19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 3.10.178
DOI: 10.46793/ACUUS2025.3.10.178

THE ROLE OF UNDERGROUND MINES IN ENERGY TRANSITION: A REVIEW

Dimitris Kaliampakos[1], Athanassios Mavrikos[2]

Abstract: Driven by global population growth, demand for energy is constantly rising. The dependence on fossil fuels as energy sources results in ever growing CO2 emissions, which in turn contributes to climate change. The transition from fossil fuel dependency towards a sustainable, low-carbon energy system is considered as a necessity for the future. A shift to renewable energy sources is associated with several problems due to their stochastic production nature that poses significant challenges for grid reliability and energy security. A solution to this end would be to be able to store excess energy from renewable sources so that it can be available when needed. The main technologies that have been proposed are underground hydrogen storage, pumped hydro storage, compressed air energy storage and gravitational energy storage. Furthermore, nuclear energy has recently come to the foreground due to its zero carbon emissions and contribution to grid stability. A common factor among all the proposed approaches is the use of underground space, underground mines in particular, and the inherent geological and structural characteristics of underground environments. Underground mines offer considerable advantages to this end and the utilization and repurpose of abandoned underground mines presents a significant opportunity. The paper discusses the factors contributing to the need for energy transition and the main obstacles that hinder the wider use of renewable energy sources. Furthermore, the advantages of underground mines and underground space in general are analyzed. The most promising storage technologies are presented through notable cases and reviewed.

Keywords: energy transition, climate change, underground space

1. INTRODUCTION

World demographics are driving up the demand for electricity, as expanding urbanization, industrial activity, and improvements in living standards require greater energy consumption (Chaurasia, 2020; Ali et al., 2025; Yakymchuk et al., 2025). World energy production continues to rely on the combustion of fossil fuels as a primary source of electricity generation. However, fossil fuels consumption increases carbon emissions thus significantly contributing to global warming, extreme weather events, sea-level rise, and biodiversity loss (World Weather Attribution, 2024). A number of scientific reports, including assessments by the Intergovernmental Panel on Climate Change (IPCC), stress the necessity of halving global emissions by 2030 to avert catastrophic climate impacts (IPCC, 2023). The environmental implications of this dynamic underline a pressing need for a comprehensive energy transition. Shifting towards renewable energy sources such as solar, wind, and hydropower is essential not only to mitigate carbon emissions but also to ensure sustainable and resilient energy systems capable of meeting future demands without further environmental deterioration (Liu and Han, 2024). Without rapid decarbonization of the energy sector, the world is on track to exceed the 1.5°C warming threshold outlined in the Paris Agreement, risking irreversible environmental and societal damage (UNEP, 2023; Foster et al., 2024; Islam and Kieu, 2021).

Despite their critical role in achieving a low-carbon future, renewable energy technologies present several limitations and challenges. Among them, the primary concern is their inherent intermittency. Solar and wind energy production is stochastic and depends on weather conditions that are variable by nature. This results in fluctuations in energy supply, quite the opposite needed for a stable electrical grid. Seemingly, the only efficient

[1]Professor, Kaliampakos Dimitris, Mining Engineer Ph.D., National Technical University of Athens, School of Mining and Metallurgical Engineering, 9 Iroon Polytechneiou Str., GR15772, Zografou, Athens, Greece, dkal@central.ntua.gr
[2]Mavrikos Athanassios, Mining Engineer Ph.D., National Technical University of Athens, School of Mining and Metallurgical Engineering, 9 Iroon Polytechneiou Str., GR15772, Zografou, Athens, Greece, mavrikos@metal.ntua.gr

way to integrate large-scale deployment of renewable energy systems is by having adequate storage capacity. Currently, many research efforts focus on energy storage technologies such as hydrogen storage, pumped hydro, compressed air and gravitational systems (Molina et al, 2025; Qin et al., 2025; Liu et al., 2025; Li and Deusen, 2025). Furthermore, nuclear energy is also considered as a key enabler due to its zero carbon emissions and ability to act as a baseload supplier in electrical grids (Wang et al., 2023; Imran et al, 2024; Fattahi et al., 2022). Underground space and in particular underground mines offer significant opportunities in this direction. As the demand for large-scale, efficient, and sustainable energy storage grows, the reutilization of underground mines presents many advantages. The geological and structural characteristics of underground space, result in reduced surface land use, the insulation properties of the surround rock mass provide thermal stability and the availability of mine infrastructure can contribute to the success of the solution. As a result, the adaptation of these storage technologies to the underground environment is increasingly studied. Moreover, underground mines can address a critical disadvantage of nuclear energy production, the disposal of nuclear waste. Underground nuclear repositories in former mines have been in operation for many years and are considered the safest option.

The paper analyzes the main storage technologies in the context of reutilization of underground mines. Through the presentation of prominent cases, the paper reviews the advantages, opportunities and challenges of each technology and draws conclusions for the future emphasizing the role of underground space as a key enabler of energy transition.

