

Seasonal High Temperature Heat Storage with Middle Deep Borehole Heat Exchangers – a Coupled-Modeling Study

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ABSTRACT

More than 50% of the overall energy demand in Germany is due to heating and cooling purposes. Therefore, groundbreaking techniques are needed to save energy and reduce greenhouse gas emissions especially in this low exergy sector. The combination of different renewable energy sources – e.g. solar thermal and geothermal – with already existing district heating systems fed by combined heat and power stations (CHP) is a promising new approach.

In summer, excess solar thermal energy is available, while in winter, when thermal energy is needed for heating systems, its quantity is usually not sufficient. There are different options to cope with the seasonal offset of thermal energy supply and demand. Besides conventional storage tanks at the surface, thermal storage in shallow aquifers and shallow borehole thermal energy storages (BTES), geothermal heat storage in medium depths is an innovative and yet barely tested concept. In difference to shallow heat storage systems, the proposed approach upgrades the naturally available geothermal energy in the subsurface by means of external heat input. This is done in summer when no space heating is required or at times when surplus energy from nearby sources is available. In winter, when other sources of energy are not sufficiently or not cheaply available, the thermal energy from the BTES system is used for heating purposes.

The presented study focuses on simulation options for the environmentally friendly and energy efficient redesign of fuel-powered heating systems by the employment of BTES. By storing excess heat from solar panels or thermal power stations of up to 110 °C in summer, a medium deep borehole thermal energy storage can be operated on temperature levels above 45 °C. Storage depths of more than 100 m to 1,500 m below surface avoid conflicts with groundwater use. Groundwater flow is decreasing with depth, making conduction the dominant heat transport process. Feasibility and design criteria of such a system have to be based on coupled simulations of both the above ground facilities (heating, ventilation and air conditioning, HVAC) and the subsurface thermal behavior. The coupled geothermal-solar thermal modeling approach is presented and discussed. A BTES system as well as an energy efficient building design will help to use sustainable energy sources for the next period of a building's lifetime.

1. INTRODUCTION

More than 50% of the overall energy demand in Germany is due to heating and cooling purposes (AGEB 2013, Figure 1, left). Therefore, groundbreaking techniques are needed to save energy and reduce greenhouse gas emissions especially in this low exergy sector. The combination of different renewable energy sources – solar thermal and geothermal – with already existing district heating systems fed by combined heat and power stations (CHP) is a promising new approach. In the following, we introduce the approach of seasonal heat storage in medium deep borehole heat exchanger (MD-BHE) arrays in combination with renewable heat sources and focus on optimizing the design of such systems with newly developed and coupled simulation approaches. Large-scale borehole thermal energy storage (BTES) is a promising technology in the development of a sustainable, renewable and low-emission heat supply concepts. Such storage systems consist of several components and assemblies like the borehole heat exchangers (BHE), other heat sources (e.g. solarthermics, combined heat and power plants, peak load boilers, heat pumps), distribution networks and heating installations.

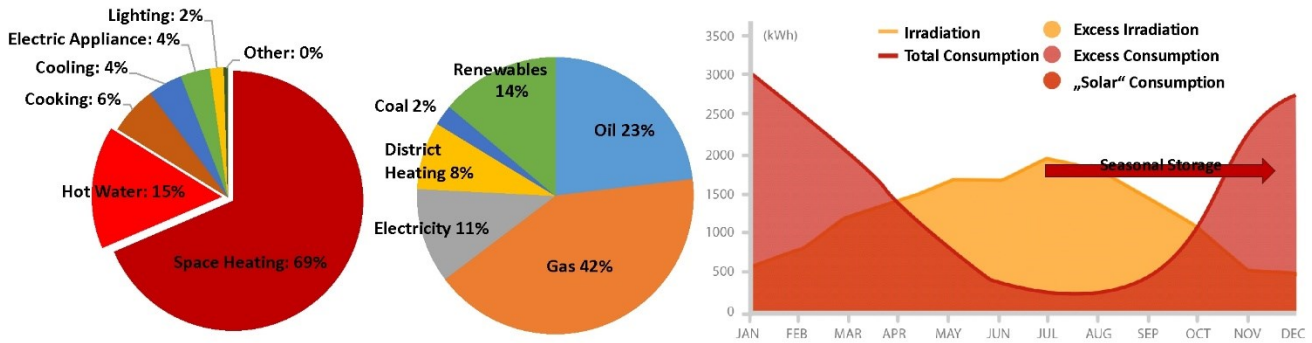


Figure 1: Energy consumption in German households (after AGEB 2013), coverage of heat demand by different heat sources in German household (after AGEB 2013) and concept of seasonal storage of solar heat to cover heat demands in winter (after www.comtes-storage.eu)

