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Geothermal Trenches For Recycling of Waste Heat From Closed Seasonal Thermal Energy Storage Facilities

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ABSTRACT

Seasonal thermal energy storage (sTES) is a key technology for innovative low-emission energy systems. The Reno-sTES concept focuses on transforming existing in-ground basin infrastructures into low-insulated sTES facilities. While this approach aims to reduce material and energy consumption compared to new installations, a weakness of large basins formerly used for other purposes is their limited thermal insulation, combined with unfavourable geometry, especially if they are situated in an environment with groundwater flow. Heat losses from such sTES, and any other buried "warm" infrastructure, cause adverse heat accumulation and temperature rise in the ambient ground (water), which may negatively affect the environment. Our study proposes implementing geothermal trenches next to Reno-sTES as a solution: a vertically arranged ground heat exchanger connected to a heat pump is placed in the groundwater downstream of the installation to capture heat losses. In a first feasibility study, an extension of the proven water-gravel sTES co-simulation framework "STORE" is presented. It features the geothermal trench as a novel component to analyse the benefits of this technology enhancement from an energetic (e.g., storage/system efficiency, amount of recycled heat) and environmental (i.e., moderated temperatures in the surrounding subsurface) perspective. Results reveal a high potential of the proposed solution: On the one hand, dissipated heat losses can effectively be captured by the trench, enhancing the overall efficiency of the combined sTES-trench system. On the other hand, environmental impacts can actively and effectively be mitigated, as temperatures can be kept below thresholds for ground and groundwater protection.

1 INTRODUCTION

The transformation of the heating and cooling sector, one of the most energy-intensive in Europe (Fleiter et al. 2017), will require efficient renewable solutions to reduce the persistent dominance of fossil fuels. Thereby, shallow geothermal energy systems and ground-source heat pumps (GSHPs) can significantly decrease carbon emissions due to their stable year-round operational regime (Lund 2007, Menberg et al. 2025).

Seasonal Thermal Energy Storage (sTES) is considered one backbone technologies of the energy transition, enabling peak shaving and high shares of fluctuating renewable energy sources (Bott et al. 2019, Fleuchaus et al. 2018). Over recent decades, numerous closed-loop, large-scale systems have been constructed to store thermal energy over extended, predominantly seasonal cycles (Lotter et al. 2000, Ochs & Müller-Steinhagen 2008). Water-Gravel Thermal Energy Storage (WGTES) systems form one category of artificial closed basins featuring engineered structures, sealing elements, and a two-component filling of gravel and water (Socaciu 2011, Bott et al. 2019). Their robust construction allows effective seasonal energy storage, but long-term warming of the surrounding subsurface and groundwater has been documented in practice and based on simulation forecasts (e.g., Benner et al. 2003, Dahash et al. 2018, Bott et al. 2024a). In parallel, shallow geothermal collectors (e.g., horizontal systems, geothermal baskets, or geothermal trench collectors) provide renewable heat to GSHPs. Space constraints often limit horizontal collectors, whereas vertical geothermal trenches offer a promising yet underused variant (Menberg et al. 2025).

In this study, combining WGTES with geothermal trenches is proposed to enable recovery of storage-related thermal losses. Thereby, waste-heat plumes originating from buried WGTES installations (Bott et al. 2024a, Bott et al. 2025) may be intercepted by geothermal trenches placed in a downstream groundwater flow. A further development of a co-simulation framework based on the STORE model (Bott et al. 2022) allows the simulation

of thermal interactions and assessment of trench performance. On this basis, their potential for waste heat recycling and enhancing overall system efficiency is investigated in this contribution.

2 MODEL COMPONENTS

The approach chosen in this study is a co-simulation, whereby different models are interfaced to represent the relevant domains in the most accurate representation. The co-simulation further ensures efficient calculation of internal sTES effects, the surrounding subsurface, the geothermal trench located therein, and the GSHP. To this end, different time steps are simulated using a ping-pong approach, and values are transferred between the models (Dahash et al. 2019). The functional mockup unit exchange format (Modelica Association 2025) can be used for this purpose, which enables model exchange between different platforms. This concept has already been used in Bott et al. (2024) for a detailed investigation of the WGTES with the subsurface and groundwater.

2.1 STORE – Water-Gravel Thermal Energy Storage Model

The STORE model (Bott et al. 2022) is used to simulate the WGTES of this study. The seasonal operation is thereby divided into sections of discharging heat from the storage (due to heating demands or cooling surpluses) and sections of charging heat to the storage (due to heat surpluses or cooling demands). The energy system itself is not represented, and interactions between these domains are not captured. STORE is developed in MATLAB/Simulink 2024b using the Simscape Library (MathWorks 2025) and simulates internal WGTES processes with an hourly resolution. Following a component-based approach, the facility is divided into its individual building components in a 2.5D fashion, as illustrated in Figure 1. The WGTES, assumed rectangular, is structured into four discrete spatial directions and subdivided into 25 vertical layers. On all layers, thermal processes between the components described below are modeled horizontally, whereas the vertical connection is only implemented in the filling medium.

