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INVESTIGATING THE IMPACT OF GROUNDWATER ON THE THERMAL LOSSES OF UNDERGROUND LARGE THERMAL ENERGY STORAGE SYSTEMS

Summary

The integration of large scale thermal energy storage (TES) systems is essential to increase the share of renewable energy in energy systems. However, underground TES installations may face technical challenges in areas with shallow groundwater (GW), where advective heat transport can increase the TES losses, affecting storage performance and increasing the GW temperature. Numerical modelling of TES allow to quantify these effects, but the implementation of models able to integrate the effects of GW may be challenging in terms of numerical effort and model complexity. In this work the GW flow field is computed in a preliminary step and then incorporated into the finite element soil domain. Three GW configurations are analysed: flow intersecting the upper TES zone, intersecting the lower zone, and flowing directly below the storage. The parameters used to assess this influence are the TES thermal losses and thermal stratification and the GW temperature downstream of the TES, the results are cross-compared with results from other tools and the simulation time is compared with the one of similar models.

Keywords: Thermal Energy Storage, Groundwater, modelling, thermal losses

Field of application for the findings: Thermal Energy Storage, Sustainable Energy Infrastructure

Addressed audience: scientific audience, planners, decision makers

1. Introduction

Supporting the energy transition in the building sector requires the integration of renewable energy sources, characterised by seasonal and daily oscillation. Solar District Heating (DH) systems are direct application of this integration, with the first plants built in Sweden and the most recent and successful developments in Denmark and China ((IEA) 2024). Thermal energy storage (TES) systems allow to decouple energy generation and demand to facilitate the integration of renewable energy sources and are a key element of solar (DH), but they can be effectively coupled also with cogeneration plants and heat pumps. A challenge of the integration of this type of systems on the district scale is however related to the large volumes required, which call for the necessity to build underground systems in order to meet social acceptance.

Water-based tank and pit TES in particular allow the highest storage densities and temperatures among the four types, and hence the most flexible integration within the district heating network and with several generation systems (Schmidt et al. 2018). A drawback of these systems is however related to the higher investment costs (Lüchinger et al. 2025), although economies of scale make it possible to reduce the price per cubic metre of storage by increasing its size. Increasing the size of the water based TES (whether tank or pit) may result in reaching the eventually present groundwater (GW) table, as schematically presented in Fig. 1. The high storage temperature results in significant temperature gradients between the TES and the surrounding soil, leading to high thermal losses, which reduce the energy available for discharge, and thus decrease its performance (Tosatto et al. 2025). Moreover, from the environmental perspective, high soil temperatures, especially in presence of GW are an undesired effect, as they increase the transport of contaminants and affect the local microbial balance (Blum et al. 2021) (Motamedi et al. 2026). The influence of these thermal losses needs to be evaluated both from the TES perspective and from the local environment (i.e. the soil).

In order to minimize the interaction between TES and GW, geotechnical measures like cut-off walls, i.e. impermeable barriers used in geotechnics to restrict the horizontal movement of liquids, in combination with pumping wells can be considered.

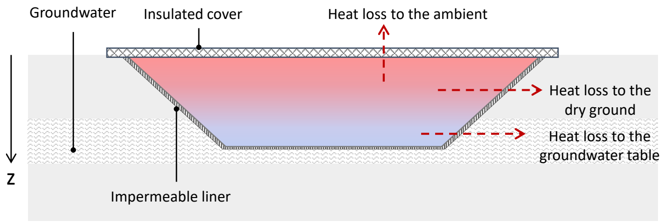

Fig. 1: Characteristic design of pit TES storage and representation of the thermal losses components in presence of GW.

The effect of GW flow on the TES performance has been studied by several authors. Dahash et al. (2021) conducted a detailed investigation on the twofold interaction between the GW and the TES using a finite element model of the TES coupled with the surrounding ground (and GW table) implemented in COMSOL Multiphysics. Sifnaios et al. (2023) investigated the possible effects of GW on the Marstal pit TES implementing a 3D model in ANSYS Fluent: in this study however the authors focused on the heat losses towards the ground while the water temperature inside the TES was applied as boundary condition. The authors investigated also different cases of GW depth. Bott et al. (2024) applied a co-simulation approach to investigate the effect of GW flow on a buried water gravel TES, modelled in MATLAB/ Simulink, while a 3D multiphysical model of the surrounding ground and groundwater is implemented in COMSOL Multiphysics.

A critical aspect observed by many authors is the significant computational effort required by models coupling GW flow and TES operation. Within the framework of the IEA ES TCP Task 45, different TES models are verified and their ability to represent the effects of GW is compared.

