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A Comparative Study of Medium Deep Borehole Thermal Energy Storage Systems Using Numerical Modelling

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ABSTRACT

In this study the application of Medium Deep Borehole Heat Exchangers (BHEs) as High Temperature Borehole Thermal Energy Storages is presented. Therefore 27 different Borehole Thermal Energy Storage configurations were compared, using a numerical program for modeling the heat transport processes in the BHEs and in the underground. The influence of different design parameters on the storage performance was studied by varying the BHE length, the number of BHEs, the spacing between the BHEs and the inlet temperature during the extraction period. A simplified underground model was assumed and a simplified operation procedure was applied over a period of 10 years of storage operation.

The simulation results show, that all the considered storage systems improved their performance with time. There is a strong influence of the studied parameters on the efficiency and the specific heat extraction rate of such storage systems. Depending on the selected parameters, the storage efficiency ranges between about 20 % and 70 % in the 10th year of storage operation. The average specific heat extraction rate for the preset extraction time of 4380 hours reaches values from about 40 $W \cdot m^{-1}$ to more than 90 $W \cdot m^{-1}$ in the 10th year of operation, which correlates to an annual specific heat extraction of about 175 KWh to more than 390 KWh per meter of BHE.

1. INTRODUCTION

More than 50 % of the final energy consumption in Germany result from space heating, cooling and water heating (AGEB, 2013). Solar energy could satisfy this heat demand to a large amount. It is available abundantly in summer season but it lacks in the heating period. Thus, the utilization of solar energy for heating of buildings is dependent on storage systems, which are able to bridge the time span between heat supply and heat demand.

Shallow Borehole Thermal Energy Storages (BTES) can accomplish this requirement (Bauer et al., 2010). Nevertheless there are some major difficulties linked to the storage of heat in the shallow underground. The major part of drinking water is produced from shallow aquifers. The increase of temperature may change the chemical and biological composition of the groundwater and thus have a negative impact on its quality. For this reason, the storage of heat at high temperatures in the shallow underground is not approvable by the responsible water authorities. On the other hand, storing heat at temperature levels of up to 90 °C has a key benefit, compared to low temperature energy storage, because higher loading temperatures in the summer season result in higher unloading temperatures during the heating period in winter. Thus, a higher overall efficiency of the heating system can be achieved. However, higher temperature levels in the storage system increase the heat losses, due to a higher temperature gradient into the surrounding subsurface. As ground temperature increases with depth, the installation of medium deep borehole heat exchanger systems (Homuth et al., 2013) at depths of 400 m to 1,500 m are considered to minimize these thermal losses. Furthermore, as most of the heat is stored at larger depths in such systems, the temperature impact on shallow aquifers is reduced.

The most important rock properties for High Temperature Borehole Thermal Energy Storages (HT-BTES) are a high specific heat capacity, a medium thermal conductivity and a low hydraulic conductivity. According to Sanner (1999) some sedimentary rocks as well as crystalline rocks are suitable for the application of HT-BTES. Igneous rocks from the Paleozoic Odenwald Crystalline Basement, Germany seem to match all of these requirements and are therefore considered as storage rocks in this study. As hydraulic conductivities in these rocks usually are very low, a conductive heat transport system is expected.

2. METHODS

The present study examines the influence of the parameters BHE length, number of BHEs and spacing between the BHEs on the storage performance of medium deep BTES. In order to achieve an optimal design, numerical models for different storage setups, varying these parameters, are computed. Storage systems with three different setup variations are investigated and listed in Table 1. In total 27 different systems are compared. Figure 1 illustrates the three different BHE configurations, which are considered in this study. Additionally, the influence of the inlet temperature, which is the temperature of the heat transfer fluid, entering the storage system, on the performance of the BTES is studied on one exemplary storage setup by varying the inlet temperature values during the extraction periods.

The numerical modeling was done using the finite element program FEFLOW (DHI-WASY, 2014; Diersch, 2014) for simulating the heat transport processes in the BHEs and in the underground. The BHEs are modeled by 1D finite element representations as described by Diersch et al. (2011) The analytical BHE solution after Eskilson and Claesson (1988) is applied, as it has shown a high efficiency, robustness and a reasonable accuracy in long term analyses (Diersch et al., 2011). The BHEs were accomplished as coaxial pipes with annular inlet of the heat transfer fluid and centered outlet (CXA). The BHE parameters were the same in all considered systems. The borehole diameter was set to 152 mm. A steal pipe was assumed as outer casing with a diameter of

127 mm and a thermal conductivity of 54 W·m^{-1}·K^{-1} and PE-X pipe was assumed as inner pipe with a diameter of 75 mm and a thermal conductivity of 0.4 W·m^{-1}·K^{-1}. The heat carrier fluid is water.

Table 1: Variation of influence parameters, which are applied on the different storage models. Inlet temperatures are varied during extraction periods.

