initial review comprised 60 articles, published between 2005-2024. The main risks in different types of storages were linked to technical factors, such as sealing and leakage, cavern integrity, geochemical, geomechanical, microbiological, hydrodynamic, or surface facility risks. Only one recent study mentioned economic and environmental risks, including social license to operate. Regarding LRC, a key non-technical risk identified was lack of experience with these caverns, which could be linked to competences and learning as human and organizational factors. This finding is in line also with results from other studies, which indicate that social factors are often insufficiently addressed in sustainable development reviews. The results highlighted the need for a holistic view on different risks for UHS, specifically emphasizing the uncertainties of technical system failure modes and deficiencies in understanding the role of non-technical factors, such as human, organizational and societal factors.

Keywords: Underground hydrogen storage, hydrogen, risk, lined rock caverns.

1. Introduction

This study aims to provide a preliminary understanding about risks in a specific context: underground hydrogen storage. Safe and efficient hydrogen storage is critical for realizing hydrogen's potential as a clean, sustainable energy source; however, its highly flammable nature and small molecular size make optimal storage solutions challenging (Bhuiyan & Siddique, 2025). The European Commission's hydrogen strategy recognizes clean hydrogen as a key energy carrier in a European integrated energy system, which supports the EU's carbon neutrality ambitions (European Commission, 2020). The importance of sustainable storage solutions increases also due to the inherent volatility of electricity production from renewable sources. Since the production and demand of hydrogen needs to be balanced, underground hydrogen storages (UHS) are seen as critical to enable the stable supply and flexible use of hydrogen, while allowing continuation of land use for various purposes. In addition, storage of hydrogen is attractive because it increases the energy security and security of supply.

There are various storage technologies available for hydrogen, each with its own advantages and challenges, regardless of its method - gaseous, liquid, or solid (Raza et al., 2022; Milky et al., 2024). Currently, predominately used storage technologies are salt caverns, depleted gas fields, aquifers, and rock caverns. In the future, a variety of storage solutions might be needed to meet diverse needs and ensure energy security.

However, when there are no traditional underground storage formations, such as salt deposits or depleted reservoirs, a lined rock cavern (LRC) has been developed as a technical solution. LRC is an underground storage facility, characterized by steel, polymer or concrete impermeable lining, designed to hold gases like hydrogen at high pressures at shallow depths (Masoudi et al., 2024). LRC is considered a feasible option for the Finnish conditions, due to lack of suitable natural geological formations. A related concept is Lined Rock Shaft (LRS), which is based on the technology developed for the LRC.

In Sweden there are two storage facilities that provide important opportunities for sharing learnings and benchmarking. The Skallen Gas Storage Facility, located close to Halmstad is the first operational LRC for natural gas storage, while HYBRIT hydrogen storage facility in Luleå is the first LRC for underground hydrogen storage under construction, based on the experience and competences developed with the Skallen facility.

Designing and operating safe and efficient UHS facilities is far from trivial, and many uncertainties remain. The objective of this preliminary review is to gain a better understanding on the risks associated with UHS, especially concerning applicability to LRC. This study is part of research project Hydrogen UnderGround (HUG), which aims at developing the basis for a large-scale underground hydrogen storage concept for the Finnish hydrogen business and technology ecosystem. This two-year project brings together many industrial partners, with VTT Technical Research Centre of Finland and Geological Survey of Finland GTK assuming the central roles in project coordination and research activities.

2. Method

The method utilized in this study was literature review, focused on safety risks in underground hydrogen storage. The literature search strategy is presented in Figure 1 and the literature review process is shown in Figure 2. Literature on hazards in similar systems (i.e., underground gas storage in natural formations) was considered especially relevant to better understand the risks of LRC and LRS as the two technologies within the scope of HUG research project, which are seen as suitable for Finland's context.

Databases	Scopus, Web of Science
Keywords • Search #1: • Search #2:	 *hydrogen AND "lined rock cavern" AND safety* *("natural gas" OR "compressed air" OR "methane") AND store* AND safety AND underground*
Date range	01.01.2005 – 30.07.2024
Record types	articles, reviews, conference proceedings
Inclusion criteria	emphasis on applicability to H2 storage context, underground hydrogen storage, operational aspects and experiences on H2 storage

Figure 1. Literature search strategy.