1.1 Seasonal heat storage

In summer, excess solar thermal energy is available, while in winter, when thermal energy is needed for heating systems, its quantity is usually not sufficient (Figure 1, right). There are different options to cope with the seasonal offset of thermal energy supply and demand. Besides traditional storage tanks at the surface, thermal storage in shallow aquifers and shallow borehole thermal energy storage (BTES, Hellström 1991, Bauer et al. 2010), geothermal heat storage in moderate to medium depths is an innovative and yet barely tested concept. In difference to shallow heat storage systems, the proposed approach upgrades the naturally available geothermal energy in the subsurface by means of external heat input. Heat storage is possible in summer when no space heating is required or at times when surplus energy from nearby sources (solar thermal energy, power-mode driven CHPs) is available. In winter when other sources of energy are not sufficiently and cheaply available, the thermal energy from the geothermal storage is used for heating purposes.

1.1 Borehole thermal energy storage (BTES)

The proposed system of a MD-BTES (Homuth et al. 2013) consists of multiple boreholes with depths of approx. 100 m – 1,500 m. The surrounding rock is utilized as a heat storage, the cementation and borehole wall serve as a heat exchanger. Typically, water (in some cases with refrigerant or other additives to prevent corrosion) is used as heat carrier fluid. In most applications, double U-pipe BHEs are coupled with heat pumps (Sass et al. 2016). Deeper boreholes are often fitted with coaxial BHEs instead (Bär et al. 2015, Schulte et al. 2016a, Welsch et al. 2016). They benefit from the fact that the inner pipe is not in contact with the grout and can be designed to have a low thermal conductivity, which can reduce heat losses of the upstream fluid within (so-called thermal short-circuiting).

For the design of a MD-BTES two separate phases have to be considered. These phases are the charging phase and the extraction phase. During the charging phase hot water is injected into the BHE to heat up the reservoir. For heat extraction, cold water is pumped into the BHE in order to retrieve the stored thermal energy from the relatively hot formation. It is important to consider the two possible flow directions in a coaxial BHE. The inlet can be either the central pipe (CXC, Figure 2, left) or the annulus (CXA, Figure 2, middle). Flow direction and inlet temperature influence the heat transfer between working fluid and subsurface. In the charging phase, the working fluid should reach the bottom of the wellbore in the insulated inner pipe before discharging the bulk of its heat into the surrounding rock at maximum depth. During the extraction phase, the cold fluid should be injected into the outer pipe to utilize the borehole wall as a heat exchanger surface at full length. This reduces heat losses of the working fluid by circulating it back to the surface through the insulated central pipe after it reached its peak temperature at the bottom of the borehole. Consequently, seasonally alternating flow directions in the BHE are beneficial.

The advantage of BTES systems over open systems is the closed circulation system, which is not allowing a direct contact or mass transfer of heat carrier fluids with the groundwater or subsurface. Geochemical alteration processes and a direct hydrochemical or biological influence on the groundwater will be prevented. Furthermore, this protects auxiliaries like pumps, etc. on the surface against scaling and corrosion. This results in a higher lifetime expectancy of such systems and a more constant and therefore more economical operation.

Medium deep borehole thermal energy storage systems (MD-BTES) show a high potential for seasonal heat storage (Schulte et al. 2016a, 2016b, Welsch et al. 2016). In contrast to conventional shallow BTES systems, the mandatory heat pump is not necessarily needed due to the higher operation temperature levels (Bär et al. 2015). Consequently, the electric power needed to operate the system can be reduced and thus, the profitability of the system is increased. Additionally, deep BTES have a much smaller surface footprint than shallow BTES with the same capacity and are therefore a viable option in densely urbanized areas.

Larger depth with higher underground temperatures compared to shallow systems results in a lower lateral temperature gradient between the heat carrier fluid and the surrounding rock. This implies a notable decrease of heat losses, which additionally enhances the

system efficiency. However, heat losses in the shallow subsurface can eliminate the temperature gains originating from the deeper section of the boreholes (Nakevska et al. 2015) and render the increased investment costs for deeper BHEs worthless. Thus, a thermal insulation in the upper section of a borehole is favorable for deeper BHEs. Furthermore, legal regulations in some countries may restrict the temperature increase of the uppermost aquifer to a certain maximum to protect drinking water from negative biological or chemical alterations (Haehnlein et al. 2010). Hence, a thermal insulation has been proposed for the upper part of medium deep BTES as well (Bär et al. 2015). On the one hand, a backfill material with reduced thermal conductivity and an increased borehole diameter are supposed to reduce the heat losses and the consequent warming of the shallow subsurface due to an increased thermal resistance between the pipes and the borehole wall. On the other hand, a backfill material with a high thermal conductivity can enhance the heat exchange at elevated ambient temperatures in the bottom part of the BHE (Figure 2, right). (Schulte et al. 2016b)

