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Medium-Deep Borehole Thermal Energy Storage (MD-BTES): from Exploration to District-Heating Grid Connection, Insights from SKEWS and PUSH-IT Projects

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ABSTRACT

Medium-Deep Borehole Thermal Energy Storage (MD-BTES) systems are a promising technology for sustainable and efficient seasonal thermal energy storage and district heating distribution. These innovative systems are designed to store excess thermal energy e.g. generated from renewable sources in the subsurface using borehole heat exchangers (BHE) and release it when needed for heating or cooling purposes. MD-BTES systems can play a crucial role in the transition towards a more sustainable energy supply, with their development encompassing various stages, from exploration to connection and implementation in district-heating grids. This contribution presents insights gained from two projects in this field, namely the SKEWS (funded by the federal government of Germany; ID: 03EE4030A) and PUSH-IT (Horizon Europe Grant agreement, ID: 101096566) projects, to highlight their contributions to advancing MD-BTES technology implementation. The exploration phase of MD-BTES involves identifying suitable geological formations for energy storage through boreholes. SKEWS, an acronym for "Saisonaler Kristalliner Erdwärmesondenspeicher" or Seasonal Crystalline Borehole Heat Storage, plays a major role in this phase. This project primarily focuses on implementing a real-scale demonstrator site with four borehole heat exchangers. The first steps contained geophysical surveying, geological mapping and analysis, aiming to identify the best site choice with the most affordable reservoir conditions for medium-deep boreholes. By employing advanced geophysical techniques, the SKEWS project identified areas with the necessary geological attributes, such as thermal conductivity and adequate permeability, for efficient energy storage and retrieval. Additionally, SKEWS produced datasets to assess the feasibility and environmental impact of drilling and installing borehole systems in urban and peri-urban areas. Ongoing, the boreholes on site have been completed with a coaxial BHE design. The SKEWS task contains an experimental storage and extraction program, ending in 2026. This approach made SKEWS an ideal BTES demonstration site within the PUSH-IT consortium. The PUSH-IT project, which stands for "Piloting Underground Storage of Heat In GeoThermal Reservoirs", takes the role of a leading research site in the development phase and addresses the thematic aspects of numerical modelling and commissioning for the integration of storage systems with existing district-heating grids, particularly at the Darmstadt site. The connection of MD-BTES with district-heating grids represents the final step in investigating the potential of MD-BTES for urban energy systems. To illustrate this, an exemplary connection scenario and a detailed explanation of the co-simulation, control, and subsurface processes modelling strategy for technological development and deployment at the TU Darmstadt campus scale will be provided. The insights and perspectives gained from these two projects are invaluable for overcoming technical, economic and regulatory challenges associated with large-scale deployment, ultimately leading to reduced greenhouse gas emissions and promoting sustainable urban energy systems.

1. INTRODUCTION

Addressing the seasonal and fluctuating energy supply challenges posed by renewable energy sources, such as solar thermal energy, the utilization of borehole thermal energy storage (BTES) emerges as a promising technology (Homuth et al., 2012). This method can guarantee a consistent and reliable heat supply even with fluctuating renewable energy sources (Lanahan and Tabares-Velasco, 2017; Miedaner et al., 2015; Welsch et al., 2016). The core technology involves the deployment of Borehole Heat Exchangers (BHE) (Figure 1), which conductively transfer heat within a water-closed loop (Bär et al., 2015). By installing multiple BHEs at a close distance, a subsurface heat storage system can be established (Welsch et al., 2016). While shallow BHE storages, extending up to a depth of 250 meters, are commonly used (Gehlin, 2016), they may pose risks to upper aquifers utilized for drinking water, as these should not be heated and might also dissipate the stored heat (Figure 1). Targeting these concerns, the concept of Medium-Deep Borehole Thermal Energy Storage (MD-BTES) was proposed (Bär et al., 2015; Schulte et al., 2016; Welsch et al., 2016). An advantageous thermal insulation of the upper part of the BHE, as well as exploiting greater depths to achieve higher temperatures with reduced surface area requirements, make MD-BTES suitable for urban environments (Welsch et al., 2018). This approach is particularly effective in regions characterized by specific basement rock features, including crystalline structure, low permeability, and high thermal conductivity. Integrating such heat storage solutions into a community's energy grid can support building heating and industrial processes, enhancing energy system efficiency and reducing greenhouse gas emissions (Hirvijoki and Hirvonen, 2022; Welsch et al., 2018).

In 2022-2023, one of the world's first research MD-BTES was set up on the Lichtwiese campus of TU Darmstadt. This development is part of the SKEWS project, supported by the German BMWK, PtJ (ID: 03EE4030A), and the European PUSH-IT project funded by EU-Horizon (ID: 101096566). The project aims not only to investigate the geological framework and integrate the storage site into the district heating grid but also to assess storage performance and efficiency using distributed Geothermal Response Test (dGRT) data and a long-term test phase. This contribution presents an update on the geological context, plans for district heating grid integration, and preliminary results regarding the storage system's performance and efficiency.