In total, the process of identification, screening and inclusion resulted in review of 60 articles, published between 2005-2024. Most of the articles (54) were published in 2020-2024, which indicates the growing demand for hydrogen-related research and recent developments in this field.

To the best of our knowledge, hydrogen storage in LRCs has only been implemented in the HYBRIT pilot project in Sweden (Johansson et al., 2018). Thus, published literature on the emerging risks specific to LRCs remains scarce.

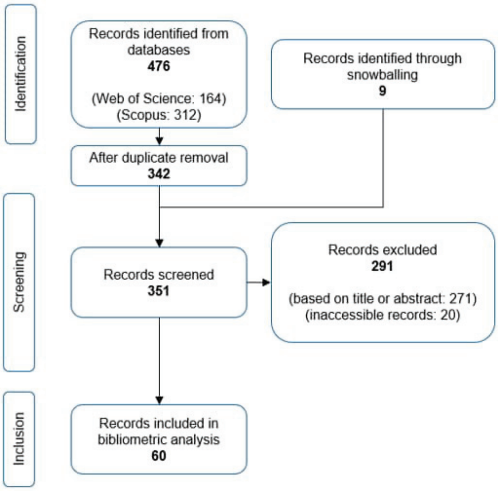

Figure 2. The literature review process.

3. Results: Hazards identification for hydrogen storage in lined-rock caverns

This section presents the results from identification of relevant hazards to support the development of a comprehensive risk assessment framework for hydrogen storage in LRCs. Selected studies are referenced to illustrate examples of different hazards categories.

We used the following categories to classify emerging hazards related to hydrogen storage in LRCs: *environmental (natural), technological, human and organizational, and social hazards*. We restricted the analysis to the following functions of hydrogen storage: surface facility operations (e.g., process monitoring, oversight, plant management), underground operations (e.g., maintenance and underground monitoring activities), storage integrity, and gas injection/discharge functions. Hazards related to hydrogen supply and distribution, and economic hazards, were outside the scope of our analysis. Regarding the life cycle of the storage system, we focused on the operation and maintenance phases.

Emerging environmental hazards in LRCs relate to hazards stemming from factors external to the storage system. Although not unique to LRCs, Qiu et al. (2024) identified the heightened risk of activating faults surrounding the caverns by the relatively more frequent injection and withdrawal patterns associated with LRC operation compared to hydrogen storage solutions based on natural formations.

Technological hazards relate to the integrity of the hydrogen storage solution. As the hydrogen containment mechanism in LRCs is based on an artificial barrier, compared to geological barriers associated with natural storage formations, the consideration of hazards focuses on the integrity of the liner and its interactions with the surrounding rock formation.

Properties of hydrogen, such as its small molecular size, its behavior during injection and withdrawal processes that give rise to changing pressure and temperature conditions, and its relatively high flammability, present emerging challenges to the design of storage solutions. Hydrogen embrittlement presents a performance degradation risk to both the wellbore (Fernandez et al., 2024) and steel linings (Patanwar et al., 2024; Sun et al., 2024). Rupture of the lining welds, either due to corrosion or strain on the lining, also presents a risk to the containment integrity (Damasceno et al., 2024).

For epoxy-based sealing layers, additional consideration must be paid to performance degradation risks arising from tensile loading, as the mechanical properties of these types of layers have traditionally been examined in applications operating with lower pressures (Li et al., 2024). In drainage systems that are designed to collect potential leaks, chemically or biologically induced clogging and corrosion present risks that need to be mitigated, as stated by Johansson et al. (2018), *"under normal conditions, the drainage system will be filled with water to prevent chemically or biologically induced clogging and to prevent oxygen for corrosion of steel lining."*.