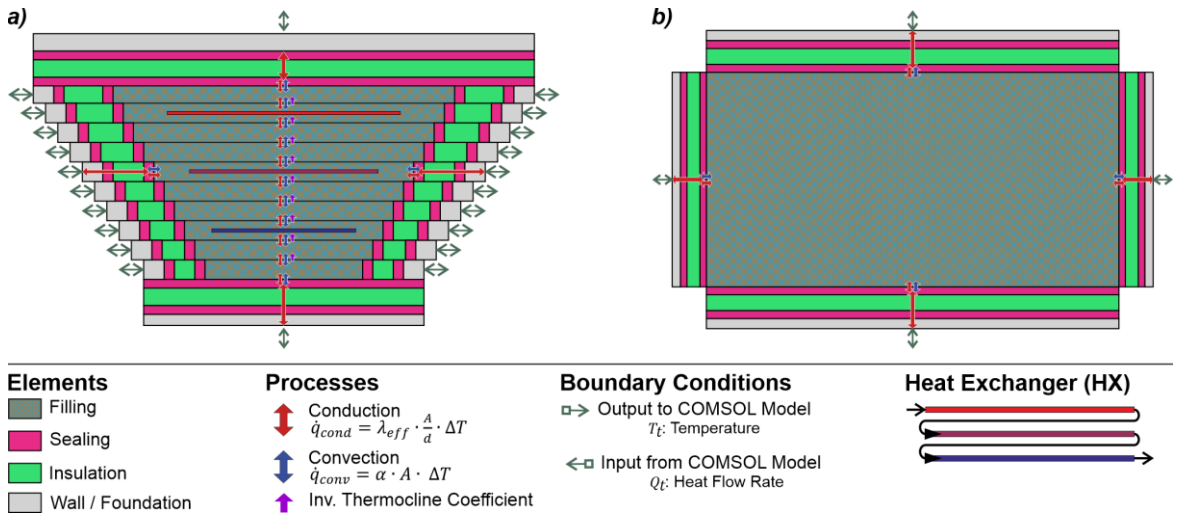


Figure 1. Conceptual setup of the STORE model used for simulation of the WGTES in this study in (a) vertical and (b) horizontal/layer view (Bott et al. 2024a).

The components include, from the inside out, first the water-saturated gravel filling. This is a simplification of the model, as the three-dimensional fluid dynamics are not resolved. Instead, convection and conduction are modeled via contact surfaces. Within some layers, a heat exchanger is modeled for charging and discharging the WGTES. These heat exchanger levels are placed based on their specified height. Each heat exchanger is designed as a pipe coil system with specified dimensions (pipe diameter, pipe wall thickness, coil spacing, resulting length/surface area). Empirical equations are then used to simulate the thermal processes within the pipes, whereby pressure losses are neglected.

The shell of the WGTES consists of an inner and an outer sealing foil made of the same material. Between these, an insulation component is assumed. To ensure the static integrity of the structure and to reflect the proposed reuse of existing basin structures (Bott et al. 2024b), the outermost component is a concrete wall. The same structure is assumed for the ceiling and the foundation. The connection to the co-simulation model in COMSOL is implemented at the outer surfaces of the ceiling, foundation, and outer sidewalls. At these contact surfaces with the environment, heat losses are recorded and transferred to the subsurface model. In contrast, after each calculation step, the STORE model receives ambient subsurface temperatures simulated in the subsurface

model. For the operation of the storage itself, demand profiles of the connected energy system (volumetric flow rates and supply temperatures) are employed.

A notable advantage of the STORE model is the highly flexible parameterization and configuration of case studies. All components are automatically set with the required dimensions (including, e.g., the thicknesses of all individual building components) and material properties via a design scenario database created during preprocessing. In addition, batch simulations can be performed as parameter studies to analyze the sensitivity of various design aspects or boundary conditions (e.g., materials, heat exchanger dimensions, cover thickness, environmental parameters). Thereby, the STORE model further parametrizes the other models by transferring the relevant values.

2.1.1 Ground-Source Heat Pump Model

The GSHP included in the framework, which is connected to the geothermal trench, is implemented as a separate MATLAB function. This model is connected in MATLAB/Simulink via appropriate thermal liquid interfaces from the Simscape library. Calculation is performed according to the thermodynamic principles of the evaporator and condenser circuits, which are here configured for heating (trench as a heat source and temperature lift to supply a heat demand) with a Carnot effectiveness of 0.55. On the sink side of the GSHP, it is assumed that a constant flow temperature has to be delivered, while the GSHP receives a constant return temperature. For simplicity, this study assumes that the sink side can always be operated, while the thermal energy supplied is varied by adjusting the supply mass flow rate, depending on the availability of the source side (i.e., the trench side).