Charging the BTES with temperatures of up to 110 °C supplied by various heat sources in combination with greater depths can allow for return temperatures of the BTES of 45 °C – 75 °C after an initial charging phase of 3 to 5 years. This is highly depending on the setup of the storage and utilization scenarios (Welsch et al. 2016). The constant supply of such high heating temperatures allows for applications with conventional radiator-based high-temperature heating systems commonly installed in older buildings. This makes MD-BTES systems even an option for old buildings without low temperature heating systems not meeting the actual energy efficiency levels. Another option is to directly feed in to district heating systems and supply heat for multiple uses possibly even at cascading temperature levels.

1.3 Design and operation of BTES

For the dimensioning and operation of a BTES system, good knowledge of the petrophysical (conductive heat transfer) and the hydraulic (convective heat transfer) properties, as well as of the initial subsurface temperature regime is a critical factor (Mielke et al. 2014). Additionally, design parameters like the heat demand and the required temperature levels of the installed heating systems are important.

Different kinds of energy flows, as well as different storage and utilization scenarios have to be assessed in simulations and feasibility studies of such systems. Specific user profiles and economic frameworks have to be considered along with local heat sources and sinks.

In designing vertical BHEs, the determination of the necessary depth as well as array configuration and amount of boreholes is crucial. Typically, the depth is estimated based on the desired power extraction per unit depth by considering steady state heat transfer. Due to long term and peak power extraction during the operation time, the heat flow will change into transient behavior. In multi BHE systems, the degree of geothermal heat enhancement by external heat input depends on various factors such as spacing of boreholes, depth of the BHEs, and amount of heat and frequency of storage phases, etc. These factors affect the level of average heat output during the heat extraction depending on the actual heat demand scenario. To find a best fit BHE scenario, the consideration of those parameters is necessary but also results in more computation time. Here, best fit scenario means the BHE system with the highest efficiency and highest production capacity possible at minimum total BHE length and economical heat storage conditions.

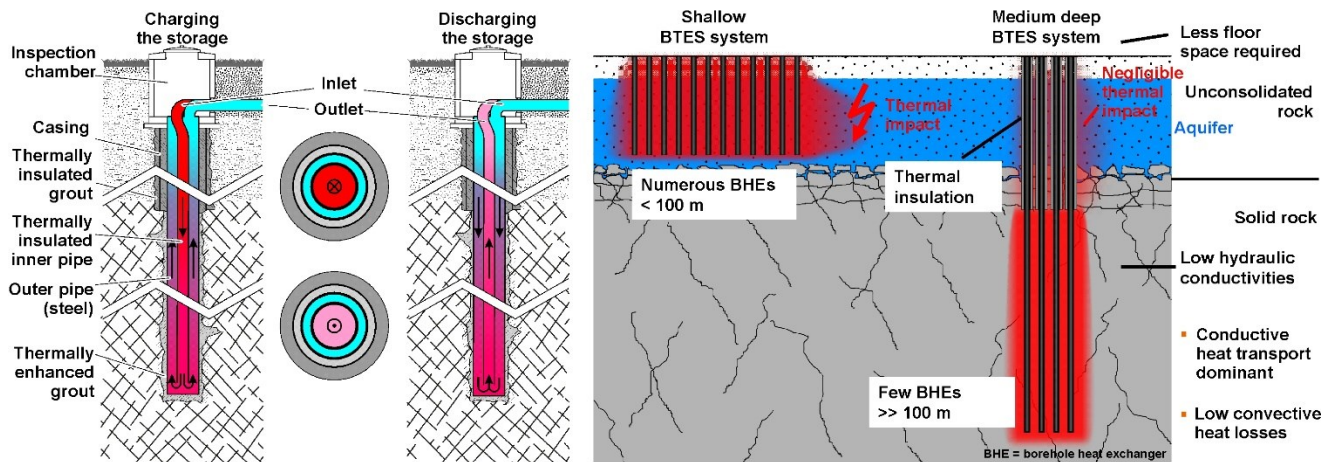


Figure 2 (left): Schematic horizontal and vertical cross sections of coaxial BHEs used as heat storage in summer (charging the storage) and winter (discharging the storage), respectively. Note that only the crystalline bedrock is used as heat storage while the caprock including possible aquifers are thermally insulated (Bär et al. 2015). (right): Thermal impact on shallow aquifers by shallow BTES compared to negligible impact by medium deep BTES constructed with thermal insulation in the upper part (Schulte 2016).

