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Potentials and Challenges of Borehole Thermal Energy Storage in Solar District Heating Grids

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ABSTRACT

In the heating and cooling sector, borehole heat exchangers (BHE) have become increasingly popular for supplying renewable energy. When grouped in compact arrays, BHEs represent suitable thermal energy storage systems for district heating (DH) grids and allow for an integration of intermittent heat sources such as solar energy or industrial waste heat. This so-called borehole thermal energy storage (BTES) is characterized by a slow thermal response and large storage capacities, which makes it particularly suitable for seasonal heat storage applications. BTES systems need only a small amount of space to tap into a large volume of subsurface rock at relatively low specific costs, which gives them an advantage over other storage technologies like water tanks, particularly in densely populated urban areas. Furthermore, scaling poses no problem in BTES as there is no exchange of groundwater like in aquifer thermal storage systems. However, a thermal impact on the groundwater cannot be eliminated altogether. Since DH grids operate at supply temperatures of above 80 °C and since BTES is most efficient on a large scale, the heating of the subsurface in the vicinity of BTES systems is excessive. Thus, the thermal impact has to be regarded critically, especially for shallow aquifers, which are often used for the extraction of drinking water. In order to gain some independence from hydrogeological site conditions and a more widespread application of BTES, heat storage can be shifted to larger depth (several hundred meters) through fewer, but deeper BHEs. Nevertheless, deeper wellbores require more sophisticated and therefore more expensive drilling methods. Despite the resulting implications for financial risk, environmental and economic life-cycle assessment shows that under favorable conditions such medium deep BTES facilitates the integration of alternative heat sources into DH grids reducing the global warming potential by half and still maintaining competitive costs.

1. INTRODUCTION

In the future, DH will play an important role for heat provision in temperate and cold climate zones. In order to extend the imperative decarbonization to DH, renewable heat sources like solar thermal collectors and industrial waste heat have to be implemented. However, the mismatch between heat production potential in summer and heat demand in winter poses a difficult challenge (Figure 1): heat storage systems with exceptionally large capacities and high storage efficiencies are required to carry large amounts of heat over several months from summer to wintertime.

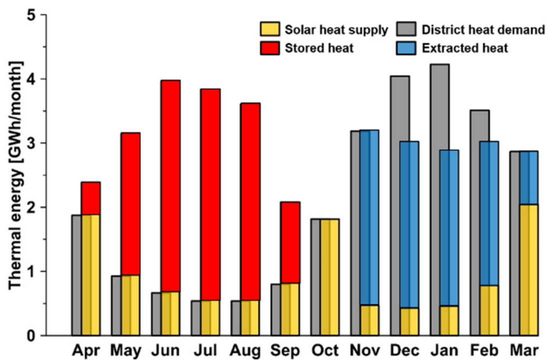

Figure 1: Mismatch between solar production potential (25 GWh/a) and heat demand in a DH grid (25 GWh/a).

BTES systems can provide the required large storage capacities (Schulte et al. 2016a). Due to numerous difficulties, this technology has not asserted itself on the market yet. However, life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) highlight significant potential (Welsch et al. 2018).

2. BOREHOLE THERMAL ENERGY STORAGE

Despite their high specific heat capacity, hot water tanks require a considerable amount of space, and thus, are typically used for short-term heat storage only. On the contrary, closed-loop geothermal systems are inherently suitable for sensible heat storage in densely populated urban areas. Closely-spaced BHE arrays can be operated as BTES systems and provide capacities sufficient for seasonal heat storage with a much lower space requirement compared to hot water tanks with matching capacities.

During summer, excess heat is stored by circulating hot water through the BHEs. The lateral thermal gradient between the fluid and subsurface results in a conductive heat transfer from the BHE to the ground, which serves as the storage medium. During winter, operation is reversed: cold water is pumped through the BHEs resulting in a conductive heat transfer from the previously heated subsurface to the fluid. On the surface, a heat pump extracts the heat from the fluid and provides thermal energy for heating purposes.

BTES systems benefit from the slow thermal response resulting from the conduction-dominated heat transfer. However, thermal losses are still inevitable. In order to reduce these losses to a minimum, the geometry of the BHE array is crucial. Thus, for seasonal heat storage the BHEs have to be arranged in a compact cylindrical layout to obtain a low surface-to-volume-ratio of the storage system.

