

# Simulation-based design of world's largest cavern thermal energy storage: Optimization of VARANTO

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## Abstract

As the global energy transition advances, cavern thermal energy storage (CTES) emerges as a key technology for large-scale, seasonal thermal energy storage within sustainable district heating networks. Thanks to its capability for storing massive quantities of thermal energy, CTES systems can balance the temporal mismatch between renewable energy supply and heat demand, improve system flexibility and support decarbonization. However, the planning and design of such large, pressurized underground systems are complex, requiring detailed assessment of the coupled thermal-hydraulic-mechanical processes that might undermine both performance and structural stability.

This study presents a simulation-driven planning approach for the world's largest CTES system (VARANTO) to be realized in three interconnected rock caverns. The system is designed to store pressurized water up to 140°C, introducing significant thermo-mechanical stresses and deformation risks within the surrounding rock mass. To address these challenges, a comprehensive model is developed in COMSOL Multiphysics® capturing transient heat transfer, groundwater interactions and stress evolution.

Simulation outcomes guide the optimization of CTES geometry, spatial configuration and orientation, ensuring maximum storage efficiency and long-term integrity. The results demonstrate how multiphysics modeling provides critical insight into thermal performance and geomechanical safety, offering a transferable framework for the design of next-generation underground energy storage systems.

**Keywords:** Cavern thermal energy storage; seasonal thermal energy storage; thermal-hydraulic-mechanical (THM) modeling; VARANTO.

## Introduction

The energy transition in urban areas faces a structural dilemma [1]. While the share of renewable energy sources (RESs) continues to grow, the temporal and spatial mismatch between energy generation and consumption remains a central challenge [2]. Approximately 50% of the EU's final energy consumption is used for heating – the majority of which is concentrated in cities, where opportunities for energy production and storage are severely limited.

In densely built environments, conventional above-ground thermal energy storage (TES) systems, such as large-scale tanks, are often infeasible due to high land costs, infrastructure bottleneck, limited space and societal resistance [3]. At the same time, the acceleration of urbanization further overloads existing thermal networks (i.e. district heating and cooling networks).

Underground thermal energy storage (UTES) offers a strategic solution by enabling seasonal decoupling of thermal energy generation (heat availability such as solar) and consumption (e.g., space heating demand) [4]. Technologies such as aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), tank thermal energy storage

(TTES), pit thermal energy storage (PTES), and cavern thermal energy storage (CTES) exploit the thermal inertia of the subsurface to store energy over months while requiring minimal surface [5].

Studies [3] and [4] indicate that ATES and BTES have lower energy density than TTES and PTES, which translates into higher charging and discharging rates for TTES and PTES. TTES is well-suited for high temperatures (>120°C), while PTES operates efficiently up to 90°C with feasible capital expenditure. However, large TTES (>40,000 m<sup>3</sup>) requires specialized geotechnical construction methods such as diaphragm walls and anchors, which drives the costs above 500 €/m<sup>3</sup> [6]. PTES, though established in Denmark (e.g., Marstal, Dornninglund, Gram), faces limitations at temperatures above 90°C and challenges in regions with high groundwater tables like Austria, where cut-off walls and insulation layers are required [7]. This raises specific costs up to ~250 €/m<sup>3</sup>. Moreover, for urban applications, PTES covers must be trafficable, adding further design complexity.

Thus, CTES emerges as a promising alternative for district heating and cooling, balancing feasibility, capacity, and visibility. Pilot projects in Finland ([INTERSTORES](#)) and Austrian initiatives ([HEATROCK](#)) demonstrate its technical and economic potential in complex urban contexts.

Despite the technical maturity of CTES, several critical research gaps hinder the large-scale implementation in dense urban areas. First, the long-term geological stability of rock formations under cyclic high-temperature loading remains insufficiently understood, raising concerns about structural integrity and durability. Second, existing modeling tools are often inadequate to simulate large-scale urban integration, dynamic heat demand, and transient system behavior, leading to the limitation of reliable planning, design and operational optimization. Furthermore, the existing models do not cover the full span of aspects (i.e. thermal-hydraulic-mechanical-chemical) as they are strongly interconnected and affect each other.