To implement an initial control scheme, temperatures in the subsurface surrounding the trench are taken into account. Corresponding limit values ensure that the subsurface is neither overheated by the WGTES nor overcooled by the trench operation. Within this defined range, the mass flow through the trench is controlled using a linear function correlated with the temperature of the subsurface. Thereby, the mass flow rate is increased to yield more extraction of subsurface heat. Accordingly, the GSHP receives a variable mass flow from the circulation pump and the flow temperatures from the trench as input values. After the thermal utilization of the source circuit, the return temperature from the GSHP and the same mass flow rate are returned to the trench model (see below).

2.2 Subsurface Model

The subsurface model used to simulate environmental processes (in particular, the evolution of the waste heat plume and, in the saturated zone, the increased dissipation of thermal losses by groundwater) was developed in COMSOL Multiphysics® 6.3. This simulation is usually performed with coarser time steps, taking into account the much slower processes in the subsurface as well as the significantly higher computational effort required for the complex multiphysics implementation. Appropriate modules (including Subsurface Flow and Heat Transfer in Solids) are used to map all relevant multiphysics processes. Thereby, similar to the STORE model, the subsurface model incorporates the height-resolved contact surfaces of the storage's outer wall, ceiling, and foundation. The model's setup is illustrated in Figure 2.

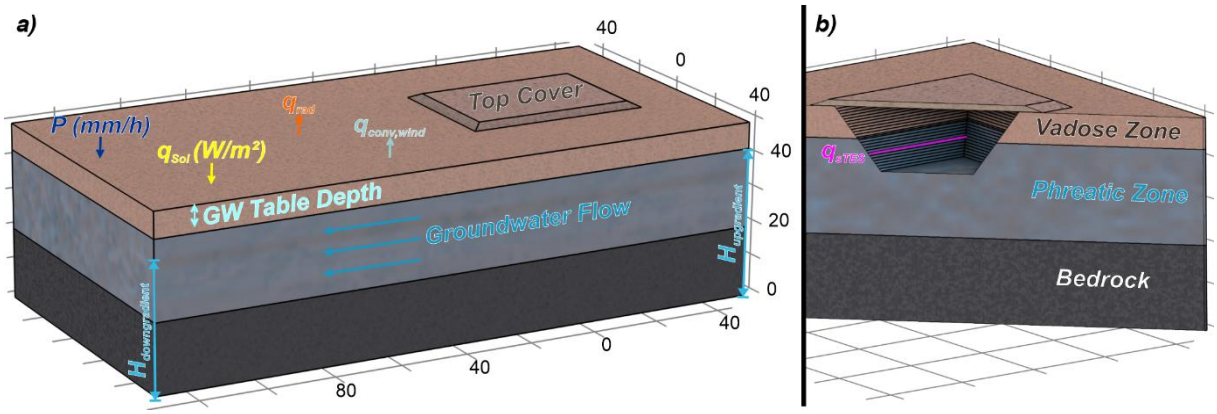


Figure 2. Conceptual Illustration of the Subsurface Model used in (a) side and (b) cut plane view (Bott et al. 2024a).

The dimensions of the WGTES (height, width, length, slope angle, number of layers) and the environment taken from the STORE design scenario database are transferred to the domains of the subsurface model. The latter includes, in particular, the top cover, which usually consists of soil with a defined height and slope angle. The

hydrogeological geometries include the layer structure (thicknesses and material parameters) and the groundwater initial and boundary conditions (groundwater flow direction, groundwater level, groundwater flow velocity, etc.). Further boundary conditions are shown in Figure 2, and include air temperature and (solar) radiation, forced convection at the surface due to wind, and, if available, other influencing factors, e.g., precipitation.

2.2.1 Geothermal Trench Model

The geothermal trench model is implemented within the subsurface model in COMSOL (Figure 5). Values for the mass flow and return temperature from the GSHP to the trench, which are transferred from the control scheme in STORE, are used to simulate the behavior of a pipe heat exchanger with a defined geometry buried in the subsurface. For this purpose, the Pipe Flow Module is used. Finally, the resulting flow temperatures at the end of the geothermal trench are returned to the STORE model.

The required geometric parameters of the geothermal trench are similar to those of the heat exchanger in the WGTES. They include the number of pipes or pipe layers and their spacing, the diameter, and, if applicable, the diameter of installation loops. Again, the thermal liquid processes are simulated based on simplified equations to yield pressure and temperature information across the pipe. Another distinctive feature of the geothermal trench model is the additional sensor technology required to control the geothermal trench. A distributed temperature sensing (DTS) cable is assumed to measure the resulting heating/active cooling of the subsurface. In the model, this is implemented via a line along which the average and maximum temperatures are evaluated.

2.3 Evaluation of Simulation Results

To evaluate the simulation results, the different submodels and practically relevant data on efficiencies, temperature levels, and energy balances are inspected. Thereby, the last operating year is evaluated, as buried WGTES only reach a quasi-stationary state after an initial heating phase of their environment. First, the purpose of seasonal storage is highlighted, using the energy balance with the amount of energy charged, discharged, and lost to the ambient. From these ratios, efficiency values are derived, which are defined as the ratio between charging and discharging. Besides, energy extracted from the ground by the trench is added to the equation as additional energy discharged. Besides, the minimum, maximum, and average WGTES filling temperatures are considered as proxies for the exergetic usefulness of the stored energy. These temperatures also indicate whether the WGTES can be effectively discharged at the end of the discharge cycle to utilize its full capacity.