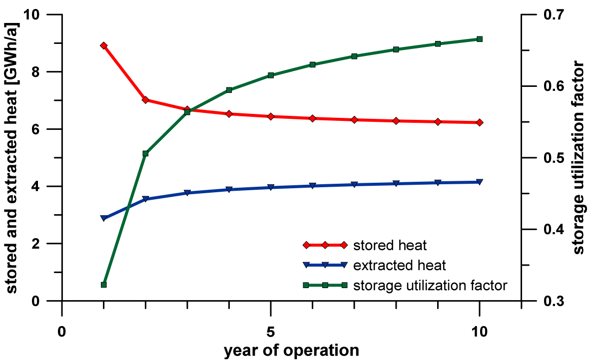

Figure 2: Stored and discharged heat and the resulting utilization factor for an exemplary BTES system of 19 coaxial BHEs, BHE length: 500 m; modified after Schulte et al. (2016a).

In contrast to a typical balanced operation of a BHE array for heating and cooling, stored solar or cogeneration heat is not entirely recovered during the discharge period, but partly remains in the ground as a thermal loss. These losses build up over several charging and discharging cycles and gradually increase the subsurface temperature, which exceeds the usual regeneration of a balanced operation. As a result of the permanently shifted temperature level of the BTES system, the amount of heat stored in summer decreases whereas the discharged heat in winter increases. The subsequent change of the stored-to-discharged heat ratio leads to a growing storage utilization factor (Figure 2). Furthermore, the elevated temperature during storage discharge improves the coefficient of performance of downstream heat pumps.

3. CHALLENGES

BTES systems face several challenges. Most importantly, underground heat storage increases ground water temperatures and can impair its quality (Schulte et al. 2016b). To maintain general applicability, heat exchange has to be shifted to less vulnerable reservoirs in larger depth (Figure 3). This allows for thermal insulation of the upper borehole sections, which reduces convective heat losses and significantly attenuates the thermal impact on sensitive aquifers in the shallow subsurface. However, for these so-called medium deep borehole thermal energy storage (MD-BTES) systems, the requirement of closely spaced parallel boreholes is even more difficult to meet: For the typical range of thermal conductivities of impermeable crystalline rocks, which are considered ideal storage formations, axial distance between BHEs should fall between 5 to 6 meters (Welsch et al. 2016). As a consequence, deep and accurate drilling raises costs and leads to high investment and financial risk.

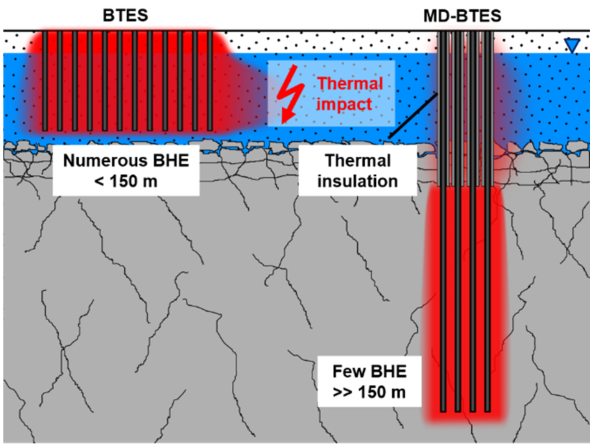

Figure 3: Heat storage can impose a critical thermal impact on aquifers. Medium deep borehole thermal energy storage (MD-BTES) circumvents the problem by accessing a less vulnerable storage reservoir in larger depth; modified after Schulte et al. (2018).

4. POTENTIALS

Despite technological and investment challenges, LCA and LCCA show that MD-BTES systems can substantially reduce greenhouse gas emissions, if predicted developments of energy prices and emission factors are taken into account (Welsch et al. 2018). Considering existing subsidies, MD-BTES systems are even profitable. Only in the unlikely business-as-usual case and without any subsidies, emission reduction by BTES will result in increased heating costs (Figure 4).