This work presents a simulation-driven planning and layout approach for the world’s largest CTES system – VARANTO, which will be realized within three adjacent rock caverns. The system is designed to store pressurized water at temperatures of up to 140°C, which introduces significant thermo-mechanical stress conditions and the potential for deformation in fault and fracture zones in vicinity of the caverns. Besides, these are potential local zones for groundwater flow, as well, which will introduce great risk for increased thermal losses [8]. Groundwater flow coming from outside of environment is roughly at temperature of 7°C, and thus temperature difference between storage and groundwater becomes very high. Consequently, a robust and integrated simulation methodology is essential for ensuring both maximum storage efficiency and long-term structural integrity.

## Methodology

### DePlaTES Framework

COMSOL Multiphysics® serves as an effective platform for modeling and analyzing the coupled multiphysical processes associated with various geometrical configurations of thermal energy storage (TES) systems such as cavern TES. The software’s axisymmetric modeling capability allows the simulation of circular geometries in a two-dimensional (2D) domain, thereby significantly reducing computational demand. Thus, the model was firstly developed as an axisymmetric planning toolkit targeting sTES types with circular cross section (e.g., cone pit, cylindrical tank) as reported in [9]. However, investigations involving groundwater flow or non-circular geometries require fully three-dimensional (3D) simulations. To address such cases, the authors developed a detailed planning model for sTES systems known as “DePlaTES” within the COMSOL Multiphysics® environment. The structure and workflow of DePlaTES – considered as a comprehensive planning toolkit for large-scale, seasonal TES applications – are illustrated in Figure 1 and further described in [10] and [8].

The DePlaTES toolkit comprises two principal components: one representing the sTES system itself and another describing the subsurface environment hosting the storage. DePlaTES offers extensive flexibility in configuring sTES designs, including construction type (partially or fully buried), geometry (tank, shallow pit, or cavern), storage medium (e.g., water, gravel, or sand), number and arrangement of charging/discharging ports and insulation materials.

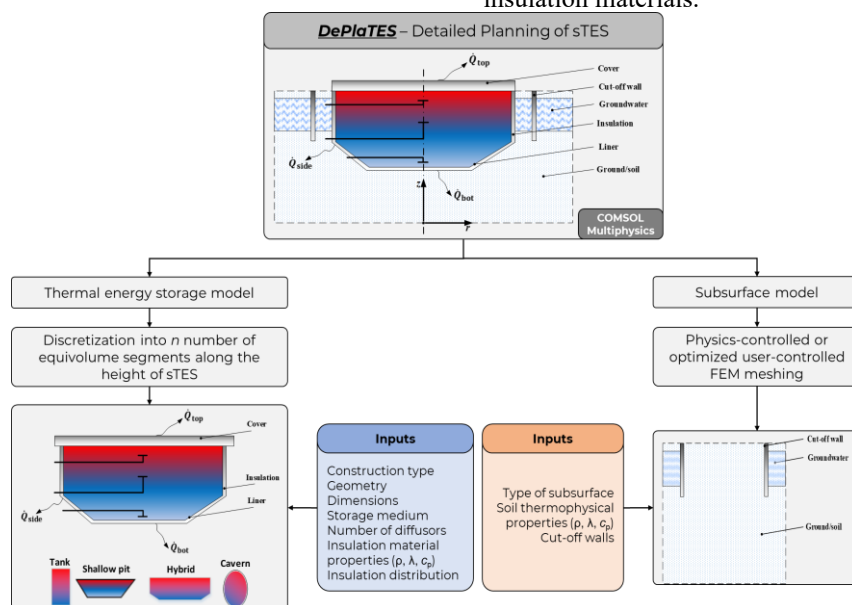


Figure 1: Structure of DePlaTES as implemented in COMSOL Multiphysics®, DePlaTES encompasses two sub models one considers large-scale TES (left-hand side) and the other focuses on the subsurface (right-hand side) [10].

Moreover, the subsurface module allows users to define groundwater presence and flow conditions, heterogeneous soil layers, and other geotechnical parameters. The user can specify the intended location of the sTES installation, prompting the toolkit to automatically import reference meteorological data for that site. Alternatively, measured local data can be imported if available.

The *DePlaTES* framework has been validated and benchmarked in several studies to obtain trust and confidence in its predictive capability. Further details on the model development, structure and validation can be found in [10] and [8].