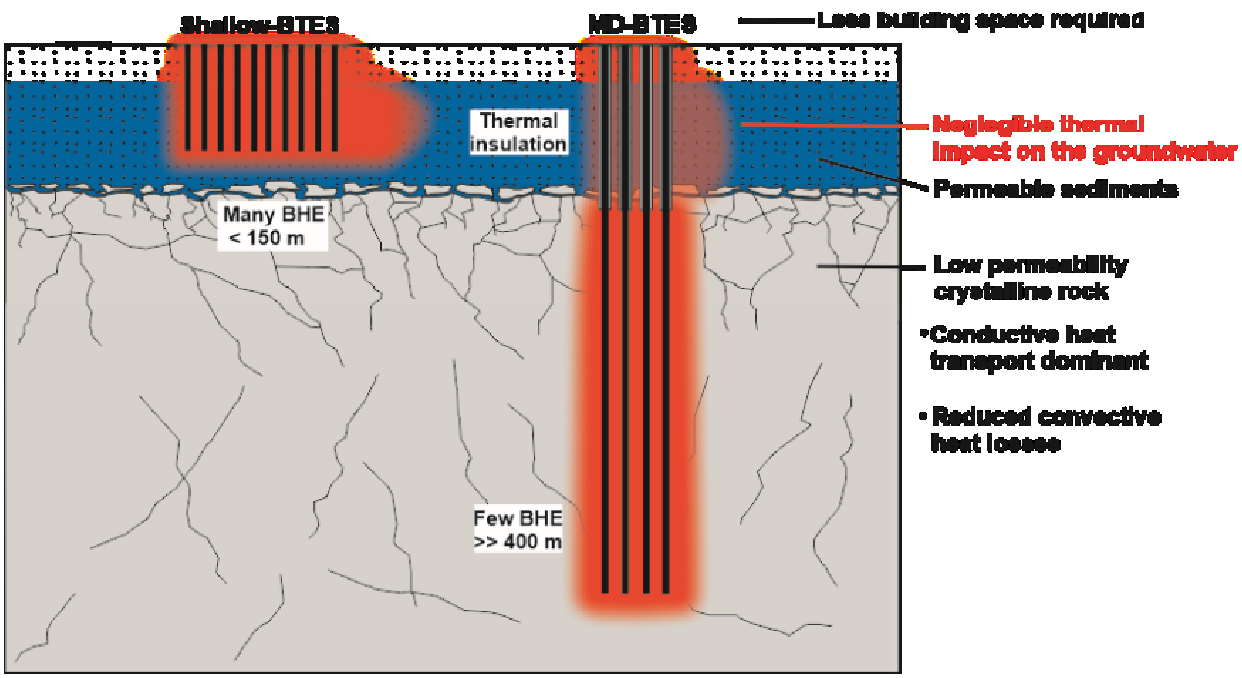

Figure 1: Characteristics of MD-BTES after Sass et al., (2016).

2. GEOLOGICAL CONTEXT

The region of Darmstadt is geologically divided into two parts due to its location on the eastern border fault system of the Upper Rhine Graben. The northwestern part is characterized by Quaternary and Tertiary sedimentary units and belongs to the Upper Rhine Graben, while the southeastern area, including the SKEWS pilot site, belongs to the northern crystalline Odenwald (Figure 2). The Odenwald Crystalline Complex, within the Variscan orogen's Saxothurigian Zone, is the largest exposed massif in the Mid-German Crystalline High.

The region around Darmstadt features a metamorphic framework and plutonic lithologies with an emplacement age of 362 +/- 9 Ma (Kirsch et al., 1988). Recent research suggests an emplacement age of 540 ± 8 Ma for the metagranites in this area (Dörr et al., 2022). The granodiorites of the Darmstadt pluton likely intruded these pre-Variscan rocks around 342 +/- 2 Ma based on recent dating. During the Permo-Carboniferous, intramountainous basins formed due to crustal extension after the variscan orogeny, filled with arid sediments. These basins contain proximal alluvial and fluvial fans and playa lake deposits. As a result, basement rocks are partially overlain unconformably by the Permo-Carboniferous siliciclastic series, some carbonates and volcanic rocks, resulting in a highly heterogeneous surface and subsurface geology.

At the Lichtwiese Campus of the TU Darmstadt geological mapping and shallow boreholes reveal various lithologies of the Frankenstein Intrusive Complex beneath a thin Quaternary cover. Just south of the Lichtwiese campus, a "mylonitic" fine-grained biotite granite (named G1) has been mapped. To the southeast of the G1 granite outcrops, pre-Variscan metabasites form a SW-NE (Variscan) trending boundary with the granite. In the northeast, the fine-grained G1 granites are adjacent to Permian sediments and Permian andesitic to basaltic volcanics. The contact between the basement rocks and Permian cover in this area remains unclear, but previous studies suggest displacement along a steeply east-dipping normal fault zone (or fault zones) could be responsible for the juxtaposition of both units.

