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# Environmental and economic assessment of borehole thermal energy storage in district heating systems

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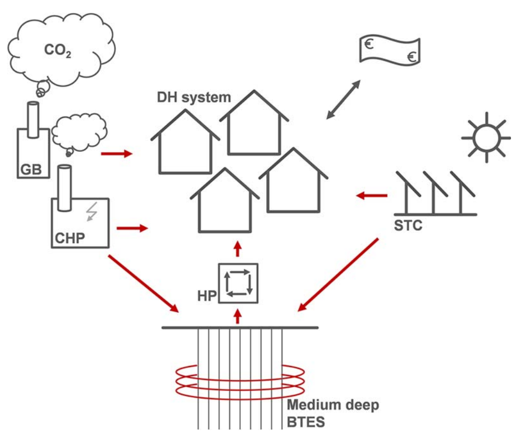
## HIGHLIGHTS

- Economic and environmental LCA of medium deep BTES in DH generation is carried out.
- Various system compositions and changing boundary conditions are investigated.
- Pareto fronts illustrate optimal system designs with and without BTES.
- Economic and environmental assumptions affect optimal system designs considerably.
- Combinations of BTES, solar heat & a small CHP are competitive with CHP-based systems.

## GRAPHICAL ABSTRACT

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## ABSTRACT

District heating will play an important role for heat provision in temperate and cold climate zones in the future. However, in the context of decarbonizing the heating sector, conventional heat sources have to be replaced by renewable energies. This replacement correlates to the necessity to integrate the fluctuating energy source of solar radiation and thus requires seasonal thermal energy storage. More recently, borehole thermal energy storage systems have been integrated into such district heating concepts. Yet, the potential greenhouse gas emission reduction and the financial benefits of these innovative district heating concepts have not been assessed with respect to the environmental burden and the associated investment cost of the modernization. This study presents a comprehensive environmental and economic life cycle assessment of a fictional district heating system with varying shares of shallow to medium deep borehole thermal energy storage and alternative heat sources replacing conventional capacity. In an exemplary district heating system covering 25 GW h of annual heat demand, borehole thermal energy storage can decrease the greenhouse gas emissions of combined heat and power plants and solar thermal collectors by over 40%. Boundary conditions assumed for the development of the energy market and the existence of subsidies have a significant impact on the emission savings and the levelized cost of heat. Considering a probable increase of energy costs and a growing share of renewables in the electricity mix, a combination of solar thermal collectors and borehole thermal energy storage with a small heat and power plant is the best solution, which is economical even without subsidies. The results of the study promote the

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## Nomenclature

*Abbreviations*

| | |
|---|---|
| BAU | business as usual scenario |
| BAU SUB | business as usual scenario including subsidies |
| BHE | borehole heat exchanger |
| BTES | borehole thermal energy storage |
| CHP | combined heat and power |
| DH | district heating |
| ECO | economic/environmental scenarios |
| EUA | European Union Emission Allowance |
| EU ETS | European Union Emissions Trading System |
| EVO | evolution scenario |
| EVO SUB | evolution scenario including subsidies |
| GB | gas boiler |
| GHG | greenhouse gas |
| HP | heat pump |
| LCA | life cycle assessment |
| P1 – P4 | selection of Pareto efficient system designs |
| SI | supplementary information |
| STC | solar thermal collector |
| TES | thermal energy storage |

*Symbols*

| | |
|---|---|
| $A_{STC}$ | solar collector area, [m$^2$] |
| $CED$ | cumulative energy demand, [TJ] |
| $L_{BHE}$ | length of borehole heat exchangers, [m] |
| $N_{BHE}$ | number of borehole heat exchangers, [–] |
| $\alpha_{CHP}$ | coefficient of share of cogeneration in the peak load demand, [–] |
| $EF$ | emission factor, [kg $CO_2$eq/kW h] |
| $F$ | operation costs, [€] |
| $GWP$ | global warming potential, [t $CO_2$eq] |
| $I$ | investment costs, [€] |
| $LCOH$ | levelized cost of heat, [€ct/kW h] |
| $M$ | maintenance costs, [€] |
| $P$ | thermal power demand/supply, [kW] |
| $Q$ | thermal energy demand/supply, [kW h] |
| $R$ | revenue, [€] |
| $a$ | year of operation, [–] |
| $r$ | interest rate, [–] |

construction of medium deep borehole thermal energy storage systems that can help to increase the share of renewable energy in the heating sector at reasonable cost.