It is worthy to point out, however, that the current version of the *DePlaTES* toolkit does not account for geomechanical processes, which represents its main limitation. Future developments will address this by integrating the geomechanics module to capture the complete coupled thermo-hydro-mechanical (THM) behavior of the storage system leading to position *DePlaTES* as a THM planning toolkit.

#### Modeling and Simulation Framework

The modeling workflow adopted in this study is illustrated in Figure 2. The process integrates field data acquisition and measurements, geometry development, numerical refinement and multi-physics simulation stages within the COMSOL Multiphysics® to ensure a consistent approach to coupled thermal-hydrological modeling of VARANTO system.

The workflow starts with the collection and preprocessing of existing datasets including the geometric and operational characteristics of the VARANTO as well as site-specific subsurface data. These datasets serve for the geometry development stage and involves defining the system configuration, boundary conditions and representative material domains.

Subsequently, initial simulations are conducted focusing on the subsurface domain to evaluate boundary conditions, temperature gradients and preliminary heat transfer behavior. The results of these initial runs inform the refinement stage during which mesh density, solver configurations and time-step can be optimized to ensure numerical stability and accuracy while maintaining computational efficiency.

After refinement (manual user-controlled refinement via parametric sweep with focus on element type, size and distribution), new simulation campaigns are executed to capture the fully coupled behavior of the CTES and subsurface system, including transient heat transfer between VARANTO and surroundings. Building upon these results, additional simulations are carried out to assess hydrogeological aspects such as groundwater flow and its influence on heat dispersion.

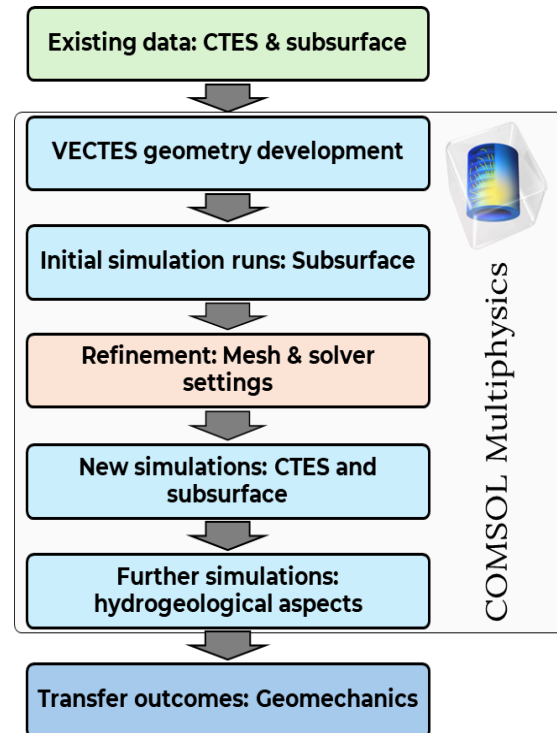


Figure 2: Modelling and simulation framework for the VARANTO demo-site for THM purposes.

Finally, the numerical outcomes of these simulations are transferred to a subsequent geomechanical model developed in Leapfrog Geo to evaluate potential mechanical impacts, such as thermal-induced deformation or stress redistribution in the surrounding ground. This step serves as a preparatory stage for future integration of THM coupling within the COMSOL Multiphysics®.

#### Simulation Setup

In the geometry development stage, the detailed configuration of the VARANTO system, including the storage volume and the associated charging and discharging channels, was created within the COMSOL Multiphysics® environment. Appropriate physics interfaces (e.g., *Heat Transfer in Solids and Fluids* module) were subsequently integrated to capture the relevant coupled thermal and fluid-dynamic processes.

Figure 3 illustrates VARANTO geometry and indicates the direction of fluid flow during charging. During discharging, the flow direction is reversed consistent with the operating principle of VARANTO as a stratified CTES. The key design parameters and boundary conditions in the simulations are summarized in **Table 1**, whereas the thermophysical properties used for the simulations are reported in Table 2.