However, first models proved that these systems are only efficient if they are large enough, i.e. when the storage capacities lie in the range of several GWh of heat per year (Welsch et al 2016). Such high heat demands are only encountered in large district heating grids, which usually consist of several subsystems like the heat source (e.g. solar thermal collectors or CHPs), the heat consumer (all connected buildings), diurnal buffer storages (i.e. water tanks), the BTES, additional heat sources for peak load coverage (e.g. a heat

pump or a gas boiler) and the distribution network. For the design and the optimization of an integrated system, numerical simulations of all subsystems are imperative.

1.4 Heat demand

The energy consumption of any kind of building is usually modeled using standard software packages (e.g. MATLAB-Simulink, TRNSYS, SimulationX, Idalce, Carnot-Toolbox) for precise calculations of the energy consumption of every single room inside a building considering the meteorological data of the Test Reference Years (TRY) provided by Germany's National Meteorological Service (DWD 2004, 2011). All parameters influencing energy sources or sinks are defined in the software packages. The required heating load is determined according to official guidelines and standards (VDI 2607, 2006 and DIN 18599-100, 2009) and can be calculated in any detail necessary. This provides an hourly, daily, monthly or annual heat demand, which has to be supplied by the heating system.

1.5 Solar thermal collectors

Solar thermal collectors as renewable heat source in urban environments are best installed on available rooftops. To assess the maximum area for solar thermal collectors the available rooftop or other unused areas near the building or within reach of the district heating network need to be evaluated. Buildings with flat roofs are usually easily adaptable for solar installations. The amount of energy produced varies depending on the location, manner of installation and type of the solar collectors. The solar heat gains of the solar thermal system can be calculated after e.g. Honsberg and Bowden (2011) for the different standard types of solar installations: e.g. flat plate collectors with optimized permanent inclination angles, flat plate collectors with seasonally changing optimized inclination angles and evacuated tube collectors situated flat on the roof with tilted tubes. The design arrangement of the solar collectors is usually restricted by the limits set by construction regulations as e.g. DIN 1055-4 (2005) as well as shading areas of existing construction elements on the roof (e.g. elevator shafts, ventilation systems), vegetation or the solar collectors themselves (Viessmann 2006). During the winter months in high latitudes, the only time when it is possible to obtain heat from the solar installation is from about 12 pm to 3 pm. This implies that the solar installation will be able to provide only a small fraction of a building's heat demand (cf. Figure 1).

A properly designed combination of a solar thermal installation and seasonal underground heat storage can significantly reduce – or even eliminate – the need of additional heat sources like CHP plants. Therefore, such a combined system can replace fuel-powered heat sources in district heating grids and facilitate a considerable reduction of CO₂ emissions.

2. MODELING

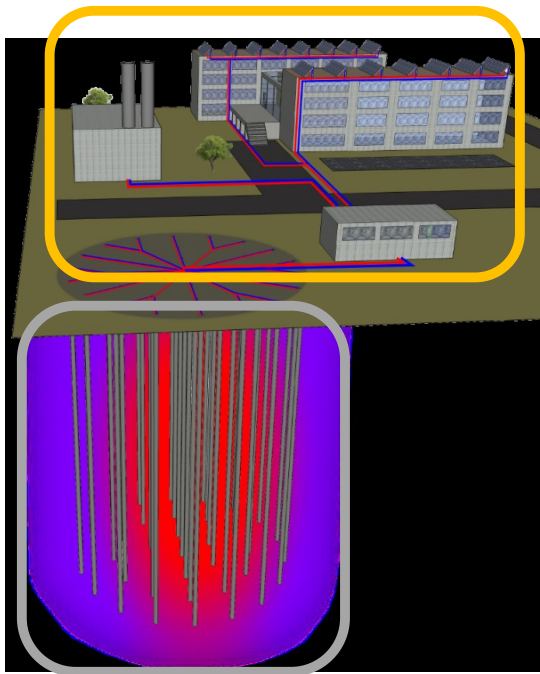
Medium deep or deep BTES systems have not been put into practice so far. This is mainly due to the high drilling costs and the large size required to achieve high efficiencies. Therefore, a proper and optimized design is imperative and can only be achieved by numerical simulation. For the simulation of borehole thermal energy storage systems, usually, analytical or numerical programs for the calculation of groundwater flow and heat transport in the subsurface are used (e.g. FEFLOW, OpenGeoSys, EED, GeoLogic etc.). A suitable simulator has to allow for the transient calculation of conductive subsurface heat transport. As explained before, due to the large depth and the option of thermal insulation of the shallow sections, convective heat transport can be considered negligible. Due to geometric restrictions at construction sites with limited available floor space, the simulator has to be able to consider inclined boreholes and arbitrary borehole locations. Ideally, it includes all typical BHE types: single-U, double-U and coaxial, it can consider partially insulated boreholes and it allows for operation by inlet temperature mode and heat load mode as an abstraction of a heat pump. Furthermore, it should provide flexible options for coupling with building simulators. Since none of the available codes allow for straightforward coupling with other algorithms to allow for mathematical optimization of the BTES design parameters a Borehole heat exchanger Array Simulation and Optimization tool (BASIMO) was developed by Schulte et al. (2016c).

