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Integrating Medium-Deep Borehole Thermal Energy Storage into a University District Heating Network: Progress from the PUSH-IT Project at TU Darmstadt

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INTRODUCTION

Achieving net-zero greenhouse gas emissions by 2050 requires substantial decarbonization of the heating and cooling sector, which constitutes approximately 50 % of total final energy consumption in Europe (Billerbeck et al., 2024). The utilization of renewable heat sources, such as solar thermal or industrial waste heat, is hindered by seasonal temporal mismatch. To address this, underground large-scale seasonal Thermal Energy Storage (UTES) technologies play important roles for optimizing the use of low-cost, low-carbon heat with low operating costs.

The PUSH-IT (Piloting Underground Storage of Heat In geoThermal reservoirs) project (EU Horizon, Grant Agreement No. 101096566) demonstrates full-scale, high-temperature (up to 90 °C) seasonal heat storage using three UTES technologies which are mine, borehole, and aquifer thermal energy storage (MTES, BTES, and ATES), across six European pilot sites (Darmstadt, Delft, Bochum, Berlin, Litoměřice, and United Downs). The project aims to advance these technologies toward higher Technology Readiness Levels (TRLs) through field implementation and validation.

The Medium-Deep Borehole Thermal Energy Storage (MD-BTES) concept, bridges the gap between shallow BTES (<200 m) and deep systems (>1,000 m) (Bär et al., 2015; Welsch et al., 2018). It utilizes fewer but deeper boreholes (400–1,000 m) in low-permeability crystalline rock, offering two main advantages: (1) a smaller surface footprint, which is particularly valuable in urban areas, and (2) minimal interference with shallow groundwater, as heat storage primarily occurs via conduction at depth.

At the TU Darmstadt demonstration site, three 750 m-deep coaxial Borehole Heat Exchangers (BHEs), initially developed under the national funded SKEWS (Seasonal Crystalline Geothermal Storage) project, are integrated into the university's district heating network. Designed for storing surplus campus heat (>70 °C) with an approximate capacity of 270 kW, the system aims to elevate the TRL from 5–6 to 7–8 by validating continuous operation and direct district heating integration. This demonstration represents a significant step toward scalable, urban-compatible seasonal heat storage for Europe's carbon-neutral energy transition.