2. Method

Defining an effective modelling set-up to investigate the interaction between GW and underground TES is fundamental to support a design that complies to specific environmental requirements for GW protection and to ensure an optimal performance (i.e., energy discharge). For the detailed modelling of underground large TES systems, the use of tools like COMSOL Multiphysics allows to extend the analysis to include the GW flow using the Darcy equation. In presence of GW flow, a 3D model is necessary for a complete representation of the involved heat transfer mechanisms, thus increasing the complexity in the evaluation of the coupling effects (i.e., the thermal losses) between the TES and the ground. The energy balance for the TES is described using eq. 1, where the thermal losses term couples the TES water domain and the soil domain (m). The heat transfer in the porous ground layer hosting the GW table (p) is modelled using eq. 2, while the GW flow is described by the Darcy equation (eq. 3).

$$\rho A_i c_p \frac{\partial T_i}{dt} = \rho \dot{V} c_p \nabla T_i + A_i \nabla \cdot (\lambda_{eff,mix} \nabla T) - \dot{q}_{loss,i} \tag{1}$$

$$\rho_p c_{p,p} \frac{\partial T_p}{\partial t} = (\nabla \cdot \lambda_p \nabla T_p) - \rho_f c_{p,f} u_{GW} \cdot \nabla T_p + \dot{q} \tag{2}$$

$$u_{GW} = -\kappa / \mu \nabla p \tag{3}$$

The fluid velocity field can be solved in a preliminary step using the sole Darcy equation for the GW domain in steady state conditions, assuming the fluid viscosity and density and the effective soil thermal conductivity (including the thermal dispersivity) as independent from the temperature. This allows to directly couple the velocity field in a model that considers the energy balance equations for the TES, the soil and the GW layer, without the need to solve the Darcy equation for all the mesh elements at every single time step.

Following this approach, the influence of GW flow and location on the TES performance is investigated and the results and the computational effort are compared with a model using a fully coupled approach, in which temperature and velocity field are solved at each iteration. The parameters used to assess this influence are the TES thermal losses, the thermal stratification and the temperature of the GW downstream of the TES.

3. Results

In a preliminary evaluation with a steady state simulation, the GW flow conditions are applied to a 100 000 m^3 buried shallow pit TES. Fig. 2 presents an overview of the GW flow streamlines for two different GW depths.

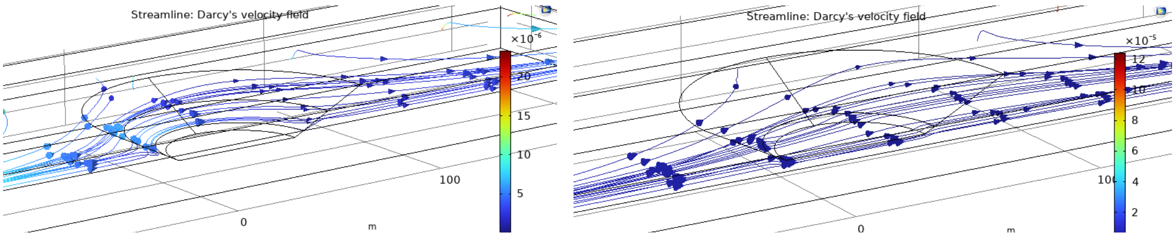

Fig. 2: 3D sketch of the GW velocity field solved in the steady state study for two different depths of the GW table: -7 m (left figure) and -14 m (right figure).

Fig. 3 shows the temperature distribution in the ground surrouding the storage assuming the GW flow conditions of Fig. 2, a uniform TES temperature of 60 °C, with a TES envelope heat transfer coefficient of 0.3 W//(m^2·K). This represents the fully discharged TES conditions in a DH grid operating between 90 °C and 60 °C. The thermal plume resulting from the advective heat transfer driven by the GW flow is visible in the zone downstream of the TES, which shows higher temperatures.

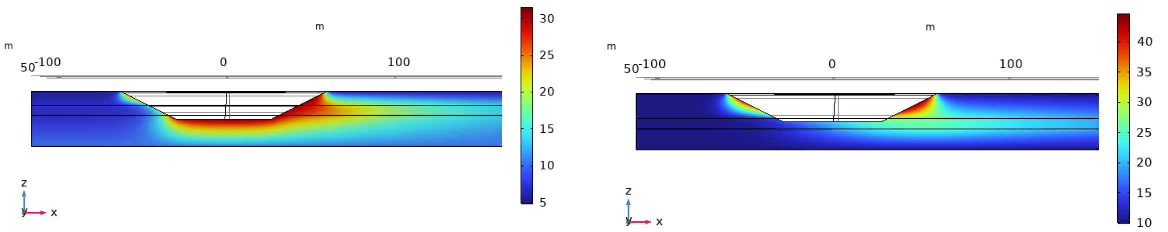

Fig. 3: 3D temperature distribution in the soil surrounding the TES in presence of GW (simplified results from steady state study with TES at 60 °C). The GW layer is located at -7 m (left figure) and -14 m (right figure).

The implementation of a dynamic simulation model allows to understand the effect of the TES dynamics on the GW temperature and the role of envelope design and geotechnical protection measures on the TES performance.

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