The above ground installations are often analyzed with modular transient simulation tools for modeling physical systems (e.g. MATLAB-Simulink, TRNSYS, SimulationX, IdaIce, Carnot-Toolbox). Some of them even include modules for BHE-simulations, but they usually comprise drastic simplifications of the physical detail.

Thus, the separate simulation of the BTES and the above ground installations is more common. In this approach, the design of the storage is only based on the heat load of the simulated above ground facilities, but the mutual interaction of fluid temperatures between the different subsystems is neglected. In reality, the subsystems interact dynamically with each other. The fluid temperatures of the heat generation system, the heating system and the underground storage are interdependent and affect the performance of each subsystem. To take into account these interdependencies, coupled simulation models, which co-simulate the subsystems of MD-BTES and the district-heating grid (with all its components) are required (Figure 3).

For the two following modeling examples (coupled simulation and design optimization) numerical simulation of a MD-BTES system was carried out either using FEFLOW or BASIMO. Both deliver the information about the capacity of the BHE system for a given size, depth, flow rate, heat extraction intervals and other factors.

Depending upon the size of the proposed MD-BTES system, the extent of the model is defined such that the model boundaries may not directly influence the BHEs. Boundary conditions are set as shown in Figure 4. A subsurface temperature distribution with a geothermal gradient of 30 °C/km is set as initial condition. This model incorporates BHE boundary conditions at the nodes with the parameter settings and loading cycles for operation as controlled by the heat demand and the HVAC simulations.



Above Ground Facilities (HVAC)

- Consist of several components (e.g. building, solar collectors, heat pump, grid)
- Modular transient simulation software for modelling physical systems (e.g. MATLAB-Simulink, TRNSYS, SimulationX)

Borehole Thermal Energy Storage (BTES)

- Consists of several interacting borehole heat exchangers (BHE)
- Finite element software for heat transport simulation (e.g. FEFLOW, OpenGeoSys, BASIMO)

Figure 3: Conceptual model of an integrated district heating system with a building as a heat consumer, a CHP and solar thermal collectors supplying the heat and a BTES as a seasonal thermal storage system connected with e.g. heat pumps and/or diurnal buffer storage.

For the HVAC simulations, a medium sized office building with an annual heat demand of 500 MWh/a, equipped with solar thermal collectors on the roof and a buffer storage, was selected with an optional connection to a district heating network powered by a heat demand driven CHP (Figure 4).

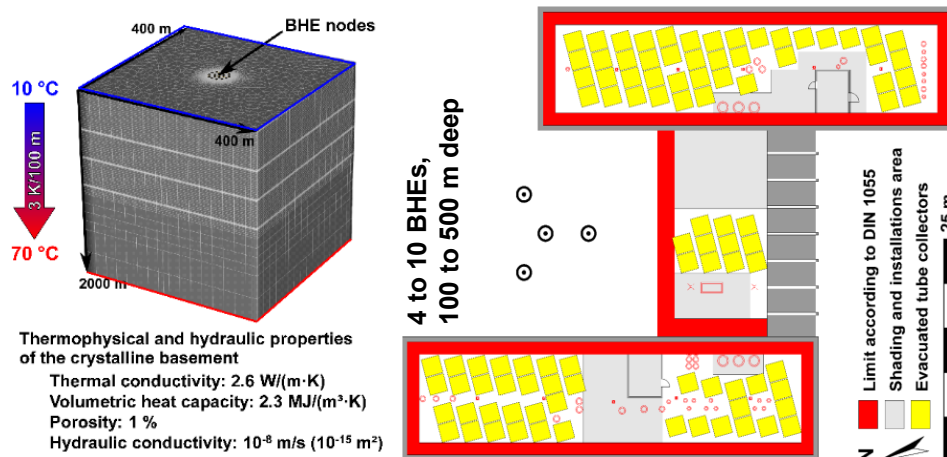


Figure 4 (left): General setup, parameters and boundary conditions of the numerical BTES models; (right): Layout of the BTES in top view of the modeled office building including the position of the solar thermal collectors installed on the building's roof for the different model setups as described in the text.