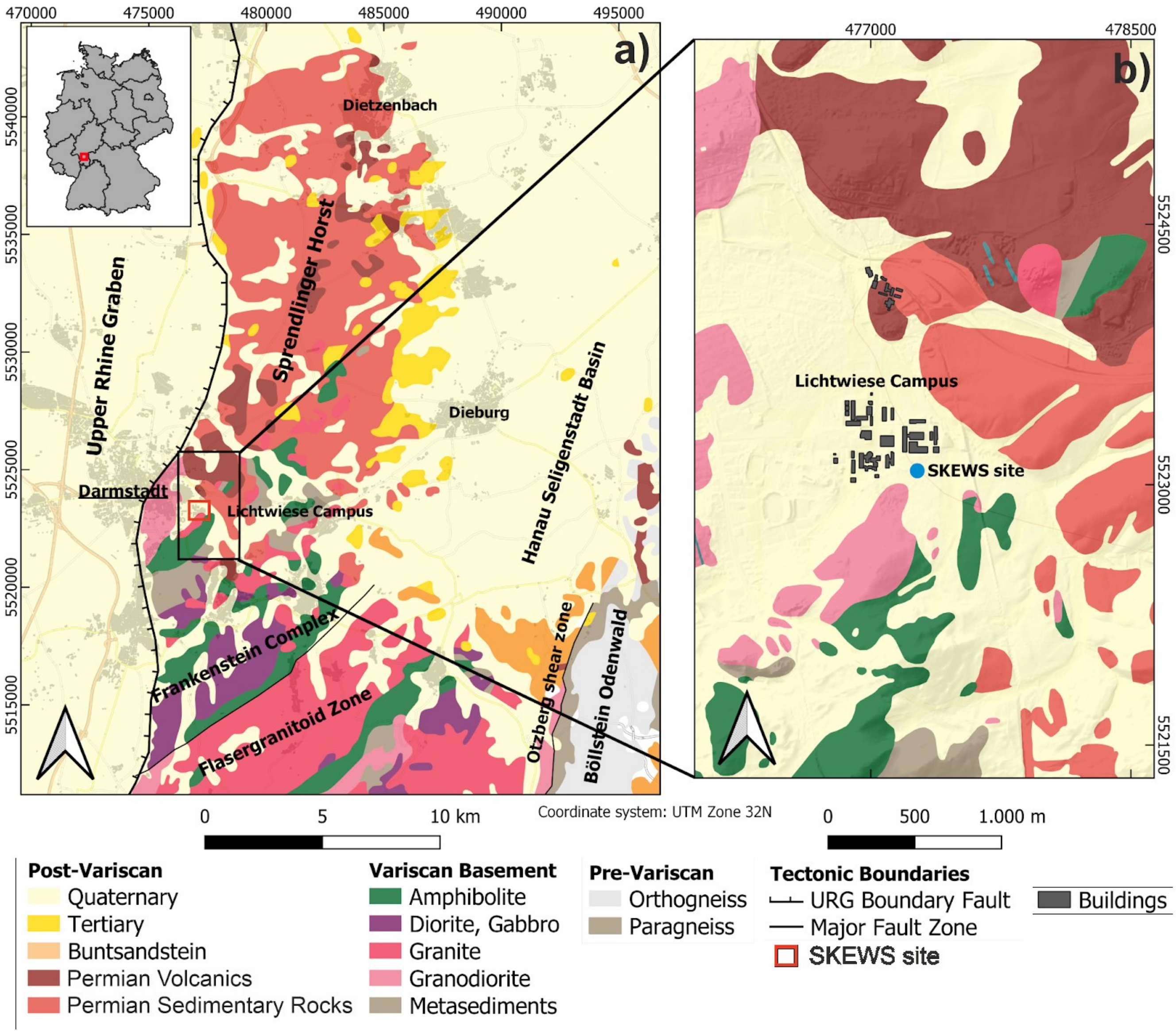

Figure 2: Regional (a) and local (b) geological setting of the study area (modified after HLNUG (2007) and Seib et al., (2022)).

3. SITE CONSTRUCTION AND STORAGE INTEGRATION

The SKEWS site construction and storage site integration followed several steps integrated into the SKEWS and PUSH-IT projects. The exploration phase plan (Figure 3) included a pre-study involving the collection of pre-existing data regarding surface geology through drilling and/or field mapping, as well as the study of publicly available resources from various sources. Subsequently, a multi-method surface and near-surface geophysical campaign was initiated, including electrical resistivity tomography, gravimetry, 2D seismic analysis, and detailed examination of nearby outcrops. The entire workflow is explained extensively in Seib et al., in press.

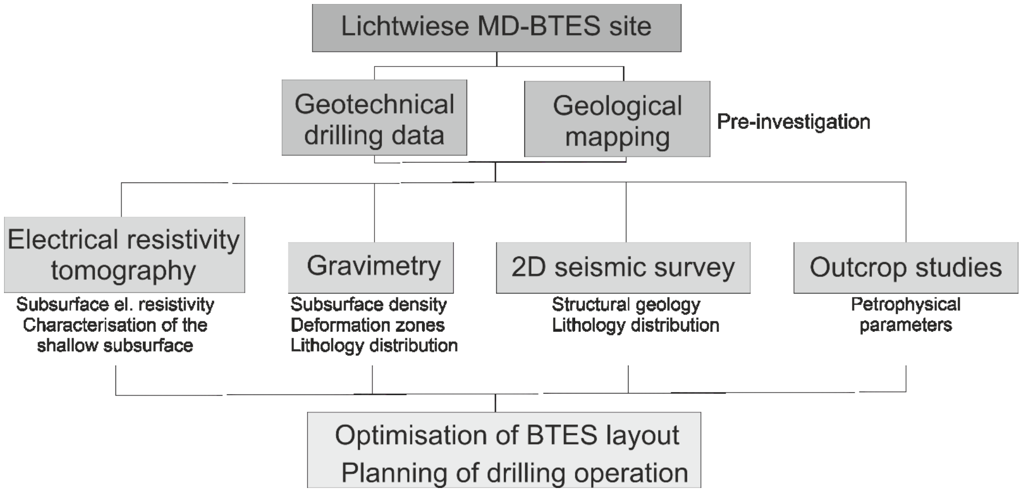

Figure 3: Concept for the exploration of the SKEWS site (Seib et al., in press).

3.1 Pre-Design and Data Collection

Historical drilling data from previous shallow drilling activities conducted in the area were collected, along with the compilation of existing geological maps and site-specific research studies (Figure 2, Figure 3). 400 archive records of local geotechnical drillings were manually analyzed to infer the surface distribution of geological units (Seib et al., 2022). However, 82 % of the boreholes do not exceed a depth of 20 m, which only allows inferences about the near-surface geology.

