

Assessing Borehole Thermal Energy Storage Patterns for Renewable Heating Solutions

Sandeep Bandarwadkar^{1*}, Lazaros Aresti², Rokas Valancius¹

¹Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Research group – Sustainable Energy in the Built Environment, Studentu str. 48, LT-51367 Kaunas, Lithuania

² Faculty of Engineering, Cyprus University of Technology, Lemesos, Cyprus

*sandeep.bandarwadkar@ktu.edu

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ABSTRACT

As the global energy transition advances, the heating sector accounted for approximately 51% of energy consumption in 2023, predominantly relying on fossil fuels. Renewable energy sources, including solar power, wind, and thermal energy, offer promising alternatives but face challenges with large-scale, long-term energy storage to balance the intermittent supply with heating demand. Borehole Thermal Energy Storage (BTES) presents a highly suitable option for addressing seasonal mismatches between energy supply and demand.

As BTES systems evolve to meet rising energy needs, optimizing heat charging capabilities across different borehole configurations has become essential for improving system efficiency. The overall aim of the current study is to review existing BTES technologies and to compute different patterns of the BTES systems. Using COMSOL Multiphysics software, this study examines the thermal behavior and heat charging performance of various patterns under a range of operational conditions. The convection-diffusion heat transfer equation has been used with the inclusion of the 1D simplified approach to model different borehole patterns and materials. The charging/discharging process was estimated based on the monitored fluid inlet and outlet of the BTES systems. Thermal properties of grouting materials were varied to analyze heat transfer efficiency and storage capacity, where the interaction of the boreholes was also discussed. Results indicate that configuration and material selection significantly impact the heat charging efficiency and overall performance of BTES systems. Insights and recommendations for future BTES applications are also provided.

1. INTRODUCTION

Decarbonizing the heating sector is one of the major challenges in achieving global climate goals. Space heating and industrial heating demands significantly

contribute to global energy consumption, with much of this demand still reliant on non-renewable energy sources. Large-scale, long-duration thermal energy storage solutions are critical to integrating renewable energy into heating applications. Among various technologies, BTES systems have gained prominence due to their capacity for seasonal storage, stability, and scalability (Durga et al., 2021).

The concept of BTES has evolved over the past decades, with early systems focusing on simple vertical borehole arrangements and basic ground heat exchanger designs. Researchers have since explored the thermal performance of BTES under different configurations and conditions. The fundamental line source model was introduced for predicting ground temperature response to borehole heat injection and extraction (Eskilson, n.d.; Koohi-Fayegh & Rosen, 2013; Zeng et al., 2002). Later, studies such as those by Zarrella et al. and Bauer et al. focused on simulating multi-borehole interactions and the influence of grout materials on system efficiency (Zarrella et al., 2011).

Material properties, especially the thermal conductivity of the grout and surrounding soil, have been found to significantly impact heat transfer rates. Recent experimental studies also highlight that the geometry of borehole fields, spacing, and operating conditions substantially affect the long-term performance and energy recovery potential (Gultekin et al., 2019). Numerical modeling efforts have further improved the prediction of borehole interactions, with research moving towards hybrid analytical-numerical models for more accurate simulation of transient behavior (Bahmani & Hakkaki-Fard, 2022; Biglarian et al., 2017). Despite the advancements, questions remain regarding the optimal configurations for borehole arrays, the role of high-performance grout and backfill materials, and the best methods to simulate heat transfer with acceptable accuracy while reducing computational complexity (Bayomy et al., 2021; Kolo et al., 2024).

To address these gaps, the present study introduces a hybrid borehole thermal energy storage configuration, combining different borehole types within a single field layout. Through comprehensive numerical simulations,

this work investigates how hybrid arrangements influence thermal interactions, enhance heat storage efficiency, and offer practical design advantages compared to conventional uniform patterns.