In contrast, the evaluation geothermal trench is characterized in particular by the operating mode of the GSHP. There, decisive factors are the amount of energy extracted from the ground and the temperature spreads achieved during operation on the source side. This yields an indication of the effectiveness of energy extraction via the GSHP. In addition, the controlled mass flow rates are taken into account to inspect the implementation of the proposed control. The combination of these values can also be used to derive the maximum and average power provided to the energy system as an additional source for the trench. Furthermore, the power consumption of the GSHP is of interest for its operation, representing an economic indication. The derived coefficient of performance (COP) ultimately shows how effectively the ratio between the sink and source sides was regulated.

3 CASE STUDY

To test the framework under lab conditions, standard geometries and synthetic datasets are used. The aim is to analyze the concept of the trench and compare the behavior of the subsurface with the performance indicators of the WGTES. The simulation period covers five years, with the step size of the STORE model set to one hour and that of the subsurface model to 2.5 days.

3.1 Location and Environmental Boundary Conditions

Synthetic, hourly resolved data sets are used for environmental boundary conditions for air temperatures and solar radiation (Figure 3). A subsurface temperature of ca. 13.6 °C (1st of April) is used for initialization. Precipitation is neglected. All profiles are based on sinusoidal functions, whereby the air temperature ranges from 0 °C to 24 °C, and the soil temperature ranges from 2.5 °C to 13.5 °C over one year. In contrast, the solar irradiation is a combination of a daily and a yearly pattern, ranging from 0 kW to 3.2 kW.

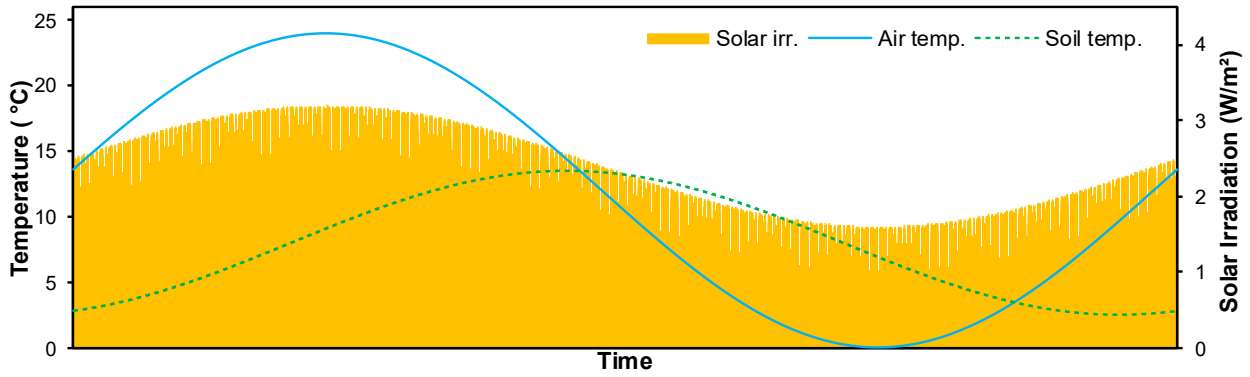


Figure 3. Datasets of environmental boundary conditions for the case study.

Groundwater flow is assumed to be homogeneous in the direction of the trench at a constant velocity of $5 \cdot 10^{-5}$ m s^{-1}. The depth of the groundwater table is 3.75 m below ground level, which corresponds to 50% of the WGTES height. The subsurface is assumed to consist of three layers, whereby material values are obtained from VDI (2010). The first 3.75 m represents the unsaturated zone, consisting of wet sand. For this, an effective thermal conductivity of 1.4 W m^{-1} K^{-1} with a porosity of 0.45 is assumed. The specific heat capacity is 2,000 J kg^{-1} K^{-1}, and the density is 2,100 kg m^{-3}. The second layer, an unconfined aquifer, is assumed to have a thickness of 15 m. The material is highly permeable saturated gravel with a porosity of 0.28 and a density of 2,200 kg m^{-3}. In this layer, the effective thermal conductivity is 1.8 W m^{-1} K^{-1}, and the specific heat capacity is 2,400 J kg^{-1} K^{-1}. Finally, a bedrock forms the bottom layer of the model, with a thickness of 3.75 m, avoiding boundary effects. The assumed material, claystone, is assumed to have a porosity of 0.05, a density of 2,500 kg m^{-3}, a thermal conductivity of 2.2 W m^{-1} K^{-1}, a specific heat capacity of 2,250 J kg^{-1} K^{-1}, and a hydraulic conductivity of 10^{-10} m s^{-1}.

