EuroSun2026

PERFORMANCE OF LARGE-SCALE UNDERGROUND THERMAL ENERGY STORAGE FOR DISTRICT HEATING AND COOLING APPLICATIONS

Summary

Underground thermal energy storage (UTES) is a key enabling technology for district heating and cooling systems by bridging the seasonal mismatch between supply and demand. While pit thermal energy storage (PTES) systems are widely studied, the influence of storage media such as water-gravel and sand on thermo-hydraulic behavior, structural requirements and economic performance remains insufficiently explored. This study presents a comparative assessment of three PTES configurations operating under identical boundary conditions but differing in storage medium and charging/discharging approach. Multiphysics modelling is employed to analyze thermo-hydraulic behavior, stratification and heat transfer mechanisms at the component level, while system-level simulations evaluate techno-economic performance and CO_2 emission reduction. Results show that water-based PTES achieves superior thermal stratification and efficiency, whereas water-gravel and sand PTES offer improved structural stability and reduced construction complexity and economic.

Keywords: Underground thermal energy storage, water-gravel pit thermal energy storage, district heating, sector coupling, techno-economic analysis.

Field of application for the findings: District heating and cooling systems, underground thermal energy storage, renewable heat integration, energy system planning.

Addressed audience: Researchers, energy system planners, district heating and cooling operators, technology developers, policy makers.

1. Introduction

Underground thermal energy storage (UTES) systems play a critical role in the integration of renewable heat sources into district heating and cooling networks (DHCNs) by compensating for the seasonal mismatch between thermal energy availability and demand (Dahash et al., 2019). These systems, commonly referred to as seasonal thermal energy storage (sTES), enable long-term thermal energy storage and support sector coupling strategies. Among available technologies, pit thermal energy storage (PTES) receives considerable attention due to its scalability and relatively low specific investment cost (Bott et al., 2019).

Previous research primarily focused on water-based PTES concepts investigating thermal stratification, system integration aspects and coupling with heat pumps. However, the use of alternative storage media such as water-gravel mixtures or sand introduces different thermo-physical and mechanical properties that may significantly influence storage performance, construction requirements and economic feasibility (Dahash et al., 2025). A systematic comparison of these configurations under consistent boundary conditions remains limited.

This work aims to provide a comprehensive comparison of different PTES configurations with respect to technical performance, economic viability and environmental impact. The work numerically investigates the impact of the storage medium considering alternatives to water-based PTES systems.

2. Methodology

Three PTES configurations are analyzed under identical design and operational conditions, differing in storage medium and heat transfer concept:

i. a water-based PTES employing diffusers enabling direct heat exchange,

ii. a water-gravel storage using embedded heat exchangers for indirect heat transfer,

iii. a sand-based storage employing indirect heat transfer via heat exchangers.

At component level, thermo-hydraulic behavior, heat transfer mechanisms, thermal stratification and thermal losses are analyzed using Multiphysics simulation models (Detailed Planning of sTES toolkit – *DePlaTES*) calibrated with experimental and literature data (Dahash et al., 2026). Particular attention is given to the mechanical implications of the storage medium, as granular materials provide increased structural stability compared to pure water storage systems. This affects structural design requirements, including cover stability and reinforcement needs. Material properties such as volumetric heat capacity, thermal conductivity and thermal diffusivity are evaluated to quantify their influence on storage dynamics and performance. A techno-economic framework is applied to compare capital and operational expenditures. Environmental performance is evaluated through avoided fossil fuel consumption and associated CO_2 emissions reductions.

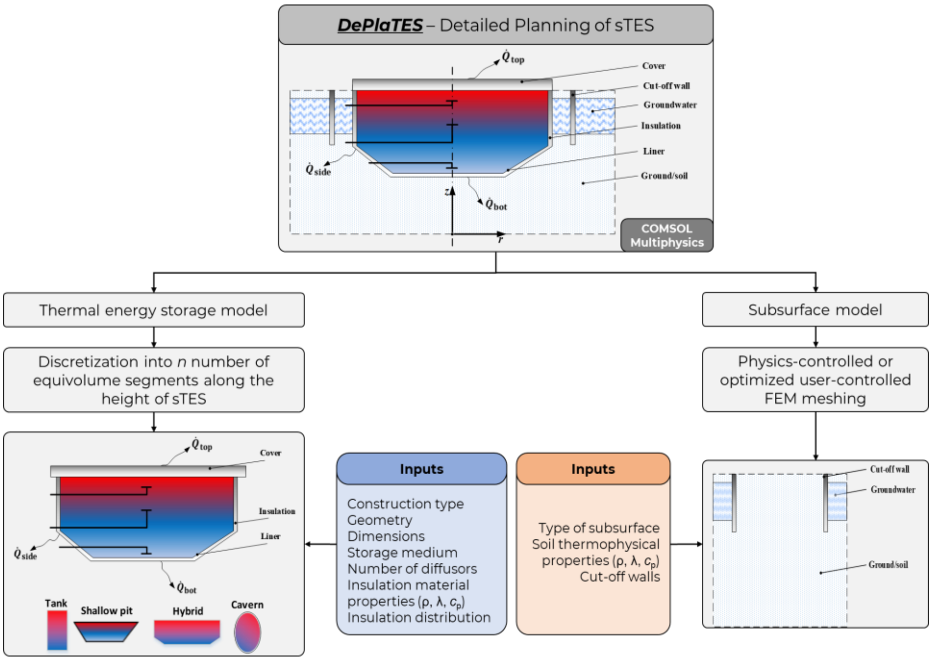

Fig. 1: Structure of DePlaTES as implemented in COMSOL Multiphysics®. DePlaTES encompasses two sub models, one considers large-scale TES (left-hand side) and the other focuses on the subsurface (right-hand side).

3. Results and Discussion

Results indicate that storage medium significantly influences both thermal performance and structural requirements. In this context, water-based PTES demonstrates superior thermal stratification behavior and high storage efficiency due to direct heat exchange and favorable thermophysical properties of storage medium. However, structural design requirements for the storage cover are more challenging due to hydrostatic loads resulting in increased material use and higher investment cost.

On a brighter note, water-gravel and sand storages exhibit enhanced mechanical stability due to the structural properties of granular materials. These configurations reduce requirements for complex cover reinforcement and enable simpler construction concepts. Although their effective volumetric heat capacity is lower compared to water-based systems, reduced structural complexity results in lower capital costs and lower embodied environmental impact.

At system level, all configurations enable seasonal load shifting and support the integration of renewable heat sources. The water-gravel configuration presents a balanced trade-off between thermal performance, investment cost and environmental impact.

4. Conclusion

This study demonstrated the importance of storage medium selection for the performance and feasibility of large-scale, underground, seasonal thermal energy storage systems. While water-based PTES provides high thermal efficiency and strong stratification characteristics, water–gravel and sand-based configurations offer advantages in structural stability, construction complexity, and embodied environmental impact. The presented comparative assessment supported informed decision-making for the design and implementation of underground thermal energy storage systems in district heating and cooling networks. Future work will focus on optimization of heat exchanger configurations and integration strategies for improved system-level performance.

5. References

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