Varied design parameters

BHE length [m]	400	700	1,000
number of BHEs	4	7	19
BHE spacing [m]	2.5	5	10

Varied inlet temperatures during heat extraction

inlet temperatures [°C]	20	30	45	55

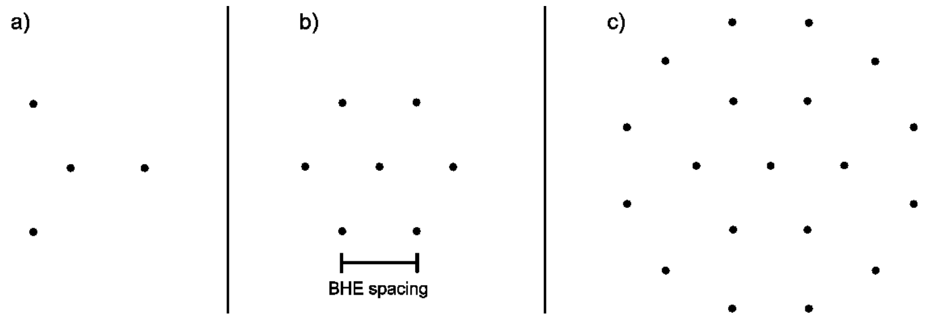

Figure 1: Storage setups in top view with a) 4 BHEs, b) 7BHEs and c) 19 BHEs.

2.1. Standard model and model boundaries

As the influence of the underground parameters on the performance of the storage systems was not part of this study so far, a very simplified single-layered rectangular-shaped underground model with the dimensions 400 m x 400 m x 2000 m was developed (Figure 2). The underground was assumed to consist of granodiorite with a thermal conductivity of 2.6 W·m^{-1}·K^{-1}, a volumetric heat capacity of 2.26 MJ·m^{-3}·K^{-1} and a porosity of 1 %. The estimated value for the hydraulic conductivity of the Odenwald Crystalline Basement is 10^{-8} m·s^{-1}. This value is in good agreement with the results from Stober and Bucher (2007), who stated hydraulic conductivities of the fractured crystalline basement up to a depth of 1 km in the range of 10^{-8} to 10^{-6} m·s^{-1}. As no groundwater flow should be regarded, the hydraulic gradient was set to zero. A geothermal gradient of 3 K/100 m was assigned, by setting a temperature boundary condition of 10 °C (assumed mean surface temperature) on the uppermost slice and a temperature boundary condition of 70 °C on the lowest slice. Where higher temperature gradients were expected during the simulations, the 3D FEM mesh was discretized: This was done in the horizontal direction around the BHE nodes and in vertical direction close to the subsurface and close to the endpoints of the BHEs at 400 m, 700 m and 1,000 m of depth (Figure 2).

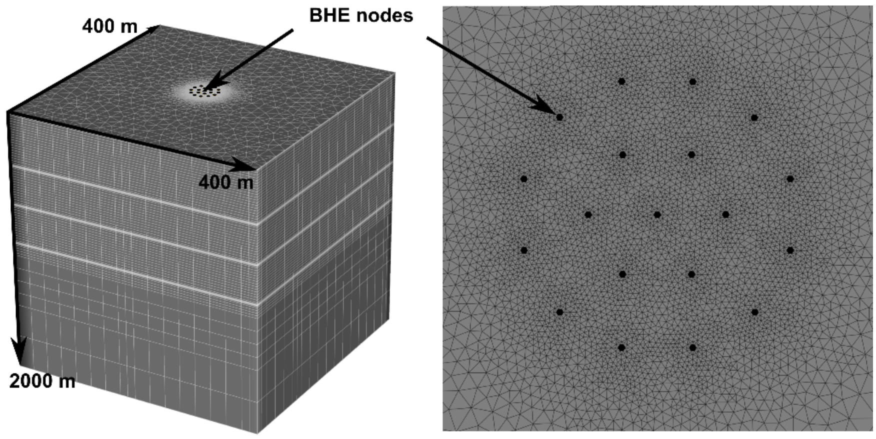

Figure 2: FEM mesh of the standard models in 3D view and in a horizontal slice around the BHE nodes.

2.2. Operating procedure

To compare their performance, a very simplified identical loading and unloading procedure has to be applied on all the different storage designs. FEFLOW 6.2 offers three different kinds of operation modes to actuate the implemented BHEs, either by a preset temperature difference between inlet and outlet temperature of the BHE, a preset inlet temperature, or a preset heating load. All three modes offer the possibility to apply a time series for the preset values. Additionally, the flow rate of the heat transfer fluid through the BHEs has to be specified, either by a constant value or by a time series as well. The preset values can either be assigned to every single BHE or to an array, which can consist of various BHEs. In the latter case, a BHE array has to be determined in the so called BHE interconnection editor, where it has to be defined, how the BHEs in the array are linked to each other in a serial arrangement. In this study, the BHEs are connected to each other in a parallel arrangement.