2.1 First coupled simulation test

For the coupled simulation example with a fixed BTES and HVAC design, the code FEFLOW (DHI-WASY 2014, Diersch 2014), which includes Eskilson & Claesson's (1988) solution for 1D BHEs, is used (Diersch et al. 2011). The heating-ventilation-air condition (HVAC) components are simulated with the Carnot Blockset (Solar-Institute Jülich 2010) for MATLAB-Simulink. This offers the advantage that it can be very easily combined with the MATLAB optimization toolbox, which offers various powerful mathematical optimization algorithms.

The challenge in coupling two simulation software packages from different companies is to get them to communicate with each other. We established and tested a client-server network connection based on the Transmission Control Protocol/Internet Protocol (TCP/IP) (Welsch et al. 2016). The TCP/IP protocol suite specifies how data has to be packetized, addressed, transmitted, routed and received at the destination. It assures that data loss is identified and corrected and it allows for a bidirectional communication. Furthermore, it offers the possibility to run the different simulation packages on separate computers.

To establish such a connection, it is necessary that both software packages allow for the execution of your own source code. FEFLOW offers a programming interface (IFM), which provides the possibility to read or change several model parameters during a simulation and also to execute own C++ code. In SIMULINK, so called S-functions blocks are available that can be integrated into the model and contain own MATLAB code. The connections are established shortly before the simulations are started. The transfer parameters are sent at distinct communication times. The communication time step size is constant and has to be defined in advance. Both programs generally maintain their own simulation time step control. However, it has to be ensured, that the simulation time steps match the communication time steps.