3.2 Geometry and Set-Ups

3.2.1 Design of the Water-Gravel Thermal Energy Storage

The WGTES of this study has a total volume of ca. 4,320 m^3. It features 7.5 m in height and consists of a square-shaped ceiling with a side length of 30 m. The slope ratio of 1:05 results in a truncated pyramid. The storage is filled with water-saturated gravel, which has a thermal conductivity of 2.4 W m^{-1} K^{-1} and a specific heat capacity of 1,545 J kg^{-1} K^{-1}. The density is 1,928 kg m^{-3}, whereby all values stem from a practical study (Benner et al. 2003). The sealing foil surrounding the filling and protecting the insulation material has a thickness of 0.002 m. It consists of polyvinylchloride with a density of 1900 kg m^{-3}, a thermal conductivity of 0.48 W m^{-1} K^{-1}, and a specific heat capacity of 900 J kg^{-1} K^{-1}. A moderate insulation thickness is chosen: It is 0.5 m at the top, 0.5 m to 0.3 m at the sidewalls, and 0.3 m at the bottom. The same material, extruded polystyrene foam, is used on all sides (density: 30 kg m^{-3}, specific heat capacity: 1,450 J kg^{-1} K^{-1}, thermal conductivity: 0.04 W m^{-1} K^{-1}). Finally, the shell is finished with concrete walls (thickness: 0.25 m at the top and sidewalls, 0.5 m for the foundation), which has a thermal conductivity of 1 W m^{-1} K^{-1}, a specific heat capacity of 1,000 J kg^{-1} K^{-1}, and a density of 2,600 kg m^{-3}. A pipe coil system with five levels is utilized for charging and discharging. The material of the 0.003 m-thick pipe walls consists of cross-linked polyethylene. The installation grid with internal and edge spacings of 0.5 m results in a heat exchanger length of ca. 8,750 m. The inner diameter of the pipes is 0.05 m. It is assumed that the storage is directly connected to the surrounding energy system/local heating network. Hence, no further components (heat exchanger, heat pump, circulation pump) are modeled.

3.2.2 Operation Scenario for the Water-Gravel Thermal Energy Storage

The assumed operating mode of the WGTES is a seasonal pattern that has already been used in previous studies to test and compare models. Here, it is scaled to the WGTES filling's volume, and higher temperatures were assumed to achieve a more intensive impact on the environment and thus potentially more significant effects of waste heat recycling through the proposed geothermal trench. Besides, it is assumed that the storage operation starts at the beginning of the heating season (i.e., on the 1st of April of a year).

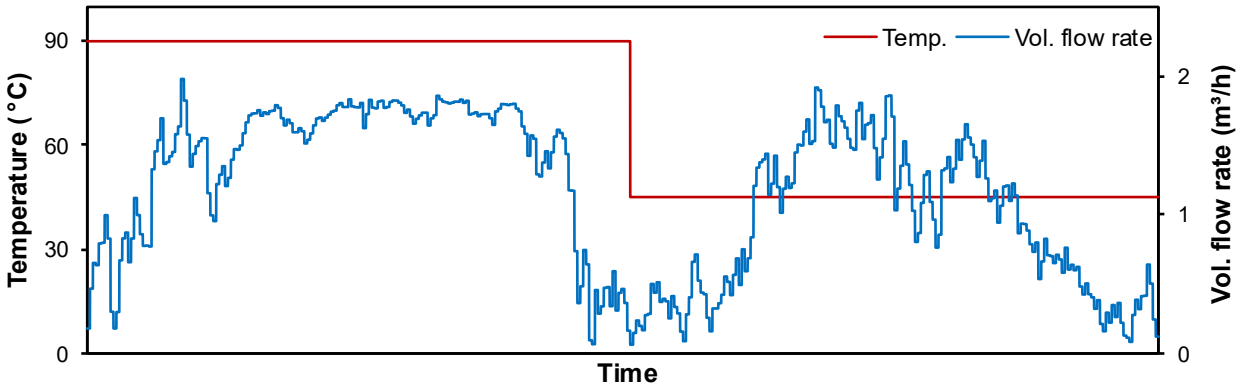


Figure 4. Datasets for the operation of the case study's WGTES.

The load profile (Figure 4) for the storage is therefore featured by high charging temperatures of 90 °C in summer and moderate discharging temperatures of 45 °C in winter. Charging is carried out from top to bottom and discharging in the opposite direction to ensure an efficient thermal stratification. Volumetric flow rates are between 0.059 $m^3 h^{-1}$ and 1.977 $m^3 h^{-1}$ over the course of the year, assuming that only a partial load of the energy system is used.