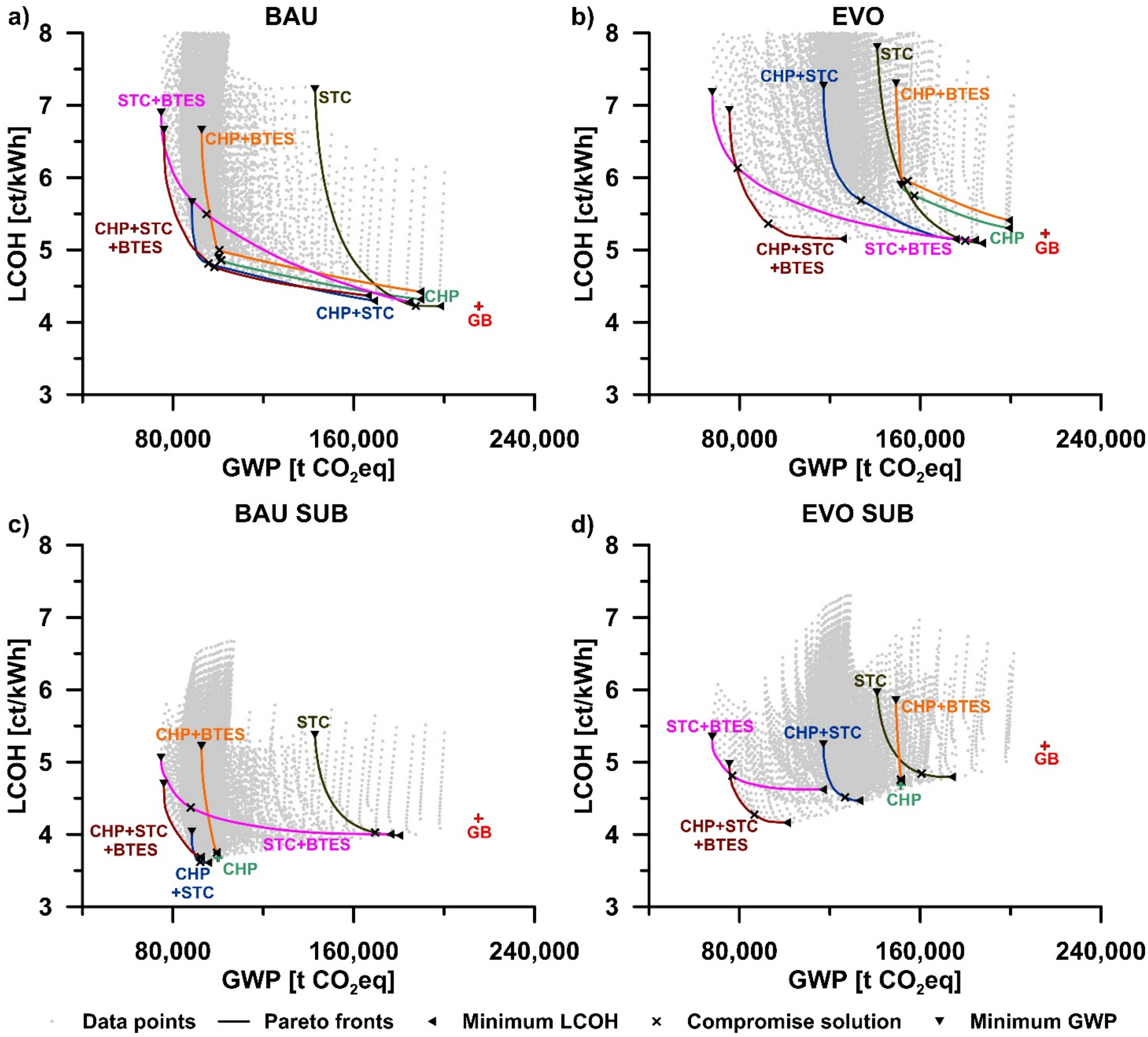

Figure 4: Levelized cost of heat (LCOH) and global warming potential (GWP) for various Pareto-optimal DH system combinations under different economic and environmental boundary conditions: business-as-usual (BAU), evolution of energy prices and emission factors (EVO), consideration of subsidies (SUB); Welsch et al. (2018).

4. CONCLUSION

Environmentally friendly BTES is possible and feasible if storage is shifted to larger depth. MD-BTES systems can significantly reduce greenhouse gas emissions. At the same time, the arising financial challenges from increased depth can be overcompensated. MD-BTES requires only little space and is therefore eminently suitable for seasonal heat storage in urban areas. Only the construction of large systems is reasonable though, as storage efficiency increases with BTES size and capacity (Figure 5). This makes MD-BTES the obvious solution for district-scale seasonal heat storage. Simply put: the bigger – the better!

However, the full potential of BTES is yet to be exploited: next generation DH grids with reduced grid temperatures can boost the environmental and economic benefits of BTES systems even further. Lower grid temperatures bring down overall heat losses, decrease the electricity consumption of heat pumps and increase the share of solar heating, which additionally cuts greenhouse gas emissions and costs.

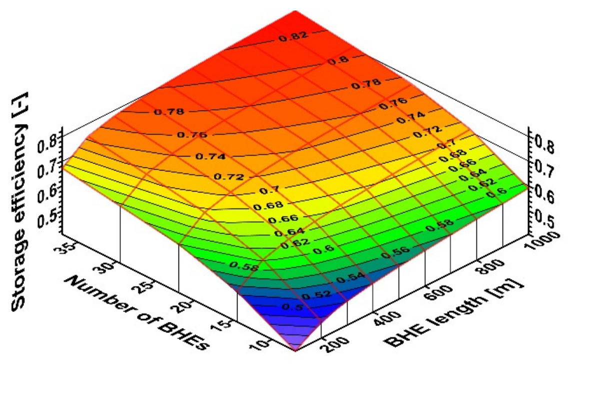

Figure 5: Storage efficiency increaseswith BTES size and capacity; Welsch et al. (2016).

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