EuroSun 2026

REDUCING WINTER ELECTRICITY DEMAND THROUGH OVER-REGENERATION OF BOREHOLE THERMAL ENERGY STORAGE: OPERATIONAL AND GROUNDWATER INSIGHTS FROM THE OST CAMPUS DEMONSTRATOR

Summary

This study investigates the role of operational strategies for Borehole Thermal Energy Storage (BTES) in reducing winter electricity demand in heat-pump-based heating systems. Using a campus-scale demonstrator, the study focuses on deliberate over-regeneration of a borehole field during summer and its impact on seasonal electricity demand profiles. In addition, the thermal interaction with groundwater is analyzed using detailed three-dimensional numerical simulations and a dedicated measurement concept. The work combines operational energy system simulations with subsurface modeling and measurement-based validation, providing experimentally grounded insights into the trade-off between annual electricity consumption and winter peak reduction.

Keywords: Borehole thermal energy storage, seasonal thermal storage, winter electricity demand, regeneration strategies, groundwater interaction

Field of application for the findings: Heat pump systems, district and campus-scale renewable heating systems

Addressed audience: Researchers, system planners, and practitioners in seasonal thermal energy storage and renewable heating

1. Introduction

The ongoing electrification of space heating is expected to substantially increase winter electricity demand in many European countries [3]. Heat pumps are a central pillar of decarbonization strategies, but their performance and electricity consumption are strongly affected by source temperature levels, particularly during cold periods. As a result, winter electricity peaks are emerging as a key system challenge. At the same time, the increasing integration of renewable energy sources, in particular solar generation, leads to a growing availability of low-cost electricity during the summer months. Seasonal Thermal Energy Storage (STES) enables a temporal decoupling between heat generation and demand by shifting thermal energy from periods of surplus to periods of scarcity. Borehole Thermal Energy Storage (BTES) is a well-established STES technology, characterized by low surface impact, long lifetime, and suitability for dense urban environments e.g. [1]. Conventionally, BTES systems are designed to operate close to natural ground temperature, where regeneration avoids long term cooling of the ground. Recent studies and practical experience indicate that this conventional operational paradigm can be deliberately relaxed [2, 4]. By actively regenerating the borehole field during summer to temperatures above the natural ground temperature, the performance of heat pump in heating mode can be improved, leading to a reduction in winter electricity demand. This comes at the cost of increased annual electricity consumption and enhanced thermal interaction with the surrounding ground and groundwater. This contribution builds on previous work on seasonal storage and winter electricity reduction and focuses on a campus-scale demonstrator. Two aspects are analyzed in detail: (i) the operational effect of over-regeneration on seasonal electricity demand, and (ii) the resulting thermal impact on the subsurface and groundwater, assessed through numerical modeling and measurement-based validation.

2. Demonstrator and operational analysis

The investigated demonstrator is a university campus where an existing fossil-based heating system is being progressively replaced by a heat pump system coupled to borehole thermal energy storage. The campus comprises two distinct geothermal installations with different maturity levels. A first, already constructed borehole field is in operation and currently supplies a single building of the campus. This field is instrumented and provides measured operational data, including thermal loads and system temperatures. These data form the empirical basis for calibrating and validating the operational simulations presented in this study. In addition, a second, larger borehole field is in the planning phase and is intended to supply the remaining campus buildings. This field has not yet been constructed and is therefore analyzed exclusively through simulations. A schematic overview of the existing and planned borehole fields, together with their spatial relation to the campus buildings, is shown in Fig. 1.

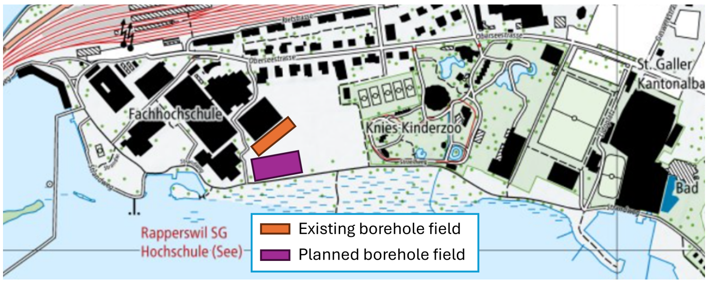

Fig. 1: Campus layout showing the existing operational borehole field supplying a single building and the planned borehole field intended to serve the remaining campus buildings.

Measured building heat demand data from recent years are used as input for operational simulations of the heat pump and borehole field system. Several regeneration concepts are analyzed, including regeneration using building cooling demand, regeneration via ambient air heat exchangers, and active regeneration using the heat pump. The simulations investigate both borehole field sizing implications and resulting electricity consumption profiles. The effect of different regeneration strategies on the electricity demand of the heat pump system over the system lifetime is shown in Fig. 2. Regeneration using building cooling demand results in a limited seasonal redistribution of electricity use and requires a deeper borehole field (84 × 320 m) to maintain acceptable long-term operating conditions. In contrast, regeneration using ambient air heat exchangers allows for a substantially shallower borehole field (84 × 150 m), with increased electricity consumption during summer operation of the air heat exchanger and a moderate reduction in winter electricity demand. The strongest seasonal shift is observed for active regeneration using the heat pump. In this case, electricity consumption is significantly increased during summer due to deliberate over-regeneration of the borehole field, leading to a marked reduction of electricity demand during the heating season. Over the simulated period, winter electricity demand decreases as higher ground temperatures are established, while total annual electricity consumption increases. This illustrates the trade-off between annual electricity use and winter peak mitigation inherent to over-regenerated BTES operation.