## 1. Introduction

By 2050, more than 80% of European residents are expected to live in urban areas [1]. Such populous areas are usually characterized by a high heat density and are therefore particularly suitable for the implementation of district heating (DH) grids. DH is considered an essential component in successfully transitioning to a sustainable and decarbonized heating sector (e.g. [2–6]). For this purpose, a large amount of fluctuating renewable energy sources must be integrated in future DH grids in order to replace conventional heat sources, while simultaneously guaranteeing the security of supply.

The concept of fourth generation district heating (4GDH, [7]) comprises a significant reduction of grid supply temperatures down to 55 °C [8]. Grid losses are thereby lowered and the energy and exergy efficiency is improved [8,9]. Moreover, low-carbon heat sources like geothermal energy or industrial waste heat, which are characterized by low-temperatures, can be integrated more efficiently (e.g. [10,11]).

Another auspicious technology for substituting fossil heat sources in DH grids is large solar thermal collector (STC) fields [12–14]. However, especially in the temperate and cold climate zones, there is a seasonal mismatch between solar supply and heat demand [15]. Seasonal thermal energy storage (TES) systems are able to offset this mismatch, thus increasing the performance of solar thermal heating systems [16] and reducing the required STC size [17].

There are several seasonal TES technologies available (for an overview see [18,19]). However, their requirements are diametrically opposed: high storage capacities are desired, but the costs and the space required need to be minimized [20]. With respect to heat storage on a district level, chemical and latent heat storage solutions are not competitive yet [19]. Only a couple of sensible heat storage technologies meet the requirements for large-scale TES. These can be differentiated into large above-ground water tanks and underground thermal energy storage (UTES) like water or gravel-water pit storage [21,22], cavern storage or aquifer storage [23,24]. Another promising type of UTES are borehole thermal energy storage (BTES) systems [25–27]. BTES utilizes the subsurface as a heat storage medium via a borehole heat exchanger (BHE) array. Even though initial costs are very high for BTES systems, specific costs in relation to the storage capacity are relatively low compared to other storage technologies [13,28]. The functionality of BTES has already been demonstrated in several projects (e.g. [12,29–34]). A basic overview of installed systems and their technology is given by Gehlin [26]. Recent studies propose the novel concept of medium deep BTES [35–40]. They can reach storage efficiencies of more than 80% [35]. Compared to shallow systems (usually < 100 m in depth), medium deep BTES consist of fewer but deeper BHEs (up to 1000 m). They require less floor area than shallow systems with a similar storage capacity and can significantly inhibit the thermal impairment of sensitive aquifers in the shallow subsurface [41]. Therefore, the utilization of medium deep BTES is more independent of the geological conditions and could lead to a more widespread application of seasonal heat storage. Nevertheless, deeper wellbores require more sophisticated and therefore more expensive drilling methods and the environmental impact of such systems has not been investigated yet. Consequently, uncertain financial implications and vague environmental benefits inhibit their market introduction.

Several studies deal with the optimization or the assessment of DH systems in terms of profitability and/or environmental impact. Most of these studies concentrate on specific technologies like heat pumps (HP) [42–44], combined heat and power (CHP) [5,45,46], the integration of industrial excess heat [47] or energy conservation measures [48–51]. Truong & Gustavsson [52] compare different DH production technologies under changing economic or environmental boundary conditions but do not include any TES in their considerations. Certainly, some valuable publications already address the integration of solar thermal technology into DH systems in combination with heat storage (e.g. [16,53–59]). But they either concentrate on specific case studies, look at economic or environmental impacts only or disregard potential changes in the economic or environmental boundary conditions. With a few exceptions (e.g. [60]), most studies assessing the environmental impacts of DH heat production only take into account the use phase. Tulus et al. [61] is the only study that combines an economic and environmental life cycle assessment (LCA) to optimize central solar