In storage solutions based on natural formations, geochemical and microbiological processes play an important role in hydrogen storage integrity and performance (Bade et al., 2024; Salina Borello et al., 2024; Tackie-Otoo & Haq, 2024; Uliasz-Misiak et al., 2024). A similar finding has been identified also by Masoudi et al. (2024), which is elaborated in their review article on lined rock caverns as a hydrogen storage solution:

"Environmental considerations are paramount. While hydrogen poses a lesser environmental treat in leakage scenarios compared to other gases, potential chemical or biological interactions within the host rock might have long-term ecological implications. For

instance, biological clogging in the drainage system, an often-overlooked aspect, warrants comprehensive research to ensure environmental compatibility."

Human and organizational factors associated with the operation and maintenance activities of underground hydrogen storage were not considered in the literature. Given the prevalence of incidents related to human factors in the analogous case of underground natural gas storage (Lackey et al., 2024), we believe that this topic warrants further attention in the future.

Regarding social acceptance, Tarkowski and Uliasz-Misiak (2022) draw attention to low public awareness of hydrogen technology and the lack of social campaigns related to raising awareness as presenting potential barriers for social acceptance. These concerns are also recognized by Stalker and others (2022), who consider the public perceptions of gas leakage from analogous fields (CO2 and natural gas storage) and discuss the potential for transferring lessons learned to the hydrogen industry. According to the authors, difficulties in conceptualizing the subsurface storage solution, lack of previous demonstration projects, unsustainability of the hydrogen production mechanism, mistrust in regulators and operators, and skepticism of societal and economic benefits of hydrogen storage might have adverse influence on social acceptance of hydrogen technologies.

4. Discussion

This section elaborates on the technical risks, concerns and uncertainties focusing on Lined Rock Caverns (LRCs) and Lined Rock Shafts (LRSs) based on findings from the literature and expert reasoning. At the end of the section, considerations for non-technical risks are also presented and discussed.

Like other applications containing pressurized gas, the most critical issue also in LRC and LRS is loss of containment (LOC), i.e., a leakage of a storage. The basic principle of the LRC and LRS is illustrated in Figure 3: LRC is a mined cavern with gas-tight layer in the inner surface and connection pipeline to the surface. LRS is a drilled shaft with gas-tight liner and plug in the top with pipeline connection to surface.

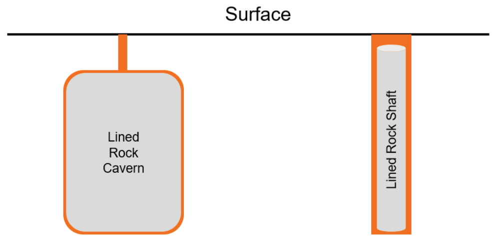

Figure 3. The principle of LRC (left) and LRS (right).

In the publicly available report about research needs of HYBRIT LRC facility in Sweden (Johansson et al., 2018) it is described that there is only one gastight liner layer in the wall structure made out of stainless steel. The basic principle of the HYBRIT cavern liner structure is presented in Figure 4. Potential system failures, or worst-case scenario considerations are presented next.

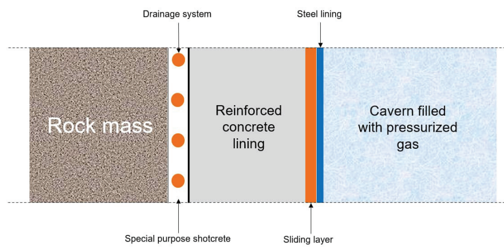

Figure 4. Layers of the LRC wall structure for storage of gas (adapted from Johansson et al., 2018).

4.1. *Causes of hydrogen leakage*

Multiple reasons may contribute to leakage incidents of the single gasproof layer. The scarce existing literature identified several ways in which the structural integrity of the cavern and the liner gas tightness may get compromised (Johansson, 2003; Johansson et al., 2018):

- Global failure of the rock mass, caused by too large uplift pressure from the stored gas.
- Rupture of the steel lining as it is loaded by the gas pressure caused by too large, one-time deformation of the surrounding rock mass.
- Low-cycle fatigue of the steel lining for caverns located at such depth where the

influence of the free ground surface will enlarge the strain range in the steel lining.
- Low cycle fatigue of the steel lining for caverns located deep enough to avoid the influence of the free ground surface.
- Local failure of the steel lining because of some structural weakness (e.g. welds, pipe lead-throughs, uneven quality of concrete).