3.2.3 Design Variants and Operational Set-Up for the Geothermal Trench

For the geothermal trench, two geometry variants are considered, while a base case assumes WGTES operation without any trench for comparison. One variant ("loops") consists of a horizontal geothermal collector laid in loops. These loops are laid on three levels (at depths of 1.5 m below ground level (BGL), 3 m BGL, and 4.5 m BGL) and have a diameter of 0.8 m, overlapping by 0.2 m. The resulting total pipe length is ca. 723 m, and all levels are operated in parallel. The second geometric variant ("graben") consists of parallel horizontal pipes on 20 levels, which is intended to minimize pressure losses in the pipes and ensure more uniform heat extraction from the ground. For this variant, a total pipe level length of 1,400 m is achieved. For the graben case, all volume flows from the flow and return are mixed. The similarities between the two geometric variants of the trench concern the pipe diameters (0.036 m) and the installation on the groundwater downstream side of the WGTES at a short distance of one meter from the outer sidewall surface, to capture the resulting waste heat plume in the near field.

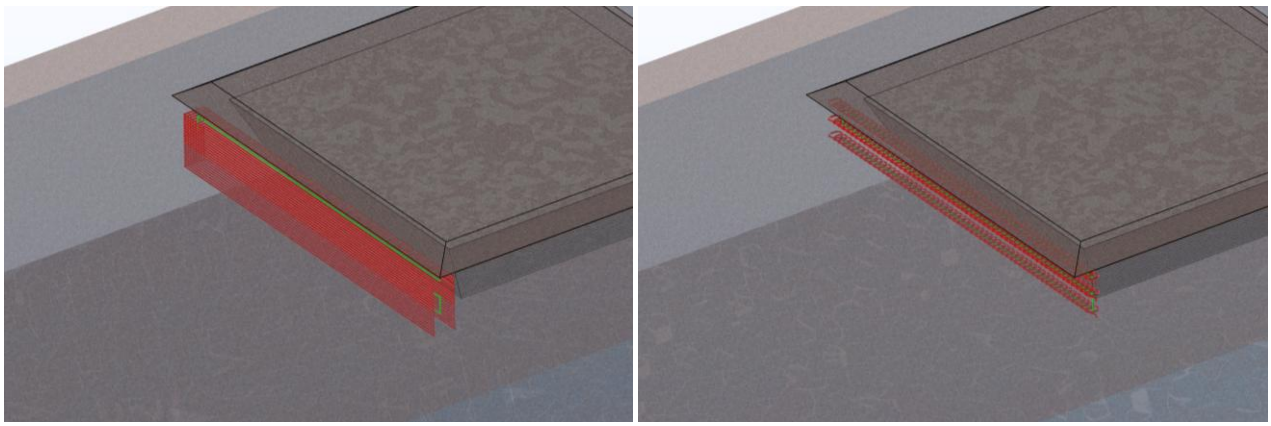


Figure 5. Graben (left) and loop (right) geothermal trench variants (red) with DTSmeasurement line (green).

The GSHP is assumed sufficiently powerful, preventing any effects of operation limits. The setpoint for the sink side is set to 45 °C, while the assumed return flow is set to 20 °C. The GSHP and the circulation pump of the trench are controlled with a lower limit of 5 °C for the return temperature from the trench to the GSHP, to prevent icing. Above this lower limit temperature, a simple linear control depending on the average subsurface temperature along the trench with a slope of 0.2 K kg^{-1} s^{-1} is employed.

4 RESULTS AND DISCUSSION

This chapter presents a comparative analysis of the simulation results. Only the last (i.e., fifth) year of operation or the situation at the end of the simulation period is considered. The base case without an operation of the

trench is used as a reference to consider the positive and negative effects of waste heat recycling and regulating the temperature conditions in the groundwater downstream from the WGTES facility.

4.1 Storage Performance

Without the geothermal trench (base case), the storage shows a moderate efficiency of 30.76 %. In this case, 62.3 MWh of the charged energy quantity (202.4 MWh) is discharged. This is offset by energy losses of 139.7 MWh. The temperature characteristics achieved for the base case show a minimum value of 40.3 °C and a maximum value of 83.2 °C. Because of the large surface area, energy losses occur mainly on the outer walls, resulting in 89.2 MWh in the last operating year, which is ca. 3.5 times higher than at the bottom or at the top.

While the temperature characteristics for the two trench scenarios do not differ much from the base case without trench operation, differences in the efficiency are significant. Looking only at the storage efficiency (without adding energy gains from the trench), the performance values decrease to 30.36 % for the graben variant and to 28.82 % for the loop variant. In the last year of operation considered, the energy losses in the loop scenario are higher (145.8 MWh vs. 141.0 MWh for the graben scenario) and, similarly, the amounts of energy recovered are lower (59.2 MWh for the loop variant vs. 61.6 MWh for the graben variant).

Finally, the results show a substantial increase in the efficiency of the overall system when operating the geothermal trench, with significant differences in effectiveness between the two design variants. In the graben case, the trench yields 37.0 MWh_{th}, while for the loop variant, the yielded energy is only 36.4 MWh_{th}. Adding these quantities extracted from the subsurface and enhanced by the GSHP, the system achieves an efficiency of 48.60 % in the graben variant and an efficiency of 46.54 % in the loop case. This proves that the proposed concept fundamentally provides added energy value.