2. METHODOLOGY

A numerical model was developed in COMSOL Multiphysics v6.1 to simulate and compare three hybrid BTES configurations within a (50x50)m computational domain. Vertical boreholes were modeled as 1D pipes, and the surrounding soil was defined via the heat Transfer in solids interface, with a thermal conductivity of 0.51 W/(m.K). The borehole dimensions used in the model were selected based on established design standards and values commonly reported in the geothermal energy system literature. Water with temperature-dependent properties was used as the circulating fluid. An available heat source could be, for example, the waste heat availability from the Kaunas CHP plant, of 22 MW. Heat is distributed according to the safe injection capacity of each borehole type, with 40 W/m for coaxial and 25 W/m for U-tube configurations. The Kaunas CHP plant is designed to produce 24 MW of electricity and 70 MW of heat, with approximately 22 MW generated by the flue-gas treatment condensation unit (*Kaunas (Lithuania): Successful Hand-over to UAB Kauno Kogeneracine Jegaive | Drupal, n.d.*). Regarding injection capacities, studies have shown that coaxial borehole heat exchangers can achieve a heat transfer rate of 42.2 W/m (or even higher) under certain conditions (He et al., 2024). For U-tube boreholes, thermal response tests have reported heat injection rates of approximately 25 W/m, depending on various factors (Morchio et al., 2022)

Assuming full energy utilization, the calculated minimum charging durations were 491 days (Pattern A), 605 days (Pattern B), and 683 days (Pattern C). This duration ensured safe thermal injection without exceeding threshold limits, while shorter periods would require load reduction or system expansion.

3. RESULTS

Following the implementation of the numerical model, the thermal response of the defined hybrid BHE configurations was analysed through a multi-perspective evaluation. Instead of assigning a fixed 22 MW thermal input, heat injection was distributed based on the safe injection capacity of each borehole type, considering their depth of 70 m. The aim was not only to quantify the heat propagation within the subsurface but also to observe the spatial and temporal dynamics of temperature evolution resulting from long-term charging. The hybrid configuration, comprising a central coaxial borehole surrounded by 24 U-tube BHEs, revealed clear variations in heat diffusion based on depth, lateral position, and temporal exposure.

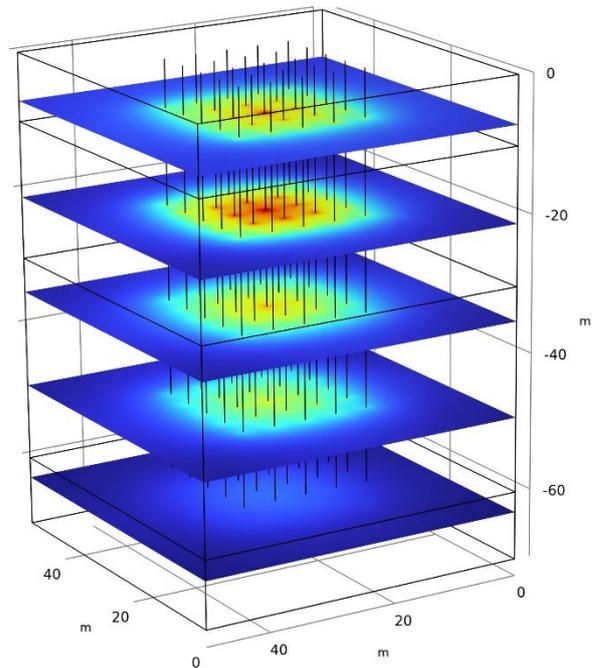


Figure 1: Temperature distribution after 491 days, showing vertical heat spread with peak values near the central coaxial borehole.