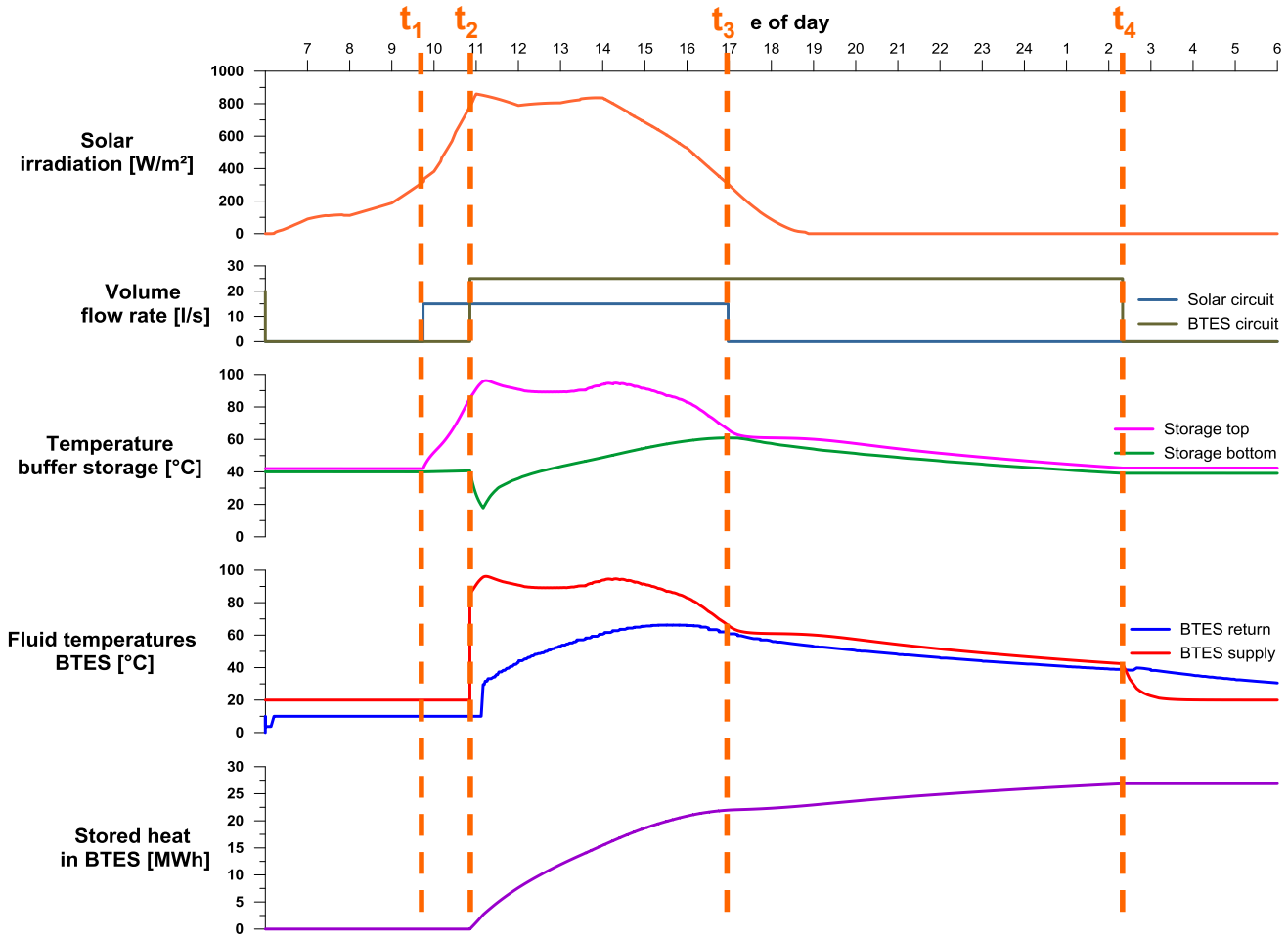


Figure 5: Resulting energy and temperature profiles for the coupled simulation examples illustrating that the different components (solar thermal collectors, buffer storage, BTES) directly influence each other.

As an example of such a coupled simulation of the HVAC and BTES components, **Error! Reference source not found.** shows the resulting energy and temperature profiles of the different interacting components over one simulated day in spring with considerable solar irradiation and a low heat demand in the morning. Shortly after sunrise, the solar collectors start heating up until the temperature threshold for charging the buffer storage is reached at 9:30 am. It then takes almost 90 minutes until the temperature of the buffer storage is high enough so that the BTES starts charging. Until 5 pm more than 20 MWh of thermal energy produced by the solar collectors can be stored in the BTES system. After sunset, the buffer storage covers the buildings heat demand and continues to charge the BTES. At about 2:30 am the buffer storage is depleted and the BTES systems begin to supply the heat demand to the building.

2.2 Optimization example

The objective of the optimization example is to find the smallest design for a BTES with a sufficient extraction capacity to supply the heat demand for the aforementioned building. The performance of BTES systems improves markedly over the first few cycles. Later, this trend levels off. Preliminary simulations indicate that medium deep BTES systems attain 80% of their final efficiency after 3 to 6 years (Welsch et al. 2016). A system, which already meets the heat demand after the first year, would turn out to be distinctly oversized after prolonged operation. Therefore, the BTES system has to cover the heat demand only after seven years.

The simulation of HVAC components would slow down the simulation and was therefore not included in the optimization example. Instead, a storage operation of 182 days per year with a constant inlet temperature of 90 °C and a flow rate of 2.5 l/s per BHE and a discharge operation of 183 days per year with a constant inlet temperature of 30 °C and a constant flow rate of 2,5 l/s per BHE was considered as a simplification. Determining the BTES system performance for seven years with BASIMO still results in large numerical efforts. Given that the optimization will need a large number of objective function calls to converge on a solution, and taking into account that the constraint function has to be evaluated for each objective function call, the total computation time is expected to be unacceptably long. Therefore, BASIMO has to be replaced as a constraint function by a proxy model generated with the aPC method. As described by Schulte et al. (2016a) the proxy model is based on a set of training simulations. The design of the numerical experiments has to ensure that each input variable's domain of definition is adequately covered by the training simulations (Siebertz et al. 2010) to allow for higher-order approximations. Based on the results of the preliminary simulations of Welsch et al. (2016), the parameter space encompasses four to ten BHEs of 100 to 500 m length, which also represents the bounds of the optimization problem. Additionally, as a fictional legal requirement the minimum BHE length is set to 200 m, also accounting for a potential partial borehole insulation required for the protection of shallow aquifers. For the application example, the potential solution has to be on the intersection of the response surface of the aPC model and the 500 MWh plane (Figure 6).