3.2 Geophysical Surveying and Geological Conceptual Model

The geophysical campaign consisted of a gravimetric survey to characterize variations in the local gravitational field, revealing differences in subsurface density and the presence of geological structures. As gravimetric measurements are often ambiguous on their own, a 2D reflection seismic survey was added to complement the dataset. To increase the availability of shallow subsurface data, several electrical resistivity tomography profiles were acquired in the vicinity of the project site. By integrating these geophysical methods, a comprehensive subsurface model was constructed, updating the geological knowledge of the site. Each method contributed unique and complementary data that, when combined, provided a multi-dimensional view of the subsurface. Based on the gathered data a new model, emphasizing the particular fault block structure in the Lichtwiese region was created (Figure 4).

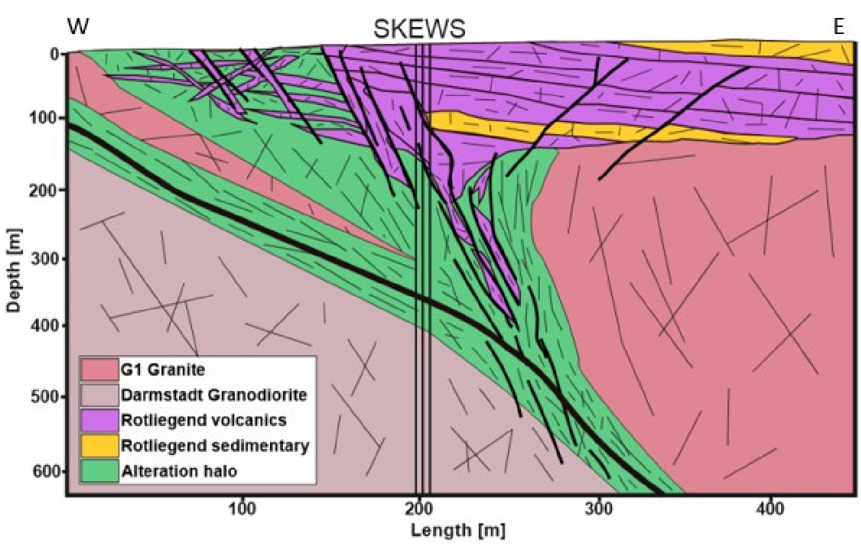

Figure 4: Conceptual structural model for the SKEWS site, with faulted basement/volcano-sedimentary interface, and the detailed structural framework, e.g. crystalline units, fault zones, and associated alteration architecture.

3.3 Drilling phase

Three groundwater monitoring wells were strategically projected and drilled around the designated BHE storage zone in February 2022, preceding the BHEs drilling phase (Figure 5). Employing a rotary drilling approach with an 8.6-inch drill bit, these wells reached depths between 24.5 m and 36.5 m. Drilling intervals of 3 m were maintained for collecting cuttings. After well completion, pumping tests were conducted to ascertain the shallow aquifer characteristics and to confirm interconnectivity and groundwater flow direction.

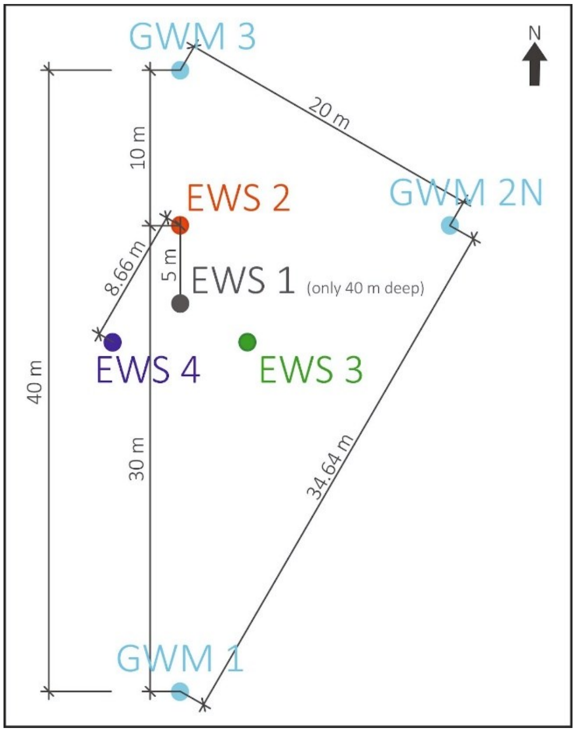

Figure 5: Arrangement of the three groundwater wells GWM 1 - 3 and the four Borehole heat exchangers EWS 1 - 4. Due to cost increases while drilling only EWS 2 - 4 were fully completed to a depth of 750 m (Landau et al. 2023).

In June 2022, construction began on the upper sections of four BHEs, extending to a depth of 46 m, using a 15" pneumatic hammer. This phase involved the installation of a 10 ¾" casing surrounded by cement with a very low hydraulic conductivity to isolate the BHEs hydrologically from the upper aquifer. Cuttings were sampled at 3 m intervals and examined binocularly, resulting in seven profiles that offered a comprehensive view of the lateral extent of the upper segment of the BHE installation.

The deep drilling phase for three BHEs (BHE 2 - 4), targeting depths up to 750 m, was conducted from July to October 2022. Owing to the increased costs associated with a transition from down-the-hole hammer to rotary drilling techniques with a clay-freshwater drilling fluid, the completion of "BHE 1" was deferred to a subsequent extension phase. The BHEs were drilled sequentially as BHE 3, BHE 4, and BHE 2, with an initial surface spacing of 8.66 m. This arrangement, including BHE 1, was intended to achieve an optimal concentric spacing of 5 m between boreholes at depth for reasons of efficiency, as recommended by previous research (Schulte et al., 2016; Welsch et al., 2016).