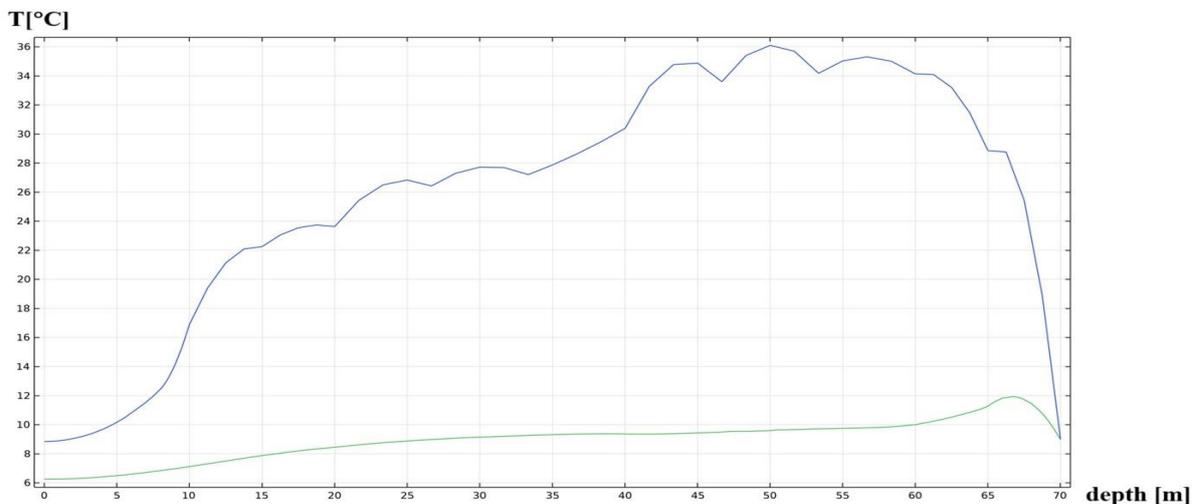


Figure 2: Temperature profile along borehole depth, showing higher peak values in the coaxial borehole (blue colour) compared to the U-tube borehole (green colour).

A multi-slice visualization at the end of the 491-day charging period (Figure 1) distinctly illustrates the vertical temperature distribution across different depth planes. Higher temperatures are consistently observed around the central coaxial borehole and its immediate surroundings, confirming its enhanced injection capacity. The upper layers exhibit stronger thermal gradients, which progressively dissipate with depth, demonstrating the gradual and controlled vertical heat penetration through the soil matrix.

To complement this, a line graph of temperature distribution along the borehole length (see in Figure 2) indicates that the coaxial BHE reached peak fluid temperatures of $\sim 35^{\circ}\text{C}$, while the U-tube boreholes exhibited significantly lower profiles, typically below 20°C . The significant variation in thermal behaviour underscores the varied injection intensities and confirms the role of the central coaxial unit involvement in generating thermal accumulation.

The lateral temperature spread at the mid-depth of the domain is presented in Figure 3, and further demonstrates radial heat distribution. A well-defined high-temperature core was formed around the central region, and gradually reduced temperature zones. The circular isotherms suggest that the temperature field was symmetrically distributed, with maximum values reaching approximately 27°C at the central intersection of the borehole grid. This heat plume evolution affirms the effectiveness of the borehole spacing in minimising thermal interference while still supporting cumulative storage.

The time-dependent temperature evolution was monitored at three locations: near the centre of the coaxial borehole (near centre), a U-tube borehole (near end), and midway between them (midpoint) (see Figure 4). There are significant differences observed after approximately 30 days. Over time, the coaxial borehole zone demonstrated a steeper and more sustained increase, reaching above 24°C at the end of the

simulation. In contrast, the U-tube area remained below 9°C . Intermediate regions exhibited moderated thermal gains, reflecting the combined effect of both sources.

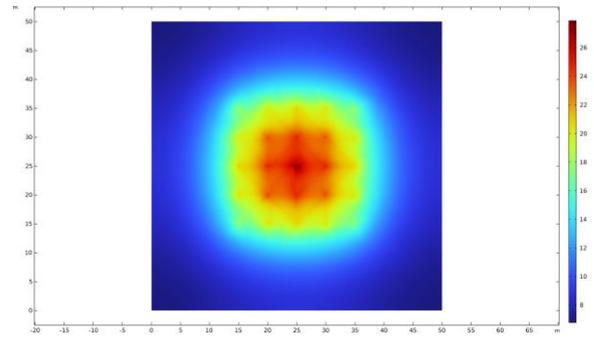


Figure 3: Lateral temperature distribution at the mid-depth after 491 days, showing a symmetric heat plume centered around the coaxial borehole.

This detailed analysis was conducted for one hybrid configuration to establish a clear thermal reference and understand the interaction between high-capacity coaxial boreholes and surrounding U-tube boreholes. The selected combination ensures strong central injection with balanced lateral distribution, enabling efficient heat spread while avoiding thermal overlap. This serves as a foundation before comparing alternative patterns.

Following the evaluation of the baseline hybrid configuration (Pattern A), two additional configurations were examined to explore alternative spatial strategies and performance trade-offs. Pattern B featured a triangular arrangement of coaxial boreholes centrally embedded within a 5×4 grid of U-tube boreholes, focusing thermal injection toward the core of the domain. In contrast, Pattern C distributed coaxial borehole at the corners of a uniform 4×4 grid layout, enabling peripheral heat input and promoting symmetrical radial propagation.