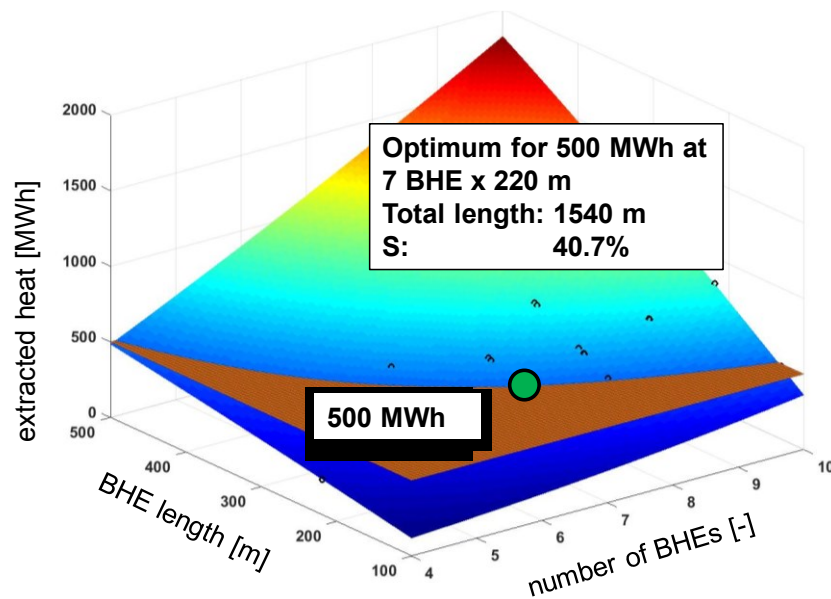


Figure 6: Result of the optimization process to find the smallest BTES design with sufficient heat extraction capacity, S: storage efficiency (after Schulte 2016).

The resulting optimal design to cover the heat demand of 500 MWh/a after seven years of operating the BTES is a system consisting of 7 BHEs, each with a length of 220 m, resulting in a total BHE length of 1540 m. Hence, the smallest possible BHE array, which considers the fictional legal requirement, consists of 7 BHEs, each 220 m deep. The genetic algorithm used for the proxy model setup performed several thousand evaluations of the objective function, which underlines the importance of using a fast proxy model instead of a comparably slow numerical simulators. While the Genetic Algorithm easily determines the ideal design of an MD-BTES system, the actual solution to the optimization problem depends on several assumptive boundary conditions and simplifications. In particular, the operational scenario of continuous storage charging and discharging cycles is unrealistic. As discussed before and shown by the coupled modeling example the operation scenario should be based on annual heat demand and supply curves with high temporal resolution. Such curves would be provided by the coupled modeling approach, which includes comprehensive building model simulations that take into account the interaction of infrastructural installations and weather conditions. This would greatly influence the long-term behavior of MD-BTES systems and possibly lead to a different result even if the total annual heat demand is the same.

Additionally, the storage efficiency S of the optimized BHE array is only 40.7%. This means that the storage losses are higher than 50%. Although the storage performance would further increase over time, this improvement already slows down significantly after a few years of operation. A larger MD-BTES system would operate at higher efficiencies but would also store and extract more heat in

each cycle. Hence, a heat demand of 500 MWh can be considered as too low for the proposed operational scenario. MD-BTES systems are rather suited for large-scale applications with a heat demand of several GWh. On the basis of previous estimates (Welsch et al. 2016) MD-BTES systems are then expected to achieve over 80% storage efficiency.

3. CONCLUSIONS AND OUTLOOK

The largest energy consumer in industrial countries is the building sector with its heating and cooling demand. Innovative energy saving concepts in this field will have the biggest impact on the reduction of CO₂ emissions. Especially the coupling of different renewable energy sources – solar thermal and geothermal – with already existing district heating systems – e.g. combined (biofuel-driven) heat and power stations (CHP) – appears to be a very promising approach to cover the heating demand of renovated or old buildings at higher temperature levels with renewable energy. Since conventional heating systems are still installed in approximately more than 90% of Germany's building stock, the presented concept is a viable option to reduce the heating energy demand and the related greenhouse gas emissions. Consequently, a high temperature storage and increased coefficients of performance are needed. However, storage configurations like the MD-BTES systems can also be utilized for low temperature heating systems, which can even make heat pumps dispensable.

The design and completion of MD-BTES systems as described are strongly depending on profound knowledge of the subsurface and the energy flows between the heat source, the storage system and the building. The estimation of the BHE depth and completion design requires iterative procedures. Coupled simulations of BHE systems and models of the above ground installations are advantageous, in particular, when regarding large heating systems, as the mutual interaction of the subsystems can be taken into account.

Still, the proposed integrated renewable energy supply and storage systems are very complex and require coupled modeling and mathematical optimization during the design phase. The developed simulator BASIMO can simulate BTES operation, is sufficiently accurate for the model purpose, can consider partial borehole insulation and can optimize BTES design. Together with the developed tools to couple either BASIMO or conventional industry BHE or BTES simulation codes to HVAC simulation software, both the simulation of these complex systems, as well as the design optimization become feasible.

Simulation results presented here and in other examples show and confirm that:

- medium deep BTES efficiency increases with size but several years are required to reach an operational status,
- partial borehole insulation inhibits heat exchange in critical aquifers and an optimized borehole insulation can increase the BHE performance,
- optimization can determine the ideal design or operational parameters,
- medium deep BTES systems in urban areas are beneficial due to the low floor space demand,
- seasonal storage of renewable heat will help to reduce CO₂ emissions.

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