2. THE UTILIZATION OF UNDERGROUND MINES IN ENERGY TRANSITION

Currently energy storage relies mainly on pumped hydro storage, which accounts for approximately 90% of the total capacity and on battery energy storage systems (IEA, 2024; REN21, 2024). However, battery storage systems are expected to grow significantly in the near future representing around 85-90% of new grid scale battery storage capacity (IEA, 2024; REN21, 2024). Energy storage systems are an essential factor in the process of energy transition and underground energy storage presents significant advantages:

- Storage capacity: underground formations offer vast void volumes, enabling energy storage at very large scales.
- Flexibility in terms of duration: underground energy storage can supply energy for days up to seasons, balancing out variations between renewable energy generation and demand.
- High thermal inertia and constant temperatures: the intrinsic insulation properties of the underground space, minimize heat losses and improve round-trip efficiency.
- Reduced surface footprint and environmental impact: by moving energy storage facilities in the underground space surface land is preserved, there is minimal visual impact and the ecosystem is not affected.
- Can accommodate a variety of technologies: underground space can support a range of storage types, like thermal storage, compressed air, gases (natural gas, hydrogen) and even pumped hydro storage.

The utilization of underground mines and underground spaces for energy storage has various strategic advantages with regards to the goals of energy transition (Cornaro and Kompatscher, 2024). One obvious advantage is the availability of existing infrastructure. Abandoned or closed underground mines have extensive tunnel and shafts networks that can be reused and serve other purposes. Around the world there is a large number of inactive underground mines that can be repurposed to meet the needs of energy storage. Underground mines are particularly well-suited for high-capacity storage technologies such as hydrogen storage, pumped hydro storage, compressed air energy storage, and gravitational systems, which require large, stable volumes to operate efficiently.

The range of storage technologies presents different advantages and trade-offs, that make each technology suitable for different roles in the process of energy transition (Fig. 1).

Underground hydrogen storage achieves an efficiency in the range of 30–40%. The main concept of this technology is that hydrogen that is produced by excess energy from renewable sources is stored in mined caverns in salt domes. It is considered appropriate for long-duration and seasonal storage at far larger scale than other technologies. Therefore, it is important for balancing renewable energy over weeks or months. Hydrogen storage can also be integrated in many sectors, such as industry, transportation and heating contributing to the decarbonization targets. However, its main disadvantages are the high capital costs and complex safety and infrastructure requirements (Sambo et al., 2022; Tackie-Otto and Haq, 2024; Ali et al., 2025).

Pumped hydro storage is probably the most mature technology, having been used in surface water reservoirs and hydroelectric power plants for over a century. It requires two reservoirs, an upper and a lower one with an adequate elevation difference and reaches an efficiency of 75-85%. Underground mines have inherent elevation differences that facilitate the deployment of this technology (Xi et al., 2022; Colas et al., 2023; Menendez et al., 2019).

Compressed air energy storage systems utilize underground salt caverns to store pressurized air. Then according to demand, the pressurized air is used to drive generators. The process offers efficiency up to 70% and has relatively rapid deployment times and reduced environmental impact compared to surface-based infrastructure. These systems are especially well-suited for medium-duration applications between 4 and 12 hours (Zhou et al, 2025; Cornaro and Kompatscher, 2024; Bu et al, 2024; Scmidt et al., 2024).

Gravitational energy storage systems capture excess electricity by lifting a heavy mass to store energy as gravitational potential. When energy is needed, the mass is lowered in a controlled manner to drive generators or mechanical linkages that convert the potential energy back into electrical power. The average efficiency of this technology is around 75-85%, depending on friction and mechanical losses. Gravitational energy storage systems have lifespans of over 40 years and low environmental impact. They can be installed in a modular design utilizing existing mine shafts to provide fast-response, long-duration storage with low capital costs and small surface footprint (Hunt et al., 2023; Kulpa et al., 2021; Wang et al., 2025).

Nuclear power plants can supply electricity reliably with zero-carbon emissions. Therefore, as a baseload supplier they strengthen grid resilience and stability and address solar and wind variability. Nuclear power plants require high capital costs, but their main disadvantage is related to the safe disposal of spent nuclear fuel. Underground repositories are generally regarded as the safest long-term solution for radioactive waste. By having engineered barriers coupled with selected properties of the surrounding host rock the isolation of nuclear waste from the biosphere is ensured (Dong et al., 2025; Mauke and Herbert, 2015; Chapman and Hooper, 2012).