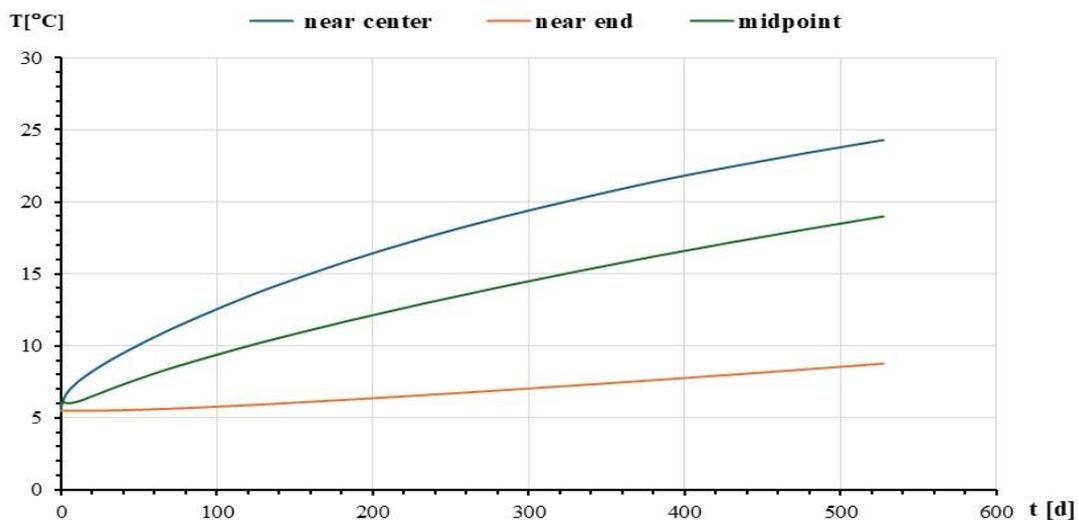


Figure 4: Temperature evolution over time at three locations: near coaxial (blue), near U-tube (purple), midway (green), showing faster and higher thermal response near the coaxial borehole.

In all configurations, the temperature evolution was tracked at three identical spatial locations, near the coaxial borehole, near the U-tube, and at the midpoint between them. Compared to Pattern A, both hybrid alternatives demonstrated notable differences in thermal behaviour. In Pattern B, the coaxial-adjacent region exhibited the fastest initial temperature rise, surpassing 15°C by day 600, attributed to the concentrated placement of coaxial boreholes. However, temperature gains in the U-tube region and midpoint were moderate, reflecting less uniform thermal dispersion.

In contrast, the pattern C delivered the most balanced thermal gradient, with all three probe points showing consistent growth and the U-tube adjacent zone reaching nearly 13°C. This is indicative of a more symmetric and distributed energy field, facilitated by the peripheral positioning of the coaxial boreholes.

While pattern A achieved the highest peak temperature near the coaxial borehole, it also resulted in pronounced temperature gradients across the field, indicating uneven spatial heat distribution and reduced thermal uniformity. The patterns B and C, though operating at lower injection capacities, demonstrated more balanced thermal fields and better utilisation of the storage volume over time, which indicated the improved heat distribution efficiency and reduced thermal interference between boreholes.

At mid-depth, the lateral temperature fields revealed distinct thermal dispersion behaviour across the three configurations. In pattern A, the thermal influence was highly centralized, with steep gradients radiating from the core, reflecting intense localised heating but reduced spatial coverage. In contrast, pattern B exhibited a moderately extended thermal zone with a more diffuse heat signature, shaped by the triangular coaxial core. The energy distribution was softer, with

reduced thermal peaks and smoother peripheral gradients, highlighting its efficiency in avoiding sharp transitions.

Pattern C presented the most uniform lateral temperature profile. The strategic placement of coaxial at the grid corners facilitated heat propagation from the periphery inward, resulting in a flatter, radially.

3. CONCLUSIONS

This study investigated the impact of several hybrid BTES configurations on subsurface heat propagation and storage performance using numerical simulation. By evaluating three distinct patterns, each combining coaxial and U-tube boreholes in varied arrangements, the thermal behaviour, spatial distribution, and operational efficiency of the systems were assessed under long-term heat injection cases. The focus was on understanding how borehole positioning influences heat accumulation, uniformity, and spatial efficiency.

The simulation results confirm that borehole arrangements significantly influence thermal performance in a hybrid BTES system. Pattern A, within its central coaxial and high capacity, achieved the highest peak temperatures but exhibited steep thermal gradients and non-uniform spatial distribution, making it suitable where centralized heat accumulation is prioritised. Pattern B delivered a faster initial response near the coaxial due to concentrated central injection, yet demonstrated lateral uniformity, making it favourable for compact layouts requiring strong core heating. In contrast, pattern C offered the most balanced temperature distribution and radial symmetry, with consistent thermal growth across all locations, positioning it as the most spatially efficient and thermally uniform configuration.