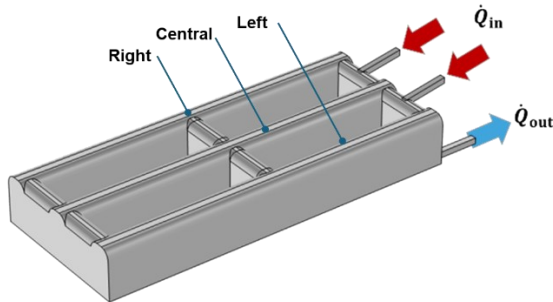


Figure 3: VARANTO initial design – VARANTO I.

Table 1: Key design parameters for VARANTO I.

Parameter	Value
Cavern length, $L_{\text{cavern}}$	310 m
Cavern width, $W_{\text{cavern}}$	22 m
Cavern height, $H_{\text{cavern}}$	41.6 m
Cavern upper radius, $R_{\text{cavern}}$	
Single cavern volume, $V_{\text{cavern}}$	333,333.3 m <sup>3</sup>
Total VARANTO width, $W_{\text{tot}}$	130 m
Total VARANTO volume, $V_{\text{tot}}$	1,000,000 m <sup>3</sup>

Table 2: Thermophysical properties and initial boundary condition used in the simulations.

Parameter	Value
Water thermal conductivity	0.6 W/(m·K)
Water specific heat capacity	4186 J/(kg·K)
Water density	988 kg/m <sup>3</sup>
Rock thermal conductivity	3.6 W/(m·K)
Rock specific heat capacity	724 J/(kg·K)
Rock density	2759 kg/m <sup>3</sup>
Initial bedrock temperature	279.17K - $\left(\frac{0.0466}{3.6 \cdot z}\right)$

The simulation setup is shown in Figure 4 and it couples *heat transfer in fluids* with *turbulent flow* to capture convection and buoyancy-driven effects within the VARANTO system, while *heat transfer and thermal stress in solids* capture conduction and thermally induced deformation in structural components. Additionally, *electrochemistry and corrosion* modules are planned for integration in *DePlaTES* to evaluate material degradation processes in VARANTO envelope.

To reduce computational complexity, a purely seasonal operation profile is adopted. During the charging phase, hot water is injected at a temperature of 95°C, while 45°C is the temperature for the injected water during discharging. The injection flow rate corresponds to the entire cavern volume (per single cavern) circulated uniformly over each charging or discharging period of three months.

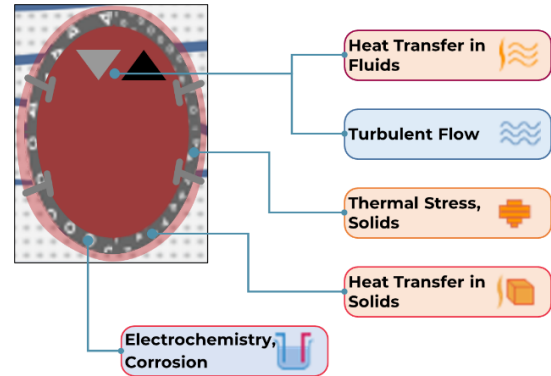


Figure 4: An illustrative sketch for a single cavern showing model setup and used/planned modules for the simulation of VARANTO CTES system.

## Simulation Results and Discussion

### Mesh Generation

The generated geometry was meshed using a non-uniform, user-controlled grid with local refinement near the charging/discharging channels, cavern boundaries, and regions exhibiting steep temperature gradients. A systematic mesh-independence analysis was performed to ensure that variations in key output parameters (e.g., thermal losses) remained within 2%. The optimal discretization was achieved through a hybrid meshing approach employing a mapped distribution within the cavern domain and free tetrahedral elements in the surrounding rock mass.

Within the caverns, each segment dimension was restricted to 1 m leading to equivolume elements along both the vertical and longitudinal directions. In the surrounding rock domain, the minimum element size was set to 1.05 m with an element growth rate of 1.35 resulting in a maximum element size of 24.5 m. This configuration provided a trade-off between computational efficiency and spatial resolution.