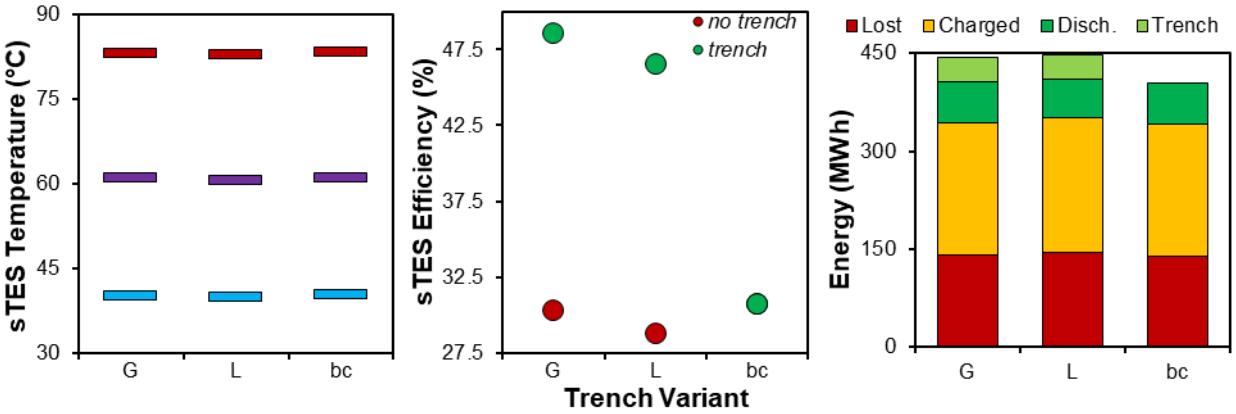


Figure 6. Storage key performance indicators for evaluation of the results of the case study for the three scenarios: "graben" (G), "loops" (L), and base case (bc). Left: minimum, mean, and maximum sTES filling temperatures; center: sTES efficiencies with and without consideration of trench energy, right: Energy balance.

4.2 Trench Performance

A closer look at the characteristic values of the geothermal trench illustrates details on its functionality and effectiveness. Figure 7 shows the annual temperature profiles for the supply and return lines from and to the GSHP. An effective temperature reduction by the GSHP is evident in the temperature difference achieved, which averages 8.34 K (min: 7.88 K, max: 8.72 K) for the graben variant and 2.05 K (min: 1.48 K, max: 2.53 K) for the loop variant. Besides the temperature ranges, the effectiveness of the control based on the mass flow rate is evident in a variation of this parameter over the course of the year. Due to the different number of heat exchanger levels, the mass flow rates are fundamentally different (on average, ca. four times higher in the case of the loop variant). These flow rates range between 0.11 kg s^{-1} and 0.13 kg s^{-1} for the graben variant and between 0.44 kg s^{-1} and 0.52 kg s^{-1} for the loop variant. In practice, different circulation pumps would be required, but finally, similar amounts of energy are extracted.

Regarding the resulting power of the trench and the GSHP, in the graben case, it reaches a maximum of 4.77 kW_{th} (mean: 4.23 kW_{th}), and in the loop scenario, a maximum of 5.49 kW_{th} (mean: 4.15 kW_{th}). In addition to the thermal energy quantities achieved, which were already presented in the previous section, the electrical energy consumption is relevant for the operation of the GSHP connected to the trench. It can serve as a proxy for economic factors.

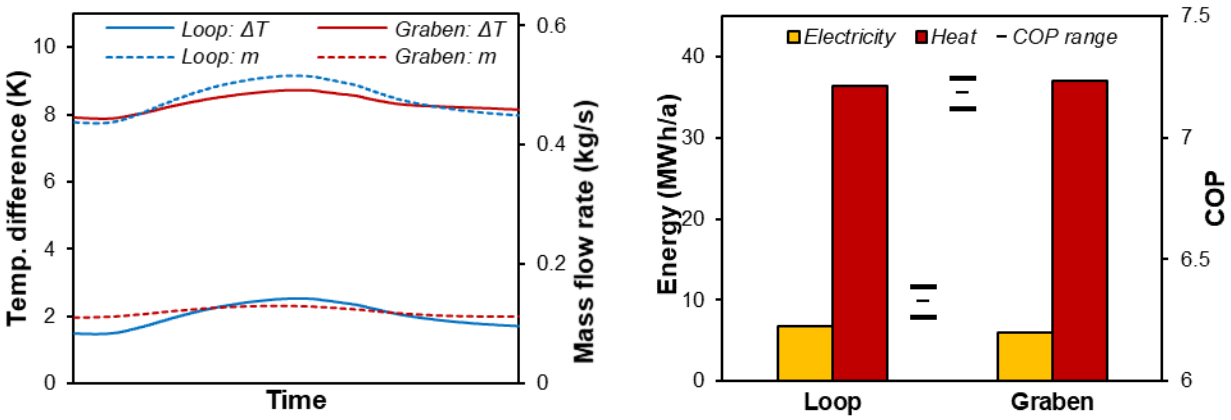


Figure 7. Geothermal trench key performance indicators for evaluation of the results of the case study.