The first borehole, BHE 3, was initiated using a 9.5-inch pneumatic down-the-hole hammer to a depth of 127 m (Figure 7). Significant groundwater inflow prompted an attempt to switch to a hydraulic hammer, resulting in notable water loss and ineffective circulation. Due to this significant fracturing and instability of the borehole, a transition to rotary drilling using clay freshwater mud was required. In addition, to address mud losses and stabilize the borehole, intermediate cementations were applied in BHE 3 between 46 m to 180 m and 344 m to 550 m, and similarly in BHE 4 and BHE 2 from 46 m to 250 m. The second cementation in BHE 3 led to blockages in the surrounding fractures, obviating the need for further cementation in the other boreholes. Ultimately, the rotary drilling method was predominantly utilized, with only limited testing of the hydraulic hammer technique.

As the verticality of the BHE is of great importance for both reservoir efficiency and collision avoidance during the drilling phase, this should be achieved using the hydraulic impact hammer technique (Krusemark et al., in prep.). In this technique, the penetration is mainly achieved by perpendicular percussive crushing of the rock. In contrast, with the rotary method, the penetration is achieved by the rapid rotation of the drill bit, which more likely follows the major boundaries of the local lithologies. However, due to the necessity of using the rotary method and the absence of directional drilling technology, deviations in the drilling path were expected in accordance with the geological conditions. Figure 6 shows an average bore path deviation of 5.0° for EWS 2, 2.3° for EWS 3, and 3.3° for EWS 4 with a general direction to NW/NWW.

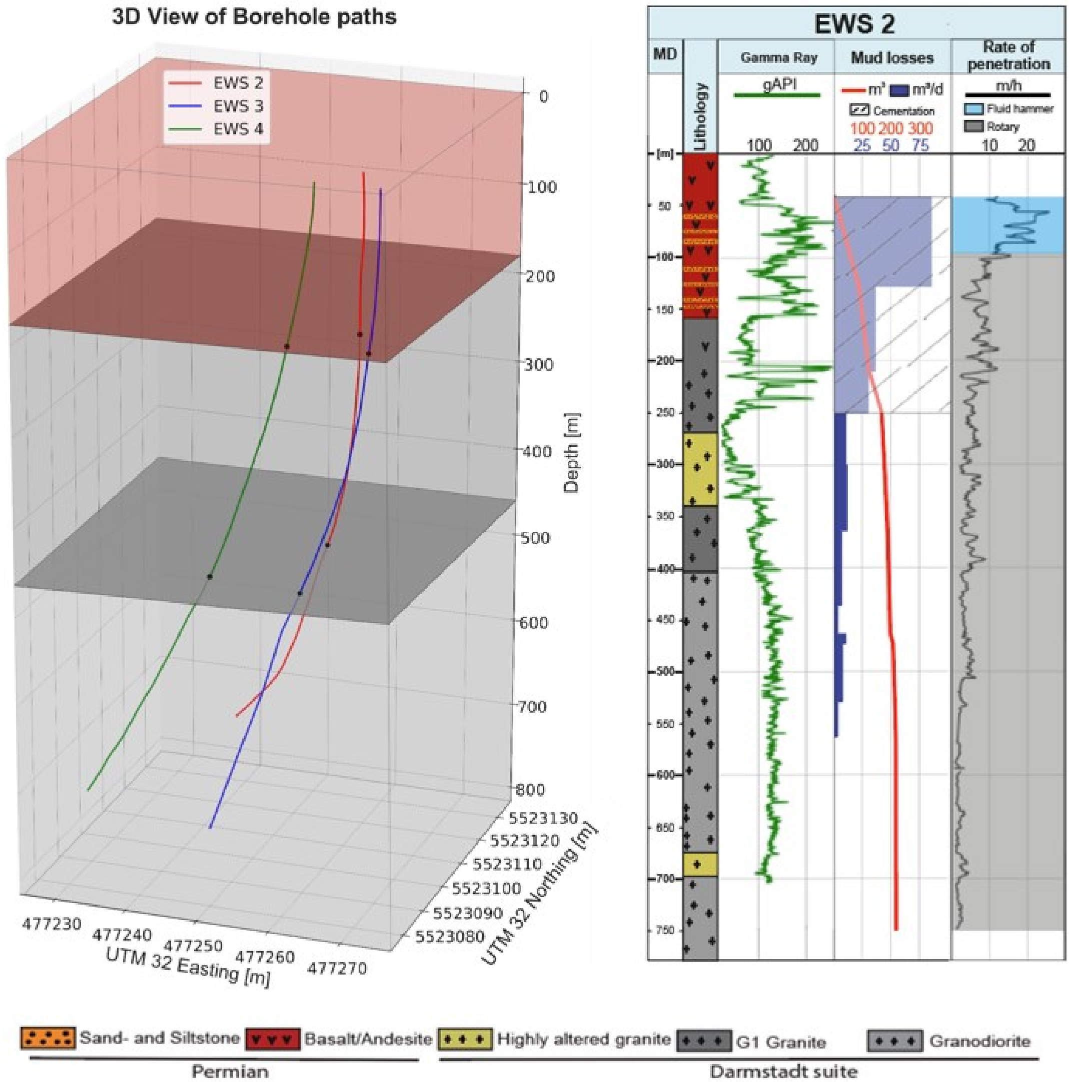

Figure 6: On the left, 3D view of the borehole paths (highly compressed in height, slightly modified after Landau et al., (2023). On the right, is the profile of EWS 3, showing different drilling techniques and the corresponding mud losses and rate of penetration (Bossennec et al. in prep).