### Estimation of Thermal Losses

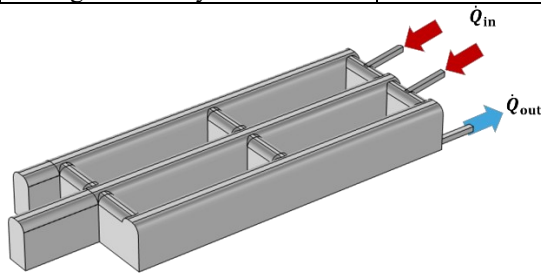
An essential key performance indicator (KPI) of sTES systems is the amount of heat lost to the surrounding ground (i.e. rock mass) during a complete storage cycle. For the VARANTO configuration, the total storage capacity is estimated at 57.5 GWh with a temperature difference of 50 K<sup>1</sup>, of which approx. 21.28 GWh are lost to the surrounding rock mass. This corresponds to an overall storage efficiency of 63%, resulting in a useful storage capacity of 36.23 GWh and effective storage volume of 630,000 m<sup>3</sup> as summarized in **Table 3**.

It was found that the high heat fluxes near the left section could enhance the fracture zones leading to further propagation within under the given geological conditions posing potential geomechanical risks for long-term operation.

Consequently, the design was optimized to VARANTO II shown in Figure 5 to minimize stress concentrations, thereby improving both thermal performance and geomechanical reliability. The VARANTO II configuration resulted from an iterative optimization framework involving multiple key design parameters (Figure 2), including cavern length, spacing and alignment. The final geometry showed (Figure 5) represents the optimal result that meets both thermal performance requirements (minimizing critical heat fluxes) and geological constraints related to rock stability and deformation zones.

*Table 3: Summary of KPIs for the initial design – VARANTO I.*

VARANTO I	
Storage capacity	57.5 GWh
Total thermal losses	21.275 GWh
Useful storage capacity	36.225 GWh
Storage efficiency	63%



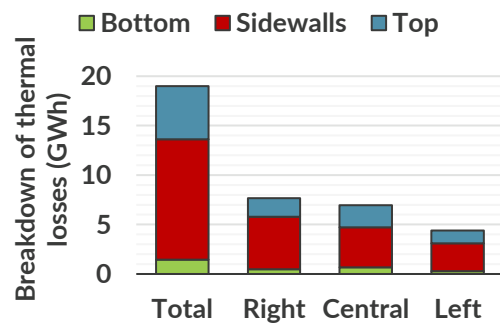
*Figure 5: VARANTO optimized design – VARANTO II.*

In the optimized configuration, the central cavern – the longest - exhibits the highest losses (6.93 GWh), followed by the right (7.65 GWh) and left (4.42 GWh) caverns. These differences are primarily linked to geometric and boundary variations, including differences in rock thermal conductivity and flow distribution between the caverns.

*Table 4: Summary of KPIs for the optimized design – VARANTO II.*

VARANTO II	
Storage capacity	57.5 GWh
Total thermal losses	19 GWh
Useful storage capacity	38.5 GWh
Storage efficiency	67%
Breakdown of thermal losses	
Top	5.4 GWh
Sidewalls	12.17 GWh
Bottom	1.43 GWh
Share of thermal losses	
Right	7.65 GWh
Central	6.93 GWh
Left	4.42 GWh

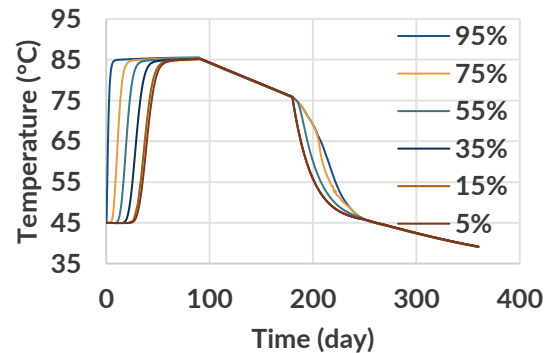
The breakdown of thermal losses is shown in Figure 6 reveals that the sidewalls account for the largest share with approx. 12.17 GWh (~ 64%) of the total losses due to the largest heat exchange area, followed by the top contribution with 5.4 GWh (~ 28%), and the bottom contributing only 1.43 GWh (~ 8%). The outcomes emphasize the need for enhanced lateral insulation and improved flow management to further minimize sidewall losses and increase the long-term efficiency of VARANTO CTES systems.



*Figure 6: Breakdown of thermal losses for the optimized design – VARANTO II.*

### Temperature evolution

The evolution of VARANTO temperature is shown in Figure 7. The profiles represent temperature variations at different vertical positions within the storage volume expressed as relative height of the total height (5-95%). During the charging phase (Days 0-90), the temperature rapidly increases to approximately 85°C despite the injection temperature of 95°C due to the high storage losses. The upper layers reach higher temperatures earlier due to buoyancy-driven flow and reduced thermal inertia, whereas the lower zones experience a delayed response.