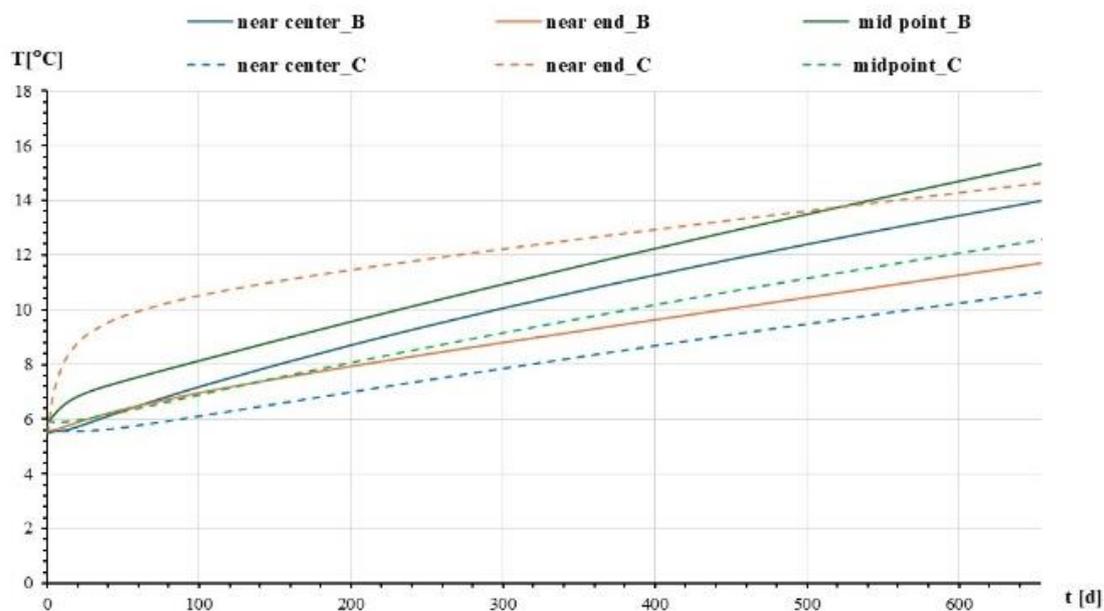


Figure 5: Temperature evolution over time of Pattern B and Pattern C.

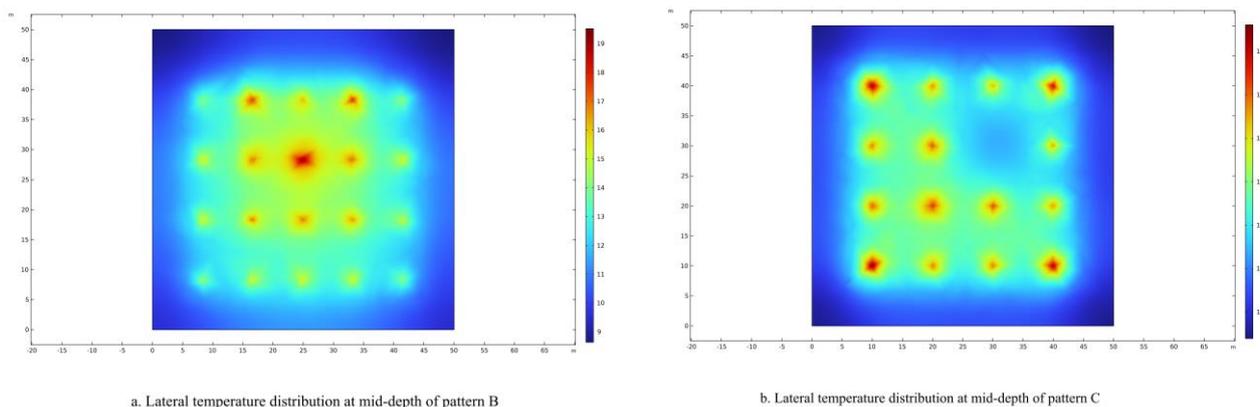


Figure 6: Lateral temperature distribution at the mid-depth of Patterns B and C.

Therefore, while pattern A excels in peak temperature performance, pattern C is the most effective in achieving uniform and controlled thermal spread, especially in systems prioritizing distributed storage and long-term spatial stability.

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