Following the completion of drilling operations, geophysical borehole logs such as caliper, gamma-ray, resistivity, acoustic televiewer, temperature, etc. were also carried out in the three boreholes (Figure 6, Figure 7). The high-resolution, three-dimensional data obtained from these logs provide a unique opportunity to construct a detailed geological model. The extensive dataset collected enables a comprehensive ecological and economic assessment of the research MD-BTES SKEWS. This evaluation considers various scaling scenarios of the storage system, ranging from 19 to 37 BHEs, to enhance transferability to other potential locations. The drilling and subsequent logging of the BHEs have not only provided the validation and refinement of prior geophysical and numerical models but also confirmed the technical viability of constructing an MD-BTES system, demonstrating its practical feasibility.

4. RESERVOIR CHARACTERIZATION

Geophysical multi-method borehole logging supports the precise characterization of different zones along the three BHEs (Figure 7). These seven zones exhibit distinct signatures regarding resistivity, magnetic susceptibility, Vp-slowness, and gamma-ray measurements, revealing the heterogeneity at the wellbore scale within the reservoir. This heterogeneity is associated with various geological features, including fractured corridors, fault zones, alterations along these structural elements, as well as distinct lithologies within the crystalline basement, which is regionally known as the Darmstadt suite. The upper 160 meters of the well contain a thick pile of basalt and inter-volcanic sediment layers known as the Rotliegend units, attributed to the Moret Formation. This unexpected thickness is explained by the well's position in a feeder dyke connected to multiple eruptive flows. Faulting between the crystalline basement and Permian basalt is noted further north from the storage site. Fracture density in the basalts and sedimentary materials is limited by lava flow boundaries, challenging direct identification in borehole imaging. The model suggests a climbing feeder dyke along a structural boundary linked to deeper crystalline basement structures, comprising granodiorite intruding the G1 granite. A structural contact between the two plutons exhibits fault characteristics, including increased fracture intensity and variable orientation. This fault zone is believed to have a multi-branch architecture and is associated with basalt layers. The fault-controlled model explains the unusual thickness of Permian basalt under the Lichtwiese campus (Figure 4).