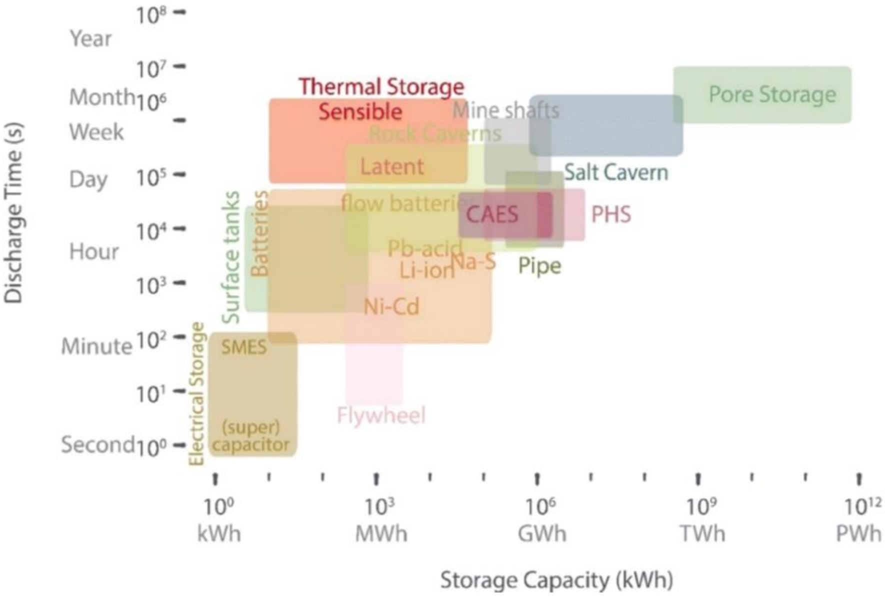

Figure 1. *Storage capacity and discharge time comparison of various energy storage technologies (source: Ali et al., 2025)*

3. REVIEW OF SELECTED CASES

Among the various underground energy storage technologies being considered only two have a Technology Readiness Level high enough to be regarded as mature and proven in large scale, namely underground hydrogen storage (especially in salt domes) and compressed air energy storage. The other technologies are in a less mature state with laboratory or pilot plant studies being conducted but further research, investments and efforts are required to scale up and prove their competitiveness.

Notable examples of underground hydrogen storage include the Clemens hydrogen storage site, created in 1983 in a salt dome at a depth of 900 m in Texas, USA. The storage volume is in the order of 580,000 m^3. Furthermore, in the UK, at Teesside, the facility was built in 1972 at a depth of 350 m. Hydrogen is stored in three caverns with each cavern having a storage volume approximately 70,000 m^3 (Matos et al., 2019).

Regarding compressed air energy storage, there are two CAES facilities in operation: the Huntorf plant in Germany and the McIntosh plant in USA (Matos et al., 2019). The former was commissioned in 1978 in two salt caverns having a total volume of 310,000 m^3, its power capacity is 290 MW having a 2-3-hour discharge period. Recently, its main purpose is to contribute to balancing the quickly growing energy production from wind farms in Northern Germany. The McIntosh CAES facility has been in operation since 1991 in Alabama, USA. It has a power capacity of 110 MW and a discharge period of about 26 hours. Hydrogen is stored in a 560,000 m^3 salt cavern (Matos et al., 2019).

Despite the differences in maturity level, deployment scale or technological developments among underground energy storage alternatives, there is a growing body of literature covering many aspects of these energy storage technologies. We have selected characteristic examples for each technology to showcase how each of them contributes to energy transition and sustainability goals.

3.1. Advanced Clean Energy Storage (ACES) Delta project, Utah, USA

The Advanced Clean Energy Storage (ACES) Delta project, in Utah, USA aims to support the decarbonization of the Western U.S. power grid by storing green hydrogen produced via electrolysis using excess renewable energy, particularly solar and wind (Fig. 2). According to the design, two underground salt caverns, each having a capacity of approximately 5,500 tons of hydrogen, will be constructed in salt domes using the solution mining technique. Their combined capacity is equivalent to 300GWh. The stored hydrogen will be used to fuel the adjacent Intermountain Power Project (IPP), which is undergoing a transition from coal to a combined-cycle gas turbine system designed to operate initially on a 30% hydrogen blend, with plans to increase to 100% hydrogen by 2045. The project has received significant financial support, including a $504 million loan guarantee from the U.S. Department of Energy, which serves as a strong indicator that government officials consider hydrogen to be a key parameter for energy transition (https://aces-delta.com/ 24.06.2025).