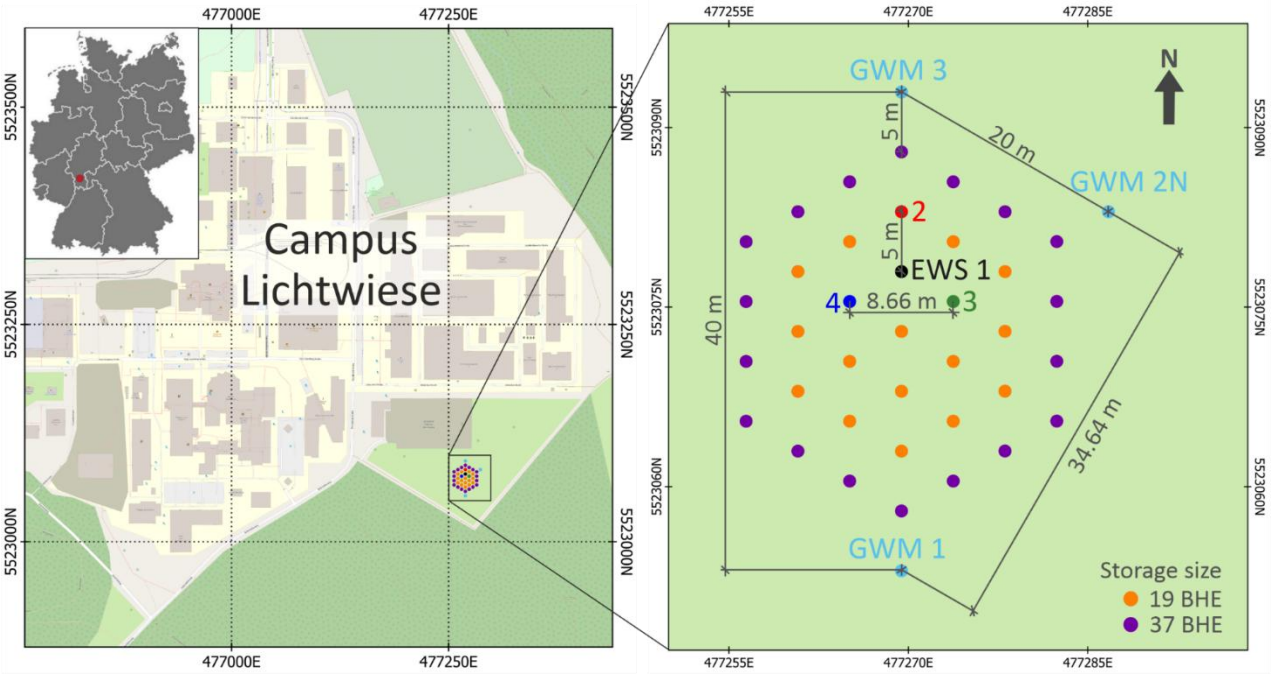


Figure 1: The MD-BTES system at the Campus Lichtwiese of TU Darmstadt consists of three 750 m-deep boreholes (EWS 1, EWS 2, and EWS 3), three groundwater monitoring wells (GWM 1, GWM 2, and GWM 3), and potential upscaling scenarios involving 19 or 37 boreholes (Krusemark et al., 2025)

1 GEOSCIENTIFIC EXPLORATION AND RESERVOIR CHARACTERIZATION

1.1 Geological setting

The site is situated in the southeastern part of Darmstadt, at the eastern boundary fault system of the Upper Rhine Graben (URG) and within the northern Odenwald crystalline complex. Preliminary models suggested a homogeneous granodioritic basement, but integrated geophysical and drilling investigations revealed a significantly more heterogeneous subsurface.

Prior to drilling, 2D seismic profiles, gravimetric data, and Electrical Resistivity Tomography (ERT) were acquired to outline geological structures (Seib et al., 2024). Drilling operations uncovered an unexpected ~160 m-thick Permian basaltic unit interbedded with volcanic sediments (Rotliegend formation), substantially thicker than initial predictions. This unit overlies the Variscan basement composed of the Lichtwiese granite and Darmstadt granodiorite.

Seismic interpretations revealed a westward-dipping fault separating the basaltic and granitic units, while ERT (electric resistivity tomography) confirmed low resistivities corresponding to altered and water-saturated basalt. The upper section (0–160 m) exhibited intense fracturing, requiring a shift from percussive to rotary drilling to stabilize the borehole walls.

1.2 Borehole layout and deviation

Post-drilling gyroscopic surveys indicated deviations from vertical alignment ranging between 2.3° and 5.0°. Consequently, the inter-borehole spacing at depth varied between 21 m and 48 m—significantly exceeding the designed 5 m separation. This deviation impacts the thermal interaction between boreholes and must be accounted for in numerical modeling and field performance evaluation (Krusemark et al., 2025).

2 THERMAL PERFORMANCE AND EXPERIMENTAL TESTING

2.1 Distributed geothermal response test (dGRT)

To assess subsurface thermal properties and the system's dynamic response, a Distributed Geothermal Response Test (dGRT) was performed on one borehole (EWS 2) over 42 days in late 2023. The test involved a constant high-power heat injection (120–125 kW, ≈ 200 W m^{-1} specific rate), allowing detailed thermal profiling via fiber-optic temperature sensing (Seib et al., 2025).

