# Simulation-based Design Of World's Largest Cavern Thermal Energy Storage: Optimization Of VARANTO

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## Abstract

As the global energy transition accelerates, large-scale seasonal thermal energy storage systems are becoming critical components of future sustainable and resilient district heating networks. Among various storage technologies, cavern thermal energy storage (CTES) offers a promising solution by enabling the storage of vast quantities of thermal energy underground with minimal land footprint. CTES systems can effectively bridge the temporal gap between renewable energy supply and heat demand, thereby enhancing the flexibility and efficiency of district heating systems and supporting decarbonization goals. Moreover, CTES systems can optimize the operation of combined heat and power with water incineration plants as they produce heat year-round including summer when heating demand is at lowest. Thus, CTES systems emerge as a crucial component for energy transition.
However, the planning and layout of CTES systems present substantial engineering challenges, particularly because they are large-scale, underground caverns. A reliable system design must consider the complex interactions between the stored thermal energy and the surrounding host rock. These interactions not only affect thermal performance but also influence mechanical stability, especially when storing pressurized hot water at high temperatures (i.e. thermal stresses).
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. Consequently, a robust and integrated simulation methodology is essential for ensuring both maximum storage efficiency and long-term structural integrity.
To address these challenges, we developed a comprehensive thermo-hydraulic-mechanical (THM) model using COMSOL Multiphysics®. The model simulates key performance aspects such as charging/discharging channels, temperature stratification, heat losses to the surrounding ground, groundwater interactions, and future stress development within the rock mass. The simulation results were used to inform and optimize the geometrical configuration of the caverns, including their spatial arrangement and orientation to maximize storage capacity while minimizing thermal losses and maintaining rock stability.
The work will showcase recent simulation results that are directly integrated into the design and planning phase of the CTES project. These include evaluations of temperature fields over time, heat flux profiles at the cavern boundaries, and future work will present induced mechanical stresses across different lithological units and geological structures. Special attention is given to modeling deformation zones and assessing their impact on both heat transfer and structural reliability.
In summary, this contribution demonstrates how multiphysics modeling plays a central role in the realization of next-generation underground thermal energy storage, offering key insights into performance optimization and risk mitigation. The approaches developed in INTERSTORES project are not only critical for the current CTES system but also provide a transferable framework for future large-scale energy storage solutions worldwide

## Figures used in the abstract

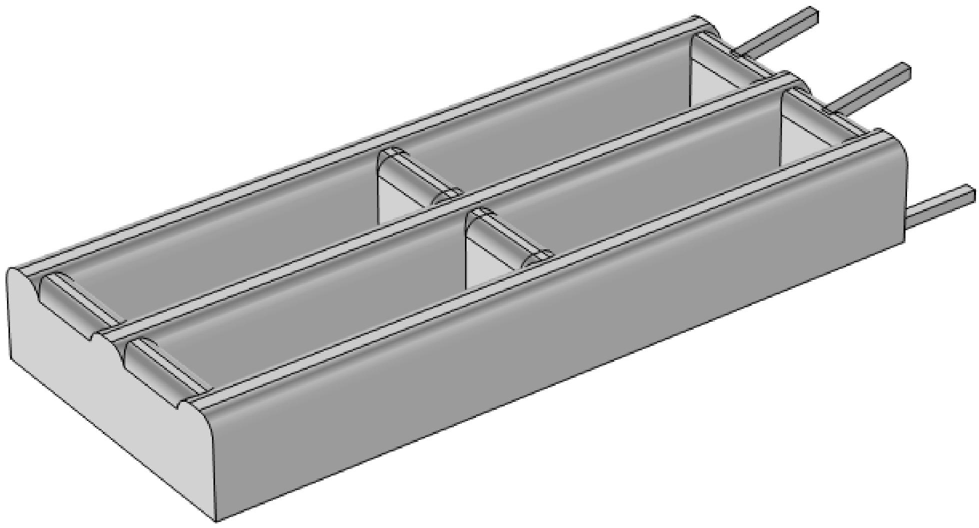


**Figure 1** : VARANTO cavern thermal energy storage with three caverns - old layout and design

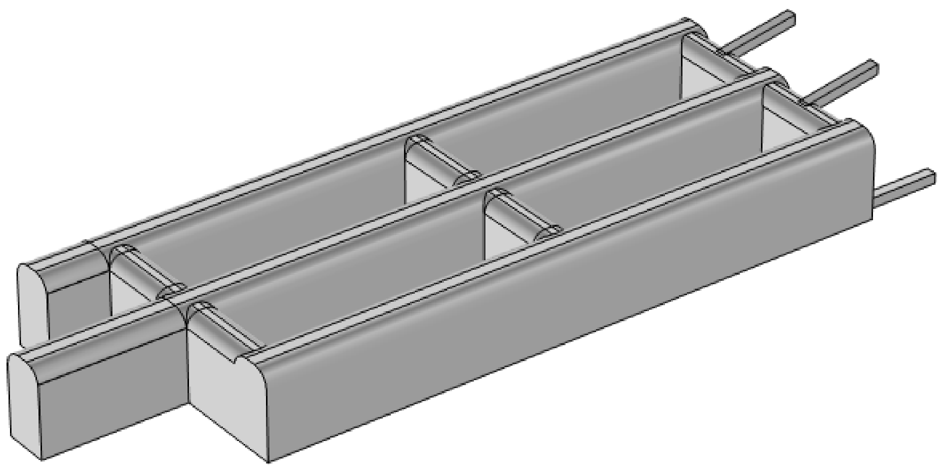
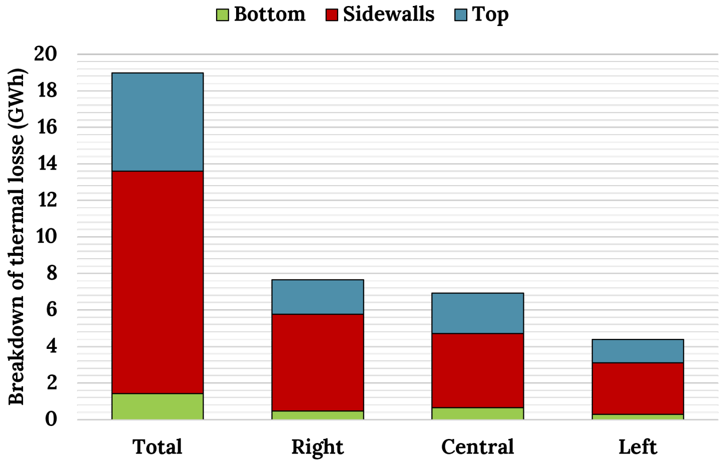


**Figure 2** : VARANTO cavern thermal energy storage with three caverns - new layout and design optimized with COMSOL




| VECTES | | |
|---|---|---|
| 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 |

**Figure 3** : Breakdown of thermal losses for the new design of VARANTO