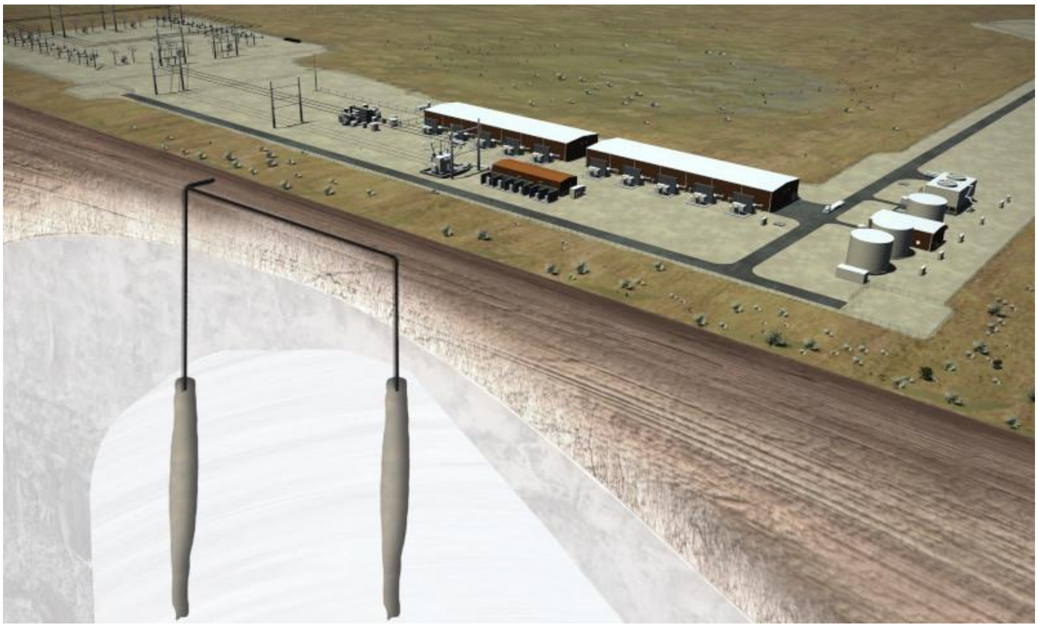

Figure 2. *Representation of the ACES Delta project in Utah, USA (source: https://aces-delta.com/ 24.06.2025)*

3.2. Compressed Air Energy Storage, Hubei Province, China

A notable example of an underground compressed air energy storage (CAES) system is the “Nengchu-1” project in Yingcheng, Hubei Province in China (Fig. 3). The facility has a power rating of 300 MW and became fully operational in early 2025. The system comprises two underground salt-caverns that are located at approximately 600 m in depth in a repurposed salt mine. The total volume of compressed air is around 700,000 m^3 that translates to a storage capacity of 1,500 MWh. The facility achieves conversion efficiencies nearing 70%, enabling it to store energy for up to eight hours and discharge for five hours daily, generating approximately 500 GWh per year. The project is expected to reduce 411,000 tons of CO_2 emissions annually, contributing significantly to the country’s green energy goals. The project was completed in two years underlining the advantages, in terms of time, logistics and economy, when CAES is deployed in repurposed salt mines (China Energy Engineering Group Co., Ltd., 2025; Li et al., 2023).

Figure 3. *Surface pressure-bearing spherical tanks at the "Nengchu-1" facilities (source: http://en.ceec.net.cn/art/2025/1/10/art_138_2510992.html 24/06/2025)*

3.3. Underground pumped hydro storage

Until now, there is no fully underground hydro pump storage facility in operation. There are some power plants that are built underground but the water reservoirs are on the surface. However, the concept has been researched in the past and is coming to the forefront again. A recent study by Xi et al. (2022) evaluates a feasibility framework for Pumped Storage Power Stations using Abandoned Mines (PSPSuM) in China's Yellow River basin, repurposing 91 disused mines to deliver a collective installed capacity of 15,830 MW (Fig. 4). Their multidisciplinary evaluation integrates spatial-structural criteria (reservoir volume, shaft stability, terrain configuration), hydro-mechanical design (optimal head, pump–turbine selection), and environmental-economic assessments, demonstrating that subterranean pumped storage can attain round-trip efficiencies of approximately 80 % while leveraging existing mine infrastructure to minimize land-use impacts. By coupling off-peak renewable generation (primarily wind and solar) with these underground reservoirs, the PSPSuM concept not only mitigates the intermittency of renewables in resource-rich regions (e.g., Inner Mongolia, Gansu, Qinghai) but also enables annual CO_2 reductions on the order of one million tons, aligning large-scale energy storage with ecological restoration and rural revitalization goals under China's dual carbon targets.

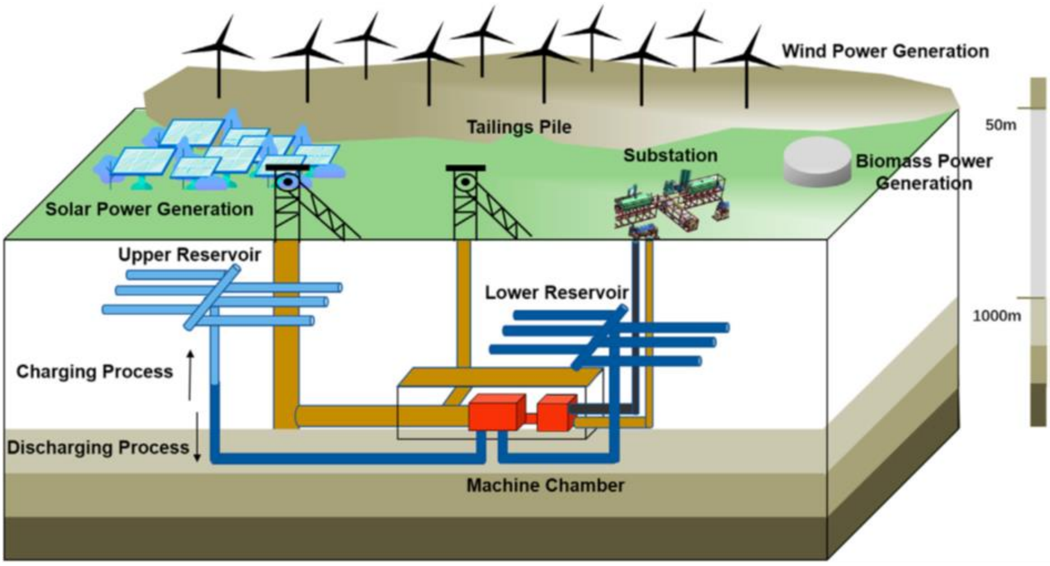

Figure 4. *The engineering concept of undereground pumped hydro storage (source: Xi et al, 2022)*