2.2 Thermal properties

Results yielded an effective thermal conductivity (λ_{eff}) of 2.3 W m^{-1} K^{-1} on average, ranging between 2.0 and 2.6 W m^{-1} K^{-1} depending on lithology and alteration intensity. The Borehole Thermal Resistance (R_b) decreased with depth, from ~0.04 m K W^{-1} near surface to ~0.01 m K W^{-1} at 700 m, indicating improved conductive coupling in deeper sections. A low-thermal-conductivity grout (0.6 W m^{-1} K^{-1}) was used in the upper 180 m to reduce unwanted heat leakage into the shallow aquifer.

2.3 Internal heat transfer and short-circuiting

Thermal analysis identified significant short-circuiting between the inner and annular flows in the coaxial configuration. Up to 50 % of input heat from the inner pipe was lost to the annulus, with approximately 41 % of that loss occurring at designed clearances in the polypropylene (PPR) liner. However, COMSOL simulations indicated that despite internal short-circuiting, the total seasonal efficiency reduction remains moderate (~1–5 %) due to the high overall storage volume and conductive heat retention.

2.4 Influence of PPR liner

The boreholes are equipped with coaxial pipes featuring a PPR (Polypropylene) inliner. A comparison was conducted between the PPR liner and a vacuum-insulated casing developed in the HOCLOOP project (www.hocloop.eu) based on dual-pipe technology. For the MD-BTES system, the vacuum-insulated inner casing does not provide a significant efficiency advantage over the PPR liner.

2.5 Long-term thermal cycling

A year-long operational test (ending February 2025) comprising five complete heating and cooling cycles demonstrated measurable heat accumulation in the reservoir, confirming the viability of seasonal storage. The thermal recovery factor (TRF) was approximately 11 %, corresponding to 930 MWh injected and 105 MWh extracted, a result consistent with expectations for a small three-borehole demonstrator system with limited surface-area-to-volume ratio. However, in upscaling scenarios with 19 or 37 boreholes, efficiencies of up to 80% can be expected to be achieved with optimal borehole spacing. (Krusemark et al., 2025).

3 DISTRICT HEATING NETWORK INTEGRATION

3.1 System Integration

The integration of the Darmstadt MD-BTES system into the Campus Lichtwiese District Heating Network (DHN) represents the core objective of the PUSH-IT deployment phase. The DHN serves a heated area of roughly 155,000 m^2 using gas-fired Combined Heat and Power (CHP) plants and boilers. Typical return temperatures of 55–75 °C make the network compatible with the BTES discharge temperature range.

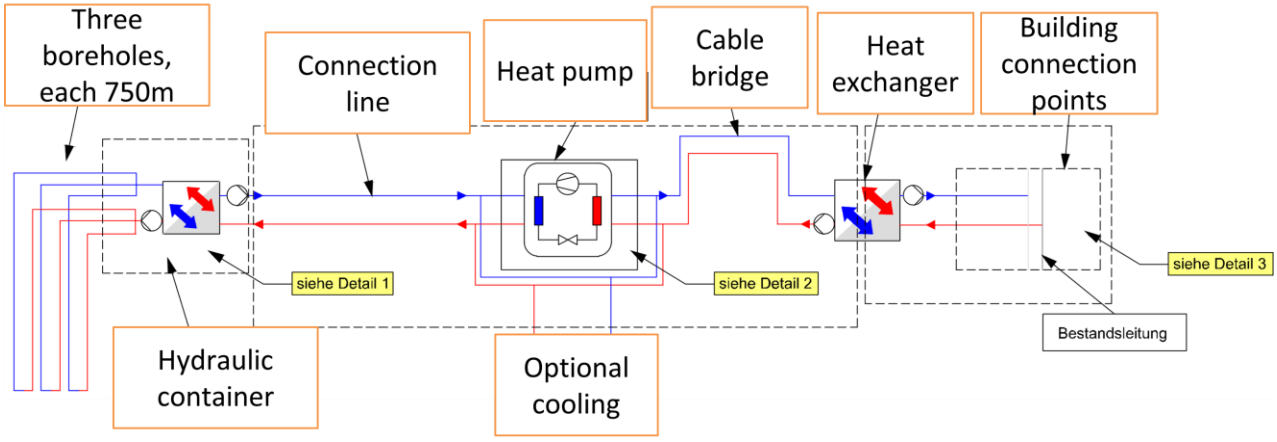


Figure 2: Connection scheme to connect three boreholes to the district heating network