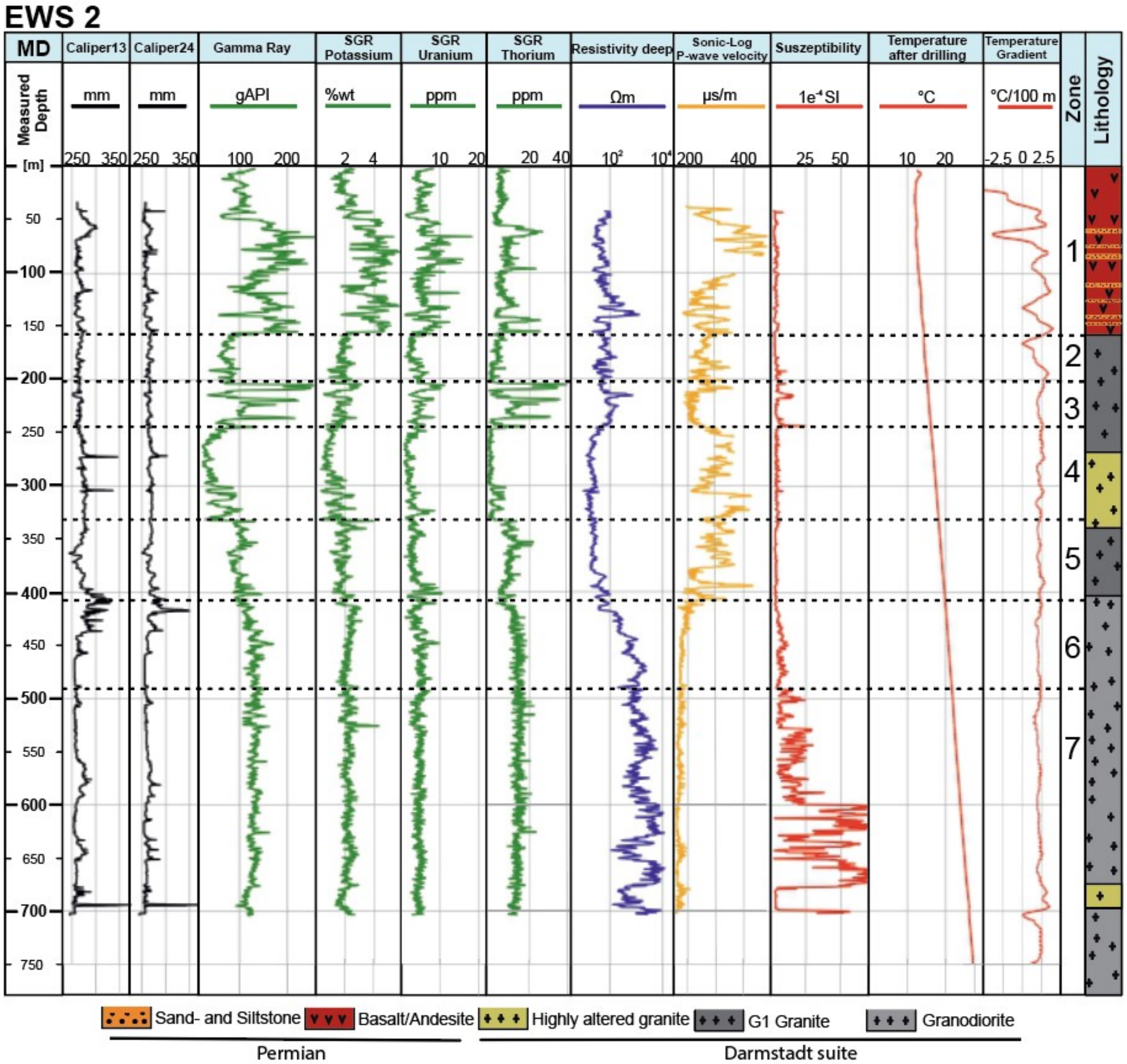

Figure 7: Example of the dataset used for reservoir characterization (here BHE 2) with borehole logs and lithological units from cutting survey, adapted from Bossennec et al. (in prep).

5. ENHANCED GEOTHERMAL RESPONSE TEST AND TRIAL OPERATION-PHASE

The research program intends to simulate artificially the response of the storage site to various types of storage regimes, with constant loading, parallel or serial connection, and fluctuations of higher frequency, for instance representing solar thermal modules. After the drilling, a distributed Geothermal Response Test (dGRT) was conducted in one of the BHEs (Figure 8). The dGRT provides in-situ thermal properties of the ground (apparent thermal conductivity) and the geothermal installations (thermal resistance of boreholes). Furthermore, the goal is to identify fractured and faulted zones characterized by increased groundwater flow. The dGRT was planned to be conducted only in one borehole, to ensure for no overlapping thermal signals. The heat was provided by a 150 kW heating unit which was connected to the BHE fluid system with a heat exchanger. The pumping rate was 2 l/s. The in- and outlet temperature were monitored with two PT100 temperature sensors each and the volume flow was logged by magnetic-inductive flow sensors. Furthermore, the temperature of the inner pipe, the annulus, and the grout were monitored using one optic fiber cable each.

After the cooldown phase of the dGRT, the storage test operation will follow. BHEs typically show an improvement in the degree of storage utilization in the first few years of operation. To understand this behavior, the storage test operation will be carried out in five shortened injection and extraction cycles. The reversal of the flow direction of the coaxial BHE from the fluid inlet through the inner tube (CXC) to fluid entry through the annular gap (CXA) when changing from injection to extraction. Each injection phase is planned to last 6 weeks. The resulting temperature curves of flow and return, as well as the temperature profiles, are intended to validate long-term simulations. The groundwater monitoring wells will be monitored during the whole testing phase with optic fibre temperature measurements and automatic logging of groundwater parameters.

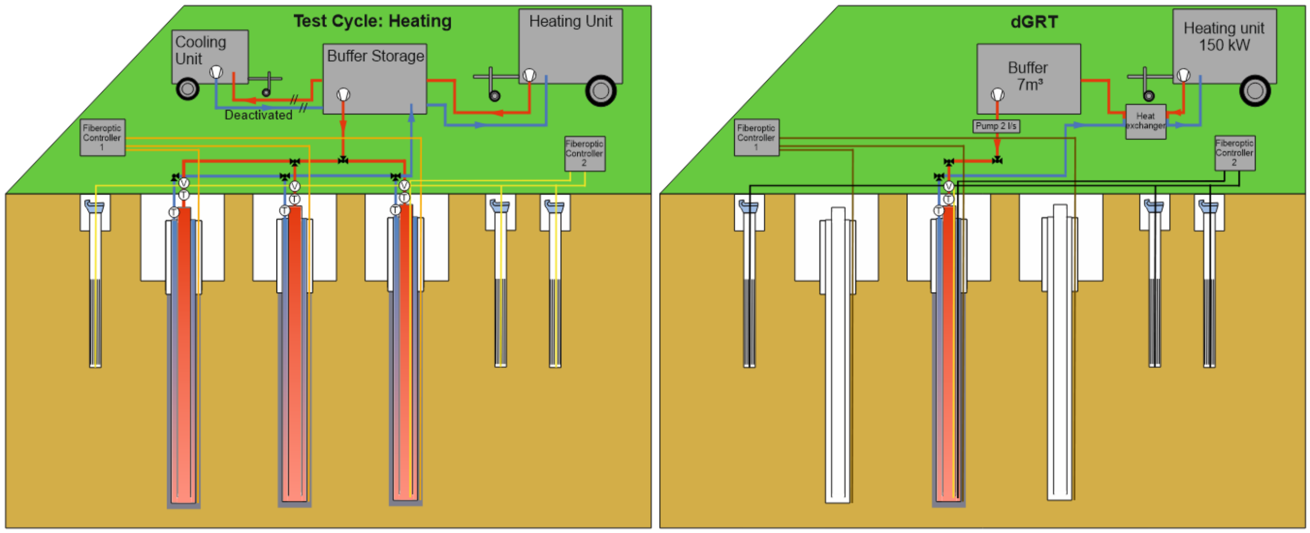

Figure 8: Test-cyle heating and dGRT installations (Seib et al. 2023)

6. GRID INTEGRATION DESIGN

After completing the dGRT and the test phase at the end of 2024, the integration of the MD-BTES into the District-Heating-Network (DHN) at TU Darmstadt will be investigated (Figure 10). This assessment will involve the charging of the storage system using solar thermal energy and residual heat from a high-performance computing facility situated in the nearby new building L1/16. Additionally, the system is designed to store excess heat from the DHN, generated by the Combined Heat and Power plant (CHP), into the MB-BTES. During the discharge phase, the storage is anticipated to deliver temperatures ranging from approximately 20°C to 45°C depending on the loading state, which will be lifted to temperatures of approx. 55 - 75°C via a high-temperature heat pump and supplied back to the DHN. The study aims to analyze the operational efficiency of the system by employing advanced control technologies and co-simulation tools. This will include determining optimal operational parameters such as the flow rates before and after the heat pump, charging and discharging cycles, electricity consumption, and associated costs. Furthermore, temperature monitoring along the connecting pipelines will be conducted using fiber optic sensors to quantify thermal losses within the system, as different connection pipe backfill materials will also be installed and tested.