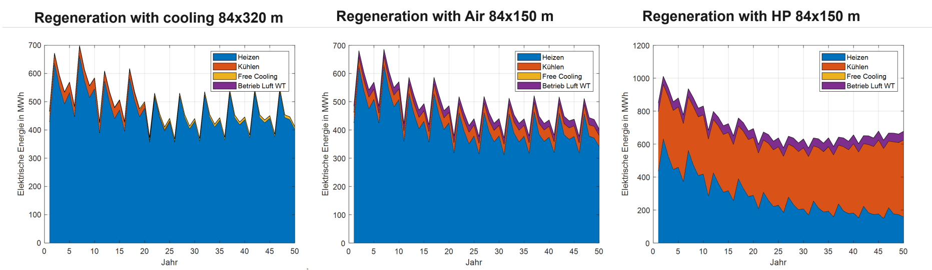

Fig. 2: Effect of different regeneration strategies on seasonal electricity demand of the heat pump system for the planned borehole field.

3. Groundwater and subsurface impact assessment

As illustrated in the campus layout (Fig. 1), the demonstrator site is located in close proximity to a lake and within an area influenced by groundwater flow. Consequently, any operation of the borehole field at elevated temperature levels has the potential to interact not only with the surrounding ground but also with the local groundwater system. This aspect is of particular relevance in the Swiss context, where current groundwater protection rules restrict artificial temperature changes in groundwater to within ±3 K at a distance of 100 m from a thermal installation over a long-term time horizon.

To assess the subsurface impact of over-regenerated BTES operation under these conditions, a three-dimensional finite-element model of the borehole field and surrounding subsurface is developed using COMSOL Multiphysics. The model represents conductive heat transport in the ground as well as advective heat transfer associated with groundwater flow, based on site-specific geological and hydrogeological information. The simulations resolve spatially and temporally varying temperature fields around the borehole field for different operational scenarios. The results indicate a pronounced directional dependence of thermal spreading, with temperature anomalies extending further in the downstream direction of the groundwater flow, as shown in Fig. 3. This asymmetric behavior highlights the importance of explicitly accounting for groundwater flow when evaluating the feasibility of over-regenerated BTES operation in sensitive hydro-geological settings. To validate the numerical model, a dedicated measurement campaign is carried out at the demonstrator site. Temperature Response Tests and distributed fiber-optic temperature sensing are performed in one of the existing boreholes of the operational borehole field, selected as the borehole located furthest downstream with respect to the groundwater flow direction. The resulting high-resolution spatial and temporal temperature data are used to calibrate groundwater flow parameters and to validate the simulated temperature fields against observed subsurface behavior.

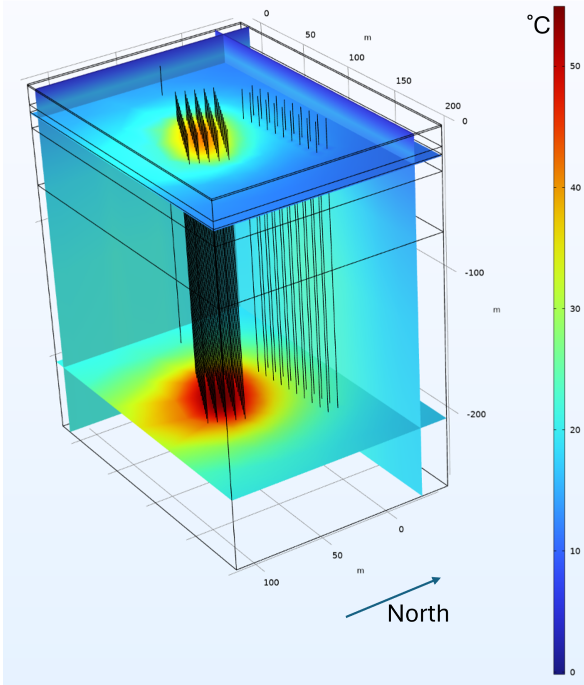

Fig. 3: Simulated temperature field around the borehole field illustrating the influence of groundwater flow on thermal spreading.

4. Discussion and conclusions

The presented analysis demonstrates that deliberate over-regeneration of BTES can substantially reduce winter electricity demand in heat-pump-based heating systems. While total annual electricity consumption increases, the shift in seasonal demand can alleviate winter peak loads, which are critical for future electricity systems with high shares of renewable generation. At the same time, elevated operating temperatures increase thermal interaction with the subsurface and groundwater. The combined use of operational simulations, three-dimensional numerical modeling, and targeted measurements provides a consistent framework to quantify these effects and to identify acceptable operational envelopes. The campus-scale demonstrator serves as a real-world test case illustrating how seasonal storage operation and environmental constraints must be assessed jointly. The results underline the importance of integrated design and operation strategies for BTES systems when targeting winter electricity demand reduction.

References

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