Eventually, the consequence of all abovementioned cases is expected to be the same, that is, hydrogen escapes from the storage to other layers in the storage wall construction and eventually to the surface endangering safety. In the worst case, hydrogen leakage to open air can lead to a vapor cloud explosion (VCE) which can cause high overpressure and damage to structures and even fatalities (Thomas et al., 2015).

4.2. *Liner leakage*

The liner leakage can be detected with hydrogen sensors integrated into the drainage system (Johansson et al., 2018). When thinking about both of these two storage types, LRC and LRS, there is not much that can be done if the single gasproof liner starts to leak: it is not possible to enter the cavern or shaft to repair the leakage while the storage is filled with hydrogen.

It is not possible either to enter the structure behind the linery, as it is directly attached to concrete lining and rock mass. Hydrogen will enter the drainage system behind the liner and the concrete layer and rise to the surface (see picture of the storage wall structure, Fig. 4). Hydrogen will probably rise mainly via drainage pipes, but it can also enter the natural cracks in the rock and move somewhere else than assumed. The risks caused by the leakage can be mitigated by collecting the leaked hydrogen from the drainage system to specific locations in the surface (Johansson et al., 2018).

For the repair, the storage cavern/shaft must be emptied first completely and inerted before it can be filled with air. If the liner leakage is large, there might be a need for an emergency discharge of hydrogen or there must be some other way to collect the stored hydrogen quite quickly. If there are several hundreds of tons of hydrogen in the storage, the price of the stored substance can be quite high so the owner of the storage might be interested in collecting the hydrogen. If the leakage goes through the draining system, the quality of the leaked hydrogen will decrease as it is in contact with the groundwater and rock minerals.

4.3. *Surface connection failure*

Notwithstanding the underground storage type, the surface connection failure is critical due to potentially large amount of the leaked high-pressure hydrogen. Both in LRC and LRS there must be at least one, or probably two separate pipeline connections to the surface - one for the injection of hydrogen into the storage and one for the withdrawal of hydrogen. The pressure inside the connection pipe is likely the same as in the storage, as the pressure reduction system is likely located on the surface.

If this pipeline starts to leak, the consequences might be more severe than in the lining leakage, because the leakage through the lining and drainage system will probably slow down the flow rate. If the connection pipe fails, the leakage rate can be quite massive. To mitigate this risk, the connection pipes size should be as small as possible but simultaneously they must fulfil the hydrogen needs of the following processes and consumers.

4.4. *Shaft cap/plug uplift failure*

There is not publicly available information about the LRS type of UHS wall structure, but presumably it is similar to LRC's structure and the similar hazard scenarios will apply. One LRS specific worst-case scenario is the shaft cap/plug uplift failure. In this case the storage leak is quick and massive. Plug failure is a violent event that might lead to hydrogen cloud detonation and destruction of surrounding structures, which is not probable in slower and smaller releases of hydrogen to open air.

Therefore, the plug structure and securing it is critical for the LRS type of storages. According to Trevail (2023), the height of the plug, i.e., overburden, is in the range of tens of meters, which means that the effective length and storage capacity of the shaft is considerably smaller than in case the whole shaft length could be utilized for storing hydrogen up to the surface level.

4.5. *Non-technical risks*

Regarding LRC, a key non-technical risk identified was lack of experience with these caverns, which was categorized in our results as a human and organizational factors hazard. Regarding lack of experience, there is a need to further consider how this could be a risk factor. On the one hand, designers and operators of such hydrogen storage facilities might be familiar with process safety principles but may not be that familiar with hydrogen. On the other hand, it is likely that there are complete newcomers to the process industries and hydrogen storage facilities. Depending on the safety significance of the roles these actors play, this may present a higher risk due to the necessity and time needed of acquiring the required skills, competencies and experience. Furthermore, complacency-related risks should not be underestimated even if the key actors are already very experienced in the process industry and in working with hydrogen.