4.2 Infrastructure and Hydraulic Connection

By August 2025, construction milestones were achieved, including an onsite hydraulic container and a 200 m connection pipeline linking the borehole field to the main mechanical engineering building. The connection line uses DN 65 PEX pipes, with approximately 140 m installed underground. In one section, standard PEX-pipes embedded in flowable foam concrete with an apparent backfill thermal conductivity of about 0.2 W m^{-1} K^{-1} were

used instead of pre-insulated pipes. Thermal modeling confirmed comparable performance to standard pre-insulated steel piping while offering potentials for reducing installation complexity and cost.



Figure 3: Progress at the Darmstadt site by the end of Q3 2025

3.2 Heat Pump Integration

To bridge the temperature gap between storage discharge (25–45 °C) and DHN return (55–75 °C), a Trane RTS050 water-cooled screw compressor heat pump (150–300 kW) was selected. This unit provides the necessary temperature lift for integration and was scheduled for installation in December 2025.

3.3 Monitoring and Instrumentation

The system is fully instrumented for real-time monitoring. Distributed Temperature Sensing (DTS) cables are installed along all BHEs and connecting pipelines, complemented by conventional temperature and soil moisture sensors. Hydro-chemical monitoring of three groundwater wells (GWM 1–3) provides assurance against potential thermal or geochemical impacts on the shallow aquifer system.

4 MODELLING, CONTROL, AND DIGITAL INTEGRATION

Advanced modeling supports the operational strategy of the Darmstadt site. A 3D finite element (FEFLOW) model, calibrated using dGRT results and borehole deviation data, captures the subsurface thermal behavior. This model is dynamically coupled with a Modelica/Dymola-based system model representing the hydraulic components, heat pump, and DHN interface.

The combined co-simulation environment functions as a digital twin, enabling predictive control for optimizing storage utilization, minimizing temperature differentials, and improving overall energy efficiency. Simulated scenarios assess system behavior under varying operational conditions and provide a foundation for the design of scalable MD-BTES arrays.

5 OUTLOOK AND FUTURE WORK

By the third quarter of 2025, the Darmstadt MD-BTES demonstration had progressed from initial exploration to full technical integration. The upcoming milestones include the installation and commissioning of the heat pump, implementation of control algorithms, and execution of charging (autumn 2025) and extraction (winter 2025–2026) phases.

Comprehensive performance evaluation will quantify system efficiency, thermal recovery, and control performance. These outcomes will inform the potential upscaling to 19 or 37 boreholes, which would substantially enhance the storage volume and raise recovery factors to commercially viable levels.

The lessons learned in Darmstadt—covering geological complexity, drilling challenges, borehole deviation management, and high-temperature operation—provide valuable insights for future urban geothermal energy storage systems. As one of Europe’s first operational high-temperature MD-BTES systems in crystalline rock, the

site demonstrates the technological readiness and practical feasibility of seasonal geothermal storage integrated into existing district heating infrastructures.

The Darmstadt demonstration represents a crucial step toward the deployment of medium-deep high-temperature borehole storage in crystalline environments. Through integrated geoscientific, thermal, and digital modeling workflows, the project validates the operational principles required for coupling geothermal storage to district heating systems. Despite limitations in recovery due to small array size, the project confirms:

- The technical feasibility of storing at up to 90 °C and retrieving heat from medium-deep crystalline formations.
- The importance of site-specific geological and drilling data for system design and model calibration.
- The viability of integration with existing DHN infrastructures through tailored hydraulic and control strategies.

The Darmstadt MD-BTES project thus provides a replicable blueprint for future large-scale seasonal heat storage installations, supporting the transition toward sustainable, low-carbon urban heating systems in Europe.

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