3.4. Gravitational energy storage systems

Although currently no full-scale underground gravitational storage facility has yet been constructed, there are some pilot projects and research initiatives that have explored the feasibility and potential of underground gravitational energy storage systems utilizing mine shafts. Gravitricity, based in UK is a company that has developed the “GraviStore” system. It is an underground gravity energy storage system, which raises and lowers heavy weights to store and deliver electrical energy. Excess renewable or cheap electricity is used to lift weights, storing their potential energy until needed. Lowering the weight turns the potential energy into kinetic energy, generating electricity. The system delivers sub-second electricity on demand, with each module capable of providing up to 8MW of electric power or 32MWh of energy. It has been engineered to repurpose existing mining infrastructure, including mine shafts and mine hoists, enabling a fast deployment timeframe and low costs.

A similar concept is described in the work of Hunt et al (2023). The authors investigate Underground Gravity Energy Storage (UGES) using regenerative braking (Fig. 5). The core idea is to exploit decommissioned mine shafts as reversible gravitational reservoirs: during peak-price periods, bulk material (e.g., sand) is released down the shaft, and the descending mass drives motor–generators operating in braking mode to convert potential energy into electricity; conversely, surplus off-peak grid power reverses the machine, elevating sand back to surface storage and thus replenishing stored energy. This bidirectional electromechanical cycle leverages existing vertical shafts and electric motor/generators to achieve high round-trip efficiency, near-zero self-discharge over long durations, and scalable capacity dictated by shaft depth and mine size. Continued advancements in mechanical engineering, materials science, and grid integration will be critical for transitioning gravitational storage from conceptual demonstration to commercial viability, particularly leveraging abandoned mine shafts as strategic energy assets.

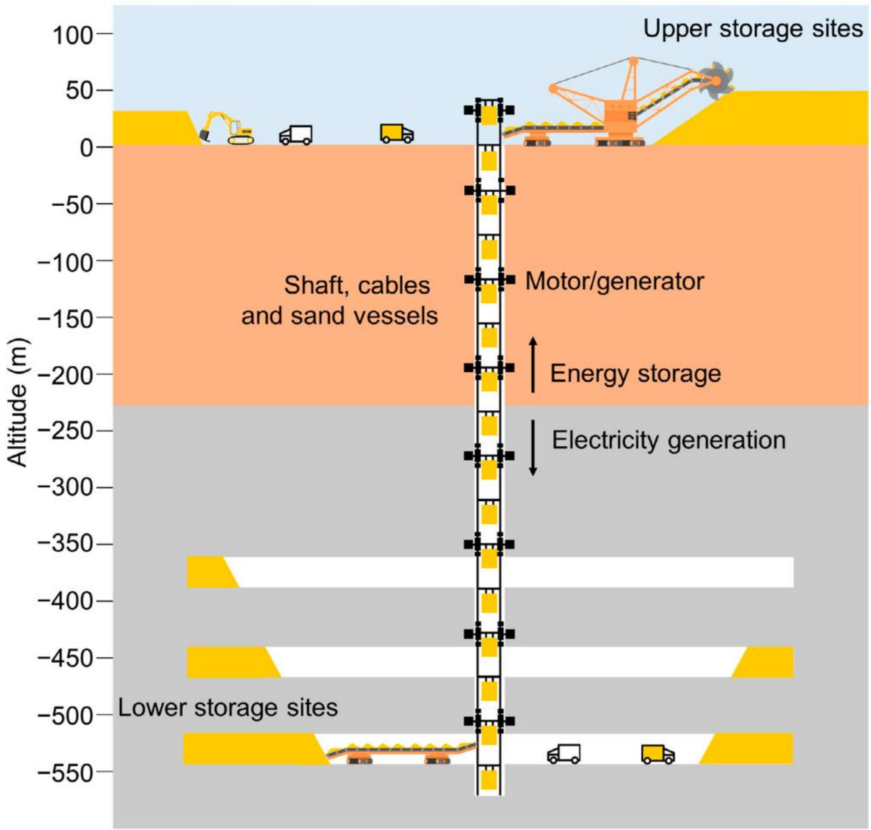

Figure 5. *A scematic representation of the proposed Underground Gravity Energy Storage system (source: Hunt et al., 2023)*

3.5. Nuclear waste disposal

Deep geological repositories have been used for long-term disposal of radioactive waste for many years, usually in former underground mines such as the Morsleben in Germany, the SFR facility in Sweden and the Waste Isolation Plant and Yucca Mountain in the USA. Two new, ongoing projects in this direction are the Forsmark deep geological repository for spent nuclear fuel in Sweden and the Onkalo repository in Finland.