The total electrical energy requirement of the GSHP is higher in the loop case, amounting to 6.81 MWh_{el}, than in the graben scenario, where only 5.98 MWh_{el} are required. Finally, Figure 7 also shows a resulting difference in the COP of the assumed GSHP. It should be noted that the idealized model does not take all losses into account. Nevertheless, the orders of magnitude of the COP values are plausible, and there is a difference between the variants, with the graben variant achieving an average value of 7.18 and a maximum value of 7.25, while in the loop variant, the average value is 6.26 and the maximum value by 6.33.

4.3 Subsurface Effects

Besides the technical added value of trench operation as a renewable heat source with improved performance values from both a storage and trench perspective, another key question is the impact of the systems on the subsurface. Here, the simulation results show how the introduction of the geothermal trench effectively reduces temperatures in the groundwater outflow and in the subsurface. The resulting waste heat plumes are shown in Figure 8.

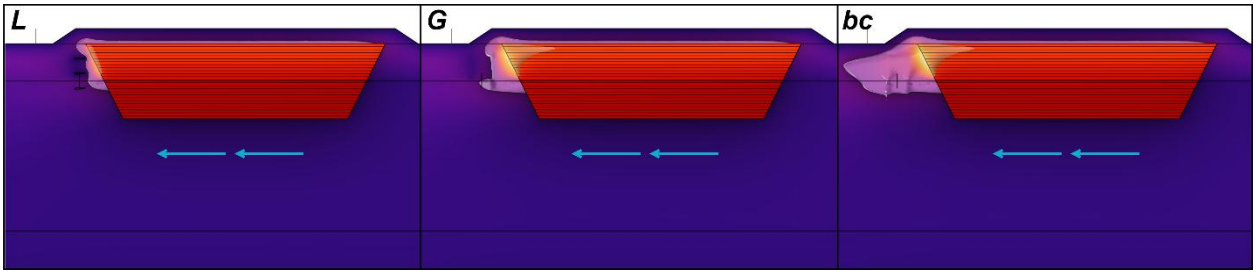


Figure 8. Temperature plume of WGTES for the two trench variants (L: loops, G: graben) and the base case (bc).

Clearly, in the base case (no trench operation), the temperature increases spread to greater distances from the WGTES. In contrast, both geometric variants of the trench show the limitation of this area of influence, with the loop variant achieving greater effectiveness in the form of a lower breakthrough. The temperatures reached in the surrounding subsurface are also relevant. The annual cycles of the DTS measuring line used for control are evaluated for this purpose, revealing that for the graben variant, a maximum temperature of 15.37 °C is reached at the trench, while in the loop variant, the maximum temperature is 1.19 K lower. Consistently, the average values differ, with 12.05 °C (graben variant) and 7.17 °C (loop variant). Without trench operation, the resulting subsurface temperatures are on average 16.11 °C and reach a maximum value of 20.83 °C.

5 CONCLUSIONS

This contribution presents a newly developed co-simulation framework for combining seasonal water-gravel thermal energy storage (WGTES) systems with near-surface geothermal trench collectors. The aim is to effectively recapture the heat lost during WGTES operation, which can be enhanced by groundwater flow around a WGTES facility. On the one hand, this is expected to deliver technical added value by providing additional energy for a connected energy system. On the other hand, positive environmental effects are expected, as temperatures in both the groundwater and the subsurface may be reduced through the use of the geothermal trench. This contribution first presents the individual framework components (WGTES model, subsurface model, trench model, and ground-source heat pump model) and how they are linked. Subsequently, a realistic case study is employed to illustrate the technical implementation: Based on predefined evaluation variables, two design variants (“loops” and “graben”) are proposed and compared with a base case.

Results show that the proposed concept can effectively achieve the envisaged objectives. In the best-case scenario, the trench can provide 37.0 MWh of additional energy. Thereby, the system efficiency can be increased by about 17.8% in the case of the graben variant. An analysis of the GSHP performance shows effective use of the return temperatures from the trench, with temperature reductions of up to 8.72 K being achieved. However, initial values of the required electrical energy of at least 5.98 MWh_{el}/a must be taken into account in the economic analysis. The positive effects from an environmental perspective are evident in a significant reduction in the waste heat plume from the storage and a reduction in temperatures in the trench area from 20.83 °C to 14.18 °C after five years of operation.

Besides these important initial findings, further model refinements are necessary to prove the effectiveness of the concept. These include optimizing the control of mass flow rates in the trench and a more realistic representation of the sink side of the GSHP. Finally, experience from field trials is essential to validate the models used and demonstrate the added value for practical application. In this regard, the Horizon Europe project INTERSTORES (INTERSTORES 2025) is expected to provide important insights, as the concept will be implemented at a test WGTES facility at the incampus in Ingolstadt (Germany) for research purposes.

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During the preparation of this work, the first author used *ChatGPT* by OpenAI and *DeepL Translator* by DeepL SE to improve language and readability. After using these tools/services, the author(s) reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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