By investigating the parameters related to the DHN system and those to the MD-BTES, a co-simulation approach will be employed to integrate thermal-hydraulic numerical simulations of BHE in the subsoil (finite element models with heat transport and groundwater flow) with detailed simulation tools for DH infrastructure (1D thermo-fluid flow). A modelica-based library for co-simulation of district heating grids with FEFLOW numeric subsurface BHE models has already been developed (Formhals et al., 2021).

The insights derived from this comprehensive analysis will contribute to the development of a guideline for the construction of medium-depth geothermal probe storage systems, with a specific focus on their integration into DHN. This guideline is intended to facilitate the replication of such systems in other urban locations, enhancing the sustainability of urban heating solutions. The outcomes will also be incorporated into the Life Cycle Assessment (LCA) and Levelized Cost of Heat (LCOH) calculations to provide a holistic evaluation of the system's environmental and economic performance.

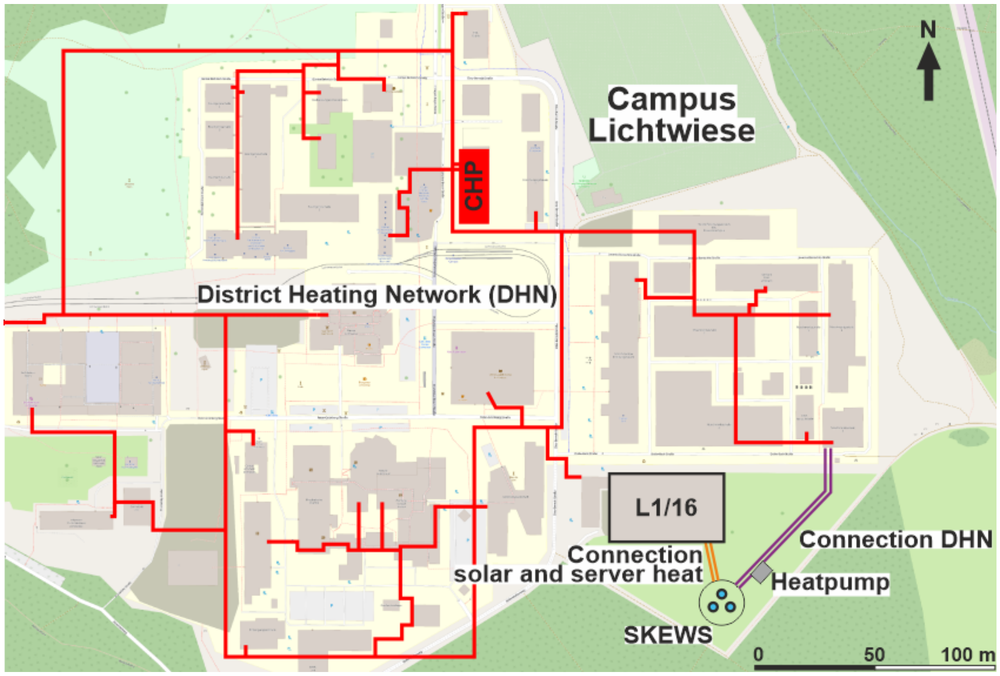

Figure 10: Conceptual design for integrating the MD-BTES (SKEWS) into the District Heating Network (DHN)(violet lines) at the Campus Lichtwiese of the TU Darmstadt. The heat sources are solar thermal collectors and waste heat from the high-performance computer in the L1/16 building.

7. OUTLOOK

MD-BTES is a promising solution for storing thermal energy for extended periods of time, thereby helping to stabilize the energy supply, reduce reliance on fossil fuels and contribute to a more sustainable and environmentally friendly energy mix. By storing excess thermal energy generated from renewable sources, MD-BTES can play an important role in reducing energy waste and increasing the overall efficiency of renewable energy systems. The primary goal of the SKEWS project is to install and test an MD-BTES (Medium-Depth Borehole Thermal Energy Storage) pilot system in crystalline rocks.

To understand and describe the performance of this reservoir, it is essential to identify geological formations capable of efficiently storing thermal energy through extensive geophysical surveys and geological assessments. This process ensures that MD-BTES systems are deployed in geologically suitable areas. Additionally, it involves constructing a demonstration site, including drilling, completion, and reservoir testing, to gather quantitative data for cost analysis and the wider implementation of MD-BTES technology. MD-BTES construction and integration into the district system involves a multi-faceted approach, including drilling techniques, geophysical surveys, and geological analyses, to create a robust and efficient reservoir capable of effectively storing and retrieving thermal energy, supporting the development of sustainable energy solutions. By having a demonstration case of how to incorporate MD-BTES into the pre-existing district heating grid, the PUSH-IT project aims to enhance the integration and expandability of MD-BTES systems within district heating systems and energy infrastructures, rendering them more versatile and accommodating of diverse energy sources. Consequently, this initiative contributes to the overarching goal of reducing greenhouse gas emissions in the heating and cooling sector.

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