The Forsmark project was approved by the Swedish government in 2022. The facility is designed to securely store up to 12,000 tons of high-level radioactive waste for up to 100,000 years. The underground repository will consist of 60 kilometers of tunnels excavated 500 meters beneath the surface in ancient 1.9-billion-year-old bedrock. The spent fuel will be encapsulated in corrosion-resistant copper canisters, which will then be surrounded by bentonite clay to prevent groundwater intrusion and ensure long-term containment. Construction is projected to span several decades, with the facility expected to begin accepting waste in the late 2030s and to be fully operational by around 2080. The estimated cost of the project is approximately 12 billion Swedish kronor (about $1.08 billion) and will be funded by the nuclear industry (SKB, 2008; Johnson, 2025).

The Onkalo repository, located near the Olkiluoto Nuclear Power Plant in Eurajoki, represents the world's first permanent disposal facility for spent nuclear fuel. The facility utilizes the KBS-3 method, involving the encapsulation of spent fuel in copper canisters, which are then placed in boreholes approximately 520 meters underground within stable granite bedrock. The canisters are surrounded by bentonite clay to provide additional isolation. Construction started in 2004, with the first trial placements of empty canisters occurring in 2024. The repository is expected to begin accepting spent fuel in the mid-2020s and is projected to be sealed by the end of the 21st century. The facility is designed to accommodate approximately 6,500 tons of uranium, equating to about 3,250 canisters, and is anticipated to remain operational for approximately 100 years before being sealed permanently (Young et al., 2020; Posiva, 2024).

4. CONCLUSIONS

The supply of raw materials to our societies has always been linked with the mining industry. A large part of that is attributed to underground mines. Around the world there is a large number of these underground mining facilities that are not used anymore. It seems that these facilities have an opportunity to be of service to our civilization one more time. This time their primary purpose will not be the extraction of raw materials but to contribute to the transition of energy production to renewable sources. The potential of transforming underground mines for energy storage that can help balance energy production fluctuations, strengthen the resilience of electric grids and ensure stability in the system is increasingly coming into the spotlight. The utilization of the vast voids and existing infrastructure of decommissioned mines can help energy storage projects to achieve quick, cost-effective deployment while minimizing new land disturbance. Legacy mine shafts and tunnels can be repurposed and meet the modern needs of energy production worldwide. From reservoirs for pumped hydro systems, airtight caverns for compressed-air energy storage and large elevation differences for gravity-based energy storage systems, closed mines can play a key role in energy transition and decarbonization.

However, the roadmap to the full integration of underground energy storage systems in energy grids worldwide is filled with many scientific and technological challenges. There are many geological and geomechanical uncertainties when we develop the underground space for energy storage. Deep geological formations exhibit complex heterogeneity in rock type, discontinuities networks and stress fields, resulting in challenges to predict long-term stability and deformation under cyclic loading. Furthermore, the interaction between stored media (gas, brine, thermal fluids, etc.) and the surrounding rock mass can cause chemical reactions, mineral dissolution or precipitation affecting porosity and permeability. Another issue is temperature variations during charging and discharging cycles. These induce thermal stresses in rock and seal materials and thermodynamic losses that can reduce round-trip efficiency. Moreover, there are specific problems associated with gases like hydrogen and CO2. In particular, due to hydrogen's small molecular size, often there is increased diffusion and leakage risks, while CO_2's acidity can accelerate rock dissolution. In addition, another factor is microbial activity consuming hydrogen or metabolizing CO_2, that affects storage volumes. Clearly underground energy storage holds considerable potential for the future of energy supply and offers key advantages to electrical grid stability, energy security and can enhance energy transition efforts. Emerging research is already focusing on addressing the challenges and critical issues that will allow the world to utilize the underground space and develop more robust and efficient energy storage systems.

5. BIBLIOGRAPHY

[1] Chaurasia, A. (2020). Population effects of increase in world energy use and CO2 emissions: 1990–2019. The Journal of Population and Sustainability, 5(1), 87–125. https://doi.org/10.3197/jps.2020.5.1.87

[2] Ali, M., Isah, A., Yekeen, N., Hassanpouryouzband, A., Sarmadivaleh, M., Okoroafor, E. R., Al Kobaisi, M., Mahmoud, M., Vahrenkamp, V., & Hoteit, H. (2025). Recent progress in underground hydrogen storage. Energy Environ. Sci., 18(12), 5740–5810. https://doi.org/10.1039/D4EE04564E

[3] Yakymchuk, A., Maxand, S., & Lewandowska, A. (2025). Economic Analysis of Global CO2 Emissions and Energy Consumption Based on the World Kaya Identity. Energies, 18(7), 1661. https://doi.org/10.3390/en18071661

[4] World Weather Attribution 2024 (2024). When Risks Become Reality: Extreme Weather In 2024, available at: https://www.worldweatherattribution.org/when-risks-become-reality-extreme-weather-in-2024/ (Accessed 25.06.2025)

[5] IPCC, (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

[6] Liu, H., & Han, P. (2024). Renewable energy development and carbon emissions: The role of electricity exchange. Journal of Cleaner Production, 439, 140807. https://doi.org/10.1016/j.jclepro.2024.140807

[7] United Nations Environment Programme (2023). Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). Nairobi. https://doi.org/10.59117/20.500.11822/43922