Other studies in the hydrogen context also indicate that social factors are largely missing or insufficiently addressed in sustainable development reviews. For instance, the strategic research project *Climate neutral, justified and sustainable H2 transition* (JustH2Transit), funded by the Research Council of Finland (2023-2026) focuses on studying just transition towards hydrogen economy. The project results have indicated the missing societal aspects in hydrogen economy scenarios. Existing scenarios are addressing techno-economic aspects and impacts to climate change mitigation, but lacking the consideration of local socio-economic, land-use and competence issues as well as political preferences related to hydrogen economy (Laitinen et al., 2024).

Although the importance of sustainability and social acceptance is growing, risks related to these factors seem somewhat distant and unrelated to the more tangible and usually quantifiable technical risks. However, risk perceptions are also linked to non-technical phenomena such as the role of human and organizational factors, trust building, responsibility and ethical business practices, and these need to be accounted for alongside the understanding of the technical phenomena and analysis of technical risks.

5. Conclusion

The aim of this study was to provide a preliminary review of risks and uncertainties associated with UHS, especially concerning applicability to LRC/LRS, which is an understudied topic.

The main risks in different types of storages, identified in the literature, were linked to technical factors, such as sealing and leakage, cavern integrity, geochemical, geomechanical, microbiological, hydrodynamic, or surface facility risks. Only one recent study mentioned economic and environmental risks, including social license to operate.

Research challenges related to LRC/LRS, such as the long-term material behaviour in different environmental conditions, emergency preparedness in case of different leakages of UHS, and also the maintainability issues are topics identified for future research.

Overall, the findings of this study highlighted the necessity for a holistic and comprehensive approach to various risks associated with UHS. It particularly emphasizes the currently inadequate consideration of non-technical risks, including those related to human, organizational, and societal factors.

Acknowledgement

This study was conducted as a part of HydrogenUnderground (HUG) project, funded by Business Finland (grant numbers VTT 6004/31/2023, GTK 7174/31/2023). We are grateful to the two reviewers for their valuable comments, which enhanced the quality of our paper.

References

Bade, S. O., Taiwo, K., Ndulue, U. F., Tomomewo, O. S., & Aisosa Oni, B. (2024). A review of underground hydrogen storage systems: Current status, modeling approaches, challenges, and future prospective. International Journal of Hydrogen Energy, 80, 449–474. https://doi.org/10.1016/j.ijhydene.2024.07.187

Bhuiyan, M. H. & Siddique, Z. (2025). Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation, International Journal of Hydrogen Energy, Volume 102, pp. 1026-1044, https://doi.org/10.1016/j.ijhydene.2025.01.033.

Damasceno, D. R., Spross, J., & Johansson, F. (2024). Reliability-based design tool for gas storage in lined rock caverns. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 18(2), 410–422. https://doi.org/10.1080/17499518.2023.2188467

European Commission (2020). A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020, EUR-Lex - 52020DC0301 - EN - EUR-Lex

Johansson, F., Spross, J., Damasceno, D., Johansson, J., & Stille, H. (2018). Investigation of research needs regarding the storage of hydrogen gas in lined rock caverns (Report No. TRITA-ABE-RPT-182). KTH Royal Institute of Technology.

Johansson, J. (2003) Cavern wall design principles. Available at: https://research.ebsco.com/linkprocessor/plink?id=1d6011b2-1419-3f4b-8b8e-049e4c4df7fd [Accessed: 13 January 2025].

Lackey, G., Mundia-Howe, M., & Pekney, N. J. (2024). Underground natural gas storage facility operations and well leakage events in the United States. Geoenergy Science and Engineering, 234, 212630. https://doi.org/10.1016/j.geoen.2023.212630

Laitinen, E., Wessberg, N., & Rikkonen, P. (2024). Socio-Technical Scenarios for Future-Proof Green Hydrogen Transition in Finland. Abstract from Strategic Research Council programmes: Future-proof society: Enhancing social and environmental wellbeing and security, Tampere, Finland.

Li, S., Qiu, K., Wang, Z., Zhao, S., & Wan, Z. (2024). Static and fatigue behaviors of epoxy-based sealing layers for underground hydrogen energy storage. International Journal of Hydrogen Energy, 60, 66–81. https://doi.org/10.1016/j.ijhydene.2024.02.059

Masoudi, M., Hassanpouryouzband, A., Hellevang, H., & R. Stuart Haszeldine (2024). Lined rock caverns: A hydrogen storage solution, Journal of Energy Storage, Volume 84, Part B, 110927, ISSN 2352-152X, https://doi.org/10.1016/j.est.2024.110927.