*Figure 7: Temperature evolution in VARANTO CTES system during an annual operation cycle.*

During the storage phase (Days 90-180), the temperature gradually declines with the same rate due to the fast internal mixing and absence of

insulation in caverns envelope. Later, in the discharging phase (Days 180-270), the temperature rapidly decreases as water is injected at 45°C. The progressive downward shift of the thermal front indicates a stable stratified regime throughout the operation cycle.

It is noteworthy to highlight that the nearly uniform cooling across all relative heights of VARANTO results from the dominance of the fast mixing driven by the buoyancy-induced natural convection during the storage phase. Accordingly:

$$Ra = \frac{g\beta\Delta TH^3}{\nu\alpha} \quad (1)$$

Whereby Ra remains largely above the critical threshold of approx. 1700 [11], indicating that buoyancy-driven convection is dominant and fast. Consequently, heat transfer is primarily fast natural convection, leading to a quasi-uniform temperature decay throughout the storage domain (max. temperature difference in the cavern is approx. 0.5 K). This is also attributed to the to non-insulated cavern envelope with the caverns reaching a quasi-steady temperature by end of charging phase.

#### Geological Characterization and Model Integration

Geological investigations involved characterizing lithological units (rock types), their thermal and mechanical properties, and identifying deformation zones such as fractures and fault zones. A geological model was developed using Leapfrog Geo modeling software, from which lithological units and deformation zones will be imported into COMSOL for thermo-hydro-mechanical (THM) modeling.

Geologically, VARANTO site is extremely heterogeneous, comprising granitic, migmatitic, and mica gneissic high-grade metamorphic rocks, as well as altered rocks resulted from fluid interactions. The site also contains several deformation zones, which pose increased risks for groundwater flow within the bedrock. Therefore, such zones can impact storage economics in two key aspects: they increase heat losses if groundwater flow is present, and they may require a stronger support system due to mechanically weaker rock. However, in crystalline rock environments, these challenges can largely be mitigated through careful geological and THMC design optimization.

Each lithological unit is described using representative numerical values derived from thermal and mechanical laboratory and in-situ measurements, with uncertainty also considered. Additionally, deformation zones are characterized by hydrogeological and mechanical parameters, which are based on field measurements and geological observations. Figure 8 illustrates the workflow from geological observation of

deformation zones to the construction of a COMSOL model. In this model, groundwater flow is simulated within the deformation zone, integrating both geological and hydrogeological data.