[8] Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.-Y., Palmer, M. D., von Schuckmann, K., Slangen, A. B. A., Szopa, S., Trewin, B., Yun, J., Gillett, N. P., Jenkins, S., Matthews, H. D., Raghavan, K., Ribes, A., Rogelj, J., Rosen, D., Zhang, X., Allen, M., Aleluia Reis, L., Andrew, R. M., Betts, R. A., Borger, A., Broersma, J. A., Burgess, S. N., Cheng, L., Friedlingstein, P., Domingues, C. M., Gambarini, M., Gasser, T., Gütschow, J., Ishii, M., Kadow, C., Kennedy, J., Killick, R. E., Krummel, P. B., Liné, A., Monselesan, D. P., Morice, C., Mühle, J., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Minx, J. C., Rigby, M., Rohde, R., Savita, A., Seneviratne, S. I., Thorne, P., Wells, C., Western, L. M., van der Werf, G. R., Wijffels, S. E., Masson-Delmotte, V., and Zhai, P. (2025). Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence, Earth Syst. Sci. Data, 17, 2641–2680, https://doi.org/10.5194/essd-17-2641-2025

[9] Islam, Md and Kieu, E. (2021). Climate Change and Food Security in Asia Pacific: Response and Resilience. 10.1007/978-3-030-70753-8

[10] Molina, R. A., Barros, J. J. C., López, M. del P. de la C., Coira, M. L., & Gochi, A. del C. (2025). A comparative sustainability assessment of several grid energy storage technologies. Applied Energy, 396, 126248. https://doi.org/10.1016/j.apenergy.2025.126248

[11] Qin, Z., Ma, J., Zhu, M., & Khan, T. (2025). Advancements in energy storage technologies: Implications for sustainable energy strategy and electricity supply towards sustainable development goals. Energy Strategy Reviews, 59, 101710. https://doi.org/10.1016/j.esr.2025.101710

[12] Liu, J., Pei, J., Wei, J., Yang, J., & Xu, H. (2025). Development status and prospect of salt cavern energy storage technology. Earth Energy Science, 1(2), 159–179. https://doi.org/10.1016/j.ees.2025.01.001

[13] Li, Z., & Deusen, D. (2025). Role of energy storage technologies in enhancing grid stability and reducing fossil fuel dependency. International Journal of Hydrogen Energy, 102, 1055–1074. https://doi.org/10.1016/j.ijhydene.2024.12.489

[14] Wang, Q., Guo, J., Li, R., & Jiang, X. (2023). Exploring the role of nuclear energy in the energy transition: A comparative perspective of the effects of coal, oil, natural gas, renewable energy, and nuclear power on economic growth and carbon emissions. Environmental Research, 221, 115290. https://doi.org/10.1016/j.envres.2023.115290

[15] Imran, M., Zaman, K., Nassani, A. A., Dincă, G., Khan, H. ur R., & Haffar, M. (2024). Does nuclear energy reduce carbon emissions despite using fuels and chemicals? Transition to clean energy and finance for green solutions. Geoscience Frontiers, 15(4), 101608. https://doi.org/10.1016/j.gsf.2023.101608

[16] Fattahi, A., Sijm, J., Broek, M. V. den, Gordón, R. M., Dieguez, M. S., & Faaij, A. (2022). Analyzing the techno-economic role of nuclear power in the Dutch net-zero energy system transition. Advances in Applied Energy, 7, 100103. https://doi.org/10.1016/j.adapen.2022.100103

[17] International Energy Agency (IEA). (2024). Global installed energy storage capacity by scenario, 2023 and 2030.

[18] Available at: https://www.iea.org/data-and-statistics/charts/global-installed-energy-storage-capacity-by-scenario-2023-and-2030 (Accessed 12.09.2025)

[19] REN21. (2024). Renewables 2024 Global Status Report. REN21 Secretariat, Paris. Available at: https://www.ren21.net/reports/global-status-report/ (Accessed 12.09.2025)

[20] Cornaro, A., & Kompatscher, M. (2024). Underground Space Use for Renewable Energy Production and Storage (pp. 259–265). https://doi.org/10.1007/978-981-97-1257-1_33

[21] Sambo, C., Dudun, A., Samuel, S. A., Esenenjor, P., Muhammed, N. S., & Haq, B. (2022). A review on worldwide underground hydrogen storage operating and potential fields. International Journal of Hydrogen Energy, 47(54), 22840–22880. https://doi.org/10.1016/j.ijhydene.2022.05.126

[22] 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

[23] Xi, F., Yan, R., Shi, J., Zhang, J., & Wang, R. (2022). Pumped storage power station using abandoned mine in the Yellow River basin: A feasibility analysis under the perspective of carbon neutrality. Frontiers in Environmental Science, Volume 10-2022. https://doi.org/10.3389/fenvs.2022.983319

[24] Colas, E., Klopries, E.-M., Tian, D., Kroll, M., Selzner, M., Bruecker, C., Khaledi, K., Kukla, P., Preuße, A., Sabarny, C., Schüttrumpf, H., & Amann, F. (2023). Overview of converting abandoned coal mines to underground pumped storage systems: Focus on the underground reservoir. Journal of Energy Storage, 73, 109153. https://doi.org/10.1016/j.est.2023.109153