Mulky, L., Srivastava, S., Lakshmi, T., Sandadi, E. R., Gour, S., Thomas, N. A., S. Shanmuga Priya, K. Sudhakar (2024) An overview of hydrogen storage technologies – Key challenges and opportunities, Materials Chemistry and Physics, Volume 325, 2024, 129710, https://doi.org/10.1016/j.matchemphys.2024.129710.

Patanwar, Y. K., Kim, H.-M., Deb, D., & Gujjala, Y. K. (2024). Underground storage of hydrogen in lined rock caverns: An overview of key components and hydrogen embrittlement challenges. International Journal of Hydrogen Energy, 50, 116–133. https://doi.org/10.1016/j.ijhydene.2023.08.342

Qiu, K., Li, S., Wang, Z., Wan, Z., & Zhao, S. (2024). Research on influence patterns of fault activation on lining structures in lined rock caverns for underground hydrogen energy storage. International Journal of Hydrogen Energy, 58, 605–620. https://doi.org/10.1016/j.ijhydene.2024.01.241

Raza, A., Arif, M., Glatz, G., Mahmoud, M., Al Kobaisi, M., Alafnan, S., & Iglauer, S. (2022). A holistic overview of underground hydrogen storage: influencing factors, current understanding, and outlook, Fuel 330 (2022) 125636, https://doi.org/10.1016/j.fuel.2022.125636

Salina Borello, E., Bocchini, S., Chiodoni, A., Coti, C., Fontana, M., Panini, F., Peter, C., Pirri, C. F., Tawil, M., Mantegazzi, A., Marzano, F., Pozzovivo, V., Verga, F., & Viberti, D. (2024). Underground Hydrogen Storage Safety: Experimental Study of Hydrogen Diffusion through Caprocks. Energies, 17(2), 394. https://doi.org/10.3390/en17020394

Salmon, P. M., King, B. J., Elstak, I., McLean, S. & Read2, G. (2024). Tomorrow's demons: a scoping review of the risks associated with emerging technologies, Ergonomics, 1-17. DOI: 10.1080/00140139.2024.241655.

Stalker, L., Roberts, J. J., Mabon, L., & Hartley, P. G. (2022). Communicating leakage risk in the hydrogen economy: Lessons already learned from geoenergy industries. Frontiers in Energy Research, 10, 869264. https://doi.org/10.3389/fenrg.2022.869264

Sun, Z., Wu, J., Fager, A., & Crouse, B. (2024). Numerical analysis of hydrogen storage in lined rock cavern under high pressure and its implications to hydrogen embrittlement. International Journal of Hydrogen Energy, 80, 1021–1029. https://doi.org/10.1016/j.ijhydene.2024.07.208

Tackie-Otoo, B. N., & Haq, M. B. (2024). A comprehensive review on geo-storage of H2 in salt caverns: Prospect and research advances. Fuel, 356, 129609. https://doi.org/10.1016/j.fuel.2023.129609

Tarkowski, R., & Uliasz-Misiak, B. (2022). Towards underground hydrogen storage: A review of barriers. Renewable and Sustainable Energy Reviews, 162, 112451. https://doi.org/10.1016/j.rser.2022.112451

Thomas, J.K., Eastwood, C. and Goodrich, M. (2015) Are unconfined hydrogen vapor cloud explosions credible? Process Safety Progress, 34(1), pp. 36–43. doi:10.1002/prs.11685.

Trevail, J. (2023). Lined rock shafts: developing a flexible hydrogen storage solution. Hydrogen Tech World. Available at: https://hydrogentechworld.com/lined-rock-shafts-developing-a-flexible-hydrogen-storage-solution [Accessed 13 January 2025].

Uliasz-Misiak, B., Misiak, J., & Lewandowska-Śmierzchalska, J. (2024). Hydrogen Storage in Porous Rocks: A Bibliometric Analysis of Research Trends. Energies, 17(4), 805. https://doi.org/10.3390/en17040805