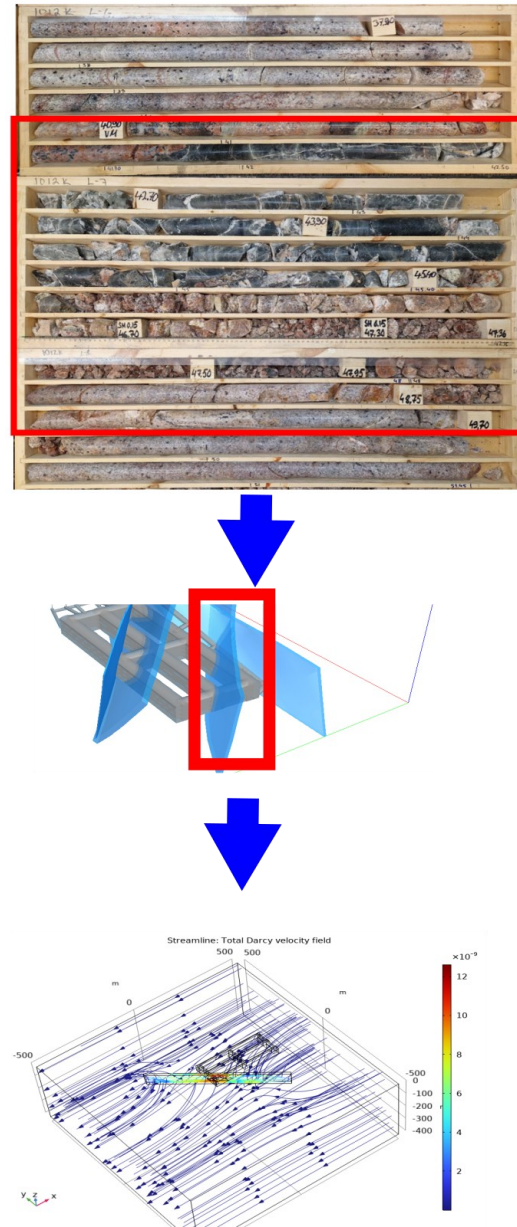


Figure 8: Top: deformation zone observed in drill cores. Middle: Modelled vertical deformation zones in Leapfrog Geo. Bottom: Simulated Darcy velocity fields illustrating groundwater flow within highlighted deformation zone (COMSOL)

#### Conclusions and Outlook

This work presented a simulation-based design and optimization framework for the VARANTO cavern thermal energy storage (CTES) system, currently the world's largest facility of its kind. With the aid COMSOL Multiphysics® and Leapfrog Geo, a series of coupled thermo-hydro-mechanical (THM) analyses were conducted to evaluate and enhance the

system's thermal efficiency, hydraulic behavior and geomechanical stability.

The optimization process led to the VARANTO II configuration, which reduced total thermal losses and improved overall storage efficiency from 63% to 67%. The findings highlighted the critical interplay between geometry and rock properties, demonstrating that integrated multiphysics modeling is essential for safe and efficient large-scale CTES operation.

Future work will focus on model validation through field data from the operational VARANTO plant and the integration of fully coupled THM simulations to capture long-term cyclic stresses. The extension of this digital framework toward techno-economic and life-cycle assessments will further support decision-making for next-generation underground thermal energy storage systems, reinforcing their role in sustainable district heating networks.

## References

- [1] G. Martínez Görbig, J. Flacke, R. Sliuzas and D. Reckien, "Unveiling energy poverty risk: A multidimensional analysis of the heat-or-eat dilemma," *Energy Research & Social Science*, vol. 125, 2025.
- [2] H. Mahon, D. O'Connor, D. Friedrich and B. Hughes, "A review of thermal energy storage technologies for seasonal loops," *Energy*, vol. 239, no. Part C, 2022.
- [3] A. Dahash, F. Ochs, M. Bianchi Janetti and W. Streicher, "Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems," *Applied Energy*, vol. 239, pp. 296-315, 2019.
- [4] C. Bott, I. Dressel and P. Bayer, "State-of-technology review of water-based closed seasonal thermal energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 113, 2019.
- [5] X. Zhou, Y. Xu, X. Zhang, D. Xu, Y. Linghu, H. Guo, Z. Wang and H. Chen, "Large scale underground seasonal thermal energy storage in China," *Journal of Energy Storage*, vol. 33, 2021.
- [6] A. Dahash, F. Ochs and A. Tosatto, "Techno-economic and exergy analysis of tank and pit thermal energy storage for renewables district heating systems," *Renewable Energy*, vol. 180, pp. 1358-1379, 2021.
- [7] C. Bott, A. Dahash, M. Noethen and P. Bayer, "Influence of thermal energy storage basins on the subsurface and shallow groundwater," *Journal of Energy Storage*, vol. 92, 2024.
- [8] A. Dahash, F. Ochs, G. Giuliani and A. Tosatto, "Understanding the interaction between groundwater and large-scale underground hot-water tanks and pits," *Sustainable Cities and Society*, 2021.
- [9] A. Dahash, M. Bianchi Janetti and F. Ochs, "Detailed Axial Symmetrical Model of Large-Scale Underground Thermal Energy Storage," in *Proceedings of the 2018 COMSOL Conference*, Lausanne (Switzerland), 22-24 October 2018, 2018.
- [10] A. Dahash, F. Ochs, A. Tosatto and W. Streicher, "Toward Efficient Numerical Modeling and Analysis of Large-Scale Thermal Energy Storage for Renewable District Heating Systems," *Applied Energy*, vol. 279, 2020.
- [11] J. S. Turner, *Buoyancy Effects in Fluids*, Cambridge : Cambridge University Press, 1973.

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<sup>i</sup> VARANTO CTES system is planned to operate with a temperature difference of 100 K with a maximum storage temperature of 140°C.