[25] Menéndez, J., Schmidt, F., Konietzky, H., Fernández-Oro, J. M., Galdo, M., Loredo, J., & Díaz-Aguado, M. B. (2019). Stability analysis of the underground infrastructure for pumped storage hydropower plants in closed coal mines. Tunnelling and Underground Space Technology, 94, 103117. https://doi.org/10.1016/j.tust.2019.103117

[26] Zhou, A., Li, P., Fan, L., Yi, Z., Tang, X., & Fei, W. (2025). Influence of drainage system on the stability of underground CAES gas storage under different lateral pressure coefficients. Tunnelling and Underground Space Technology, 159, 106444. https://doi.org/10.1016/j.tust.2025.106444

[27] Bu, X., Huang, S., Liu, S., Yang, Y., Shu, J., Tan, X., Chen, H., & Wang, G. (2024). Efficient utilization of abandoned mines for isobaric compressed air energy storage. Energy, 311, 133392. https://doi.org/10.1016/j.energy.2024.133392

[28] Schmidt, F., Menéndez, J., Konietzky, H., Jiang, Z., Fernández-Oro, J. M., Álvarez, L., & Bernardo-Sánchez, A. (2024). Technical feasibility of lined mining tunnels in closed coal mines as underground reservoirs of compressed air energy storage systems. Journal of Energy Storage, 78, 110055. https://doi.org/10.1016/j.est.2023.110055

[29] Hunt, J. D., Zakeri, B., Jurasz, J., Tong, W., Dąbek, P. B., Brandão, R., Patro, E. R., Đurin, B., Filho, W. L., Wada, Y., Ruijven, B. v., & Riahi, K. (2023). Underground Gravity Energy Storage: A Solution for Long-Term Energy Storage. Energies, 16(2), 825. https://doi.org/10.3390/en16020825

[30] Kulpa, J., Kamiński, P., Stecuła, K., Prostański, D., Matusiak, P., Kowol, D., Kopacz, M., & Olczak, P. (2021). Technical and Economic Aspects of Electric Energy Storage in a Mine Shaft—Budryk Case Study. Energies, 14(21). https://doi.org/10.3390/en14217337

[31] Wang, Q., Guo, J., Li, R., & Jiang, X. (2023). Exploring the role of nuclear energy in the energy transition: A comparative perspective of the effects of coal, oil, natural gas, renewable energy, and nuclear power on economic growth and carbon emissions. Environmental Research, 221, 115290. https://doi.org/10.1016/j.envres.2023.115290

[32] Dong, D., Wang, Z., Guan, J., & Xiao, Y. (2025). Research on safe disposal technology and progress of radioactive nuclear waste. Nuclear Engineering and Design, 435, 113934. https://doi.org/10.1016/j.nucengdes.2025.113934

[33] Mauke, R., & Herbert, H.-J. (2015). Large scale in-situ experiments on sealing constructions in underground disposal facilities for radioactive wastes – Examples of recent BfS- and GRS-activities. Progress in Nuclear Energy, 84, 6–17. https://doi.org/10.1016/j.pnucene.2015.04.010

[34] Chapman, N., & Hooper, A. (2012). The disposal of radioactive wastes underground. Proceedings of the Geologists' Association, 123(1), 46–63. https://doi.org/10.1016/j.pgeola.2011.10.001

[35] Matos, C. R., Carneiro, J. F., & Silva, P. P. (2019). Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. Journal of Energy Storage, 21, 241–258. https://doi.org/10.1016/j.est.2018.11.023

[36] Advanced Clean Energy Storage (ACES) Delta project, https://aces-delta.com/ (Accessed 24.06.2025)

[37] China Energy Engineering Group Co., Ltd., http://en.ceec.net.cn/art/2025/1/10/art_138_2510992.html (Accessed 25.06.2025)

[38] Li, H., Ma, H., Liu, J., Zhu, S., Zhao, K., Zheng, Z., Zeng, Z., & Yang, C. (2023). Large-scale CAES in bedded rock salt: A case study in Jiangsu Province, China. Energy, 281, 128271. https://doi.org/10.1016/j.energy.2023.128271

[39] SKB, 2008. Site description of Forsmark at completion of the site investigation phase. Technical Report TR-08-05, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden (https://skb.se/publication/1868223/TR-08-05.pdf Accessed 25/06/2025)

[40] Johnson, S., (2025, January 15). Sweden starts building 100,000 year storage site for spent nuclear fuel. Reuters. https://www.reuters.com/business/energy/sweden-starts-building-100000-year-storage-site-spent-nuclear-fuel-2025-01-15/ (Accessed 25.06.2025)

[41] Young, R. P., Nasseri, M. H. B., & Sehizadeh, M. (2020). Mechanical and seismic anisotropy of rocks from the ONKALO underground rock characterization facility. International Journal of Rock Mechanics and Mining Sciences, 126, 104190. https://doi.org/10.1016/j.ijrmms.2019.104190

[42] Posiva Oy, (2024). Introducing ONKALO and its principle of operation, https://www.posiva.fi/en/index/news/pressreleasesstockexchangereleases/2024/thisisonkaloandthisishowitworks.html (Accessed 25.06.2025)