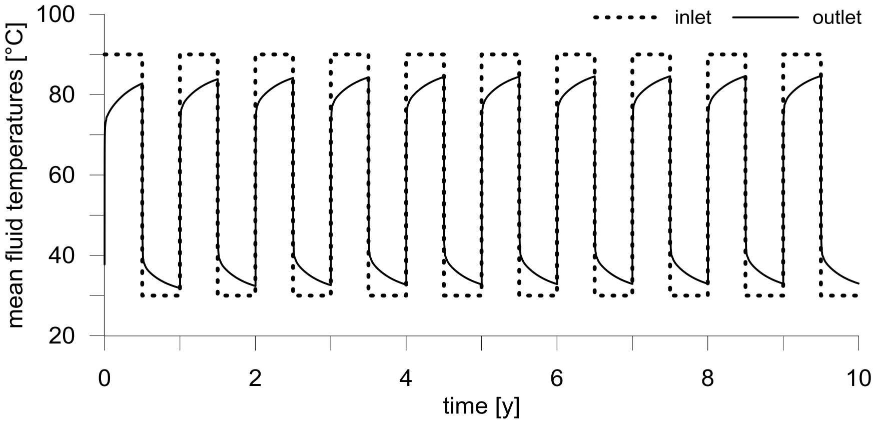

Figure 3: Time series of the preset inlet temperatures for the regarded operation scenario and computed outlet temperature for an exemplary storage set up.

Following the results of some preliminary optimization studies, the flow rate through each BHE of an array was set to 4 $l \cdot s^{-1}$ for the whole simulation time. The operation of the arrays was actuated by a time series, giving the preset inlet temperature of the storage system over a time span of 10 years. To generate an alternating operation between heat storage and heat extraction, the inlet temperature was changed every 6 months as shown in Figure 3. During the heat storage periods, the inlet temperature was set to a constant value of 90 °C. Figure 3 also shows the mean outlet temperature of an exemplary storage system, calculated during the numerical simulation. As the temperature of the underground is lower than the temperature of the heat transfer fluid in the BHEs, the underground is heated up continuously, while the heat transfer fluid is cooled down on its way through the BHEs. The warmer the storage gets, the less heat is transferred from the heat transfer fluid in the BHE to the underground. As a result, the outlet temperature of the fluid increases with time. During the extraction periods, the fluid temperature in the standard procedure was set to a constant value of 30 °C. Heat is transferred from the underground to the colder transfer fluid in the BHEs. The outlet temperature decreases with increasing extraction time, due to the cooling of the storage.

3. RESULTS

The preset inlet temperatures and the calculated mean outlet temperatures of the heat transfer fluid are used to analyze the behavior of the different storage systems. The heat rate ΔQ, which is exchanged between the heat carrier fluid and the storage, can be calculated by

$$\Delta Q = \Delta T \cdot c_V \cdot \dot{V} \tag{1}$$

where ΔT is the temperature difference between the inlet and outlet temperature of the fluid, $\dot{V}$ is the flow rate through the BHE array and c_V is the volumetric heat capacity of the fluid.

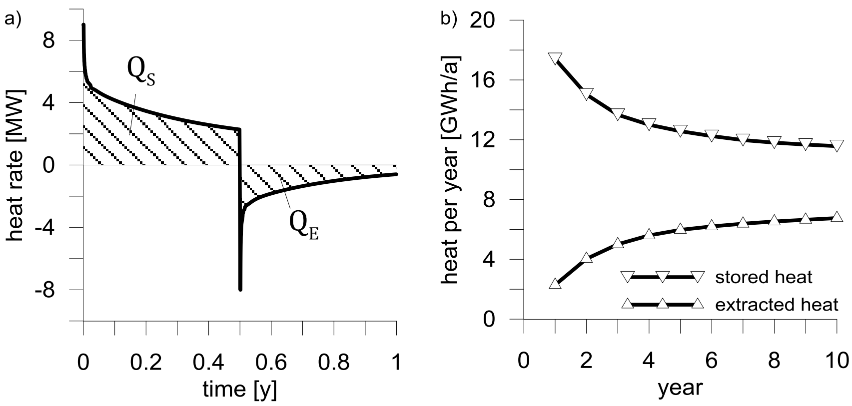

Figure 4: a) Calculated heat rate during the first year of operation of an exemplary BTES. The marked areas correspond to the total heat stored (Q_S) and the total heat extracted (Q_E) during the regarded time span; b) absolute values of the total heat stored and extracted per year of an exemplary BTES for ten years of operation.

By integrating the heat rate over a complete storage or extraction period, the total heat stored or extracted during this period can be calculated (Figure 4). These values are mainly dependent on the total BHE length of a storage system. As the total BHE length varies from storage system to storage system, the values of the total heat stored or extracted are not applicable for the comparison of the performance of the different storage systems. For this reason, the ratio of the absolute value of extracted to stored heat, the storage efficiency η is defined by

$$\eta = \frac{|Q_E|}{Q_S} \tag{2}$$

where Q_S is the heat stored during a certain year and Q_E is the heat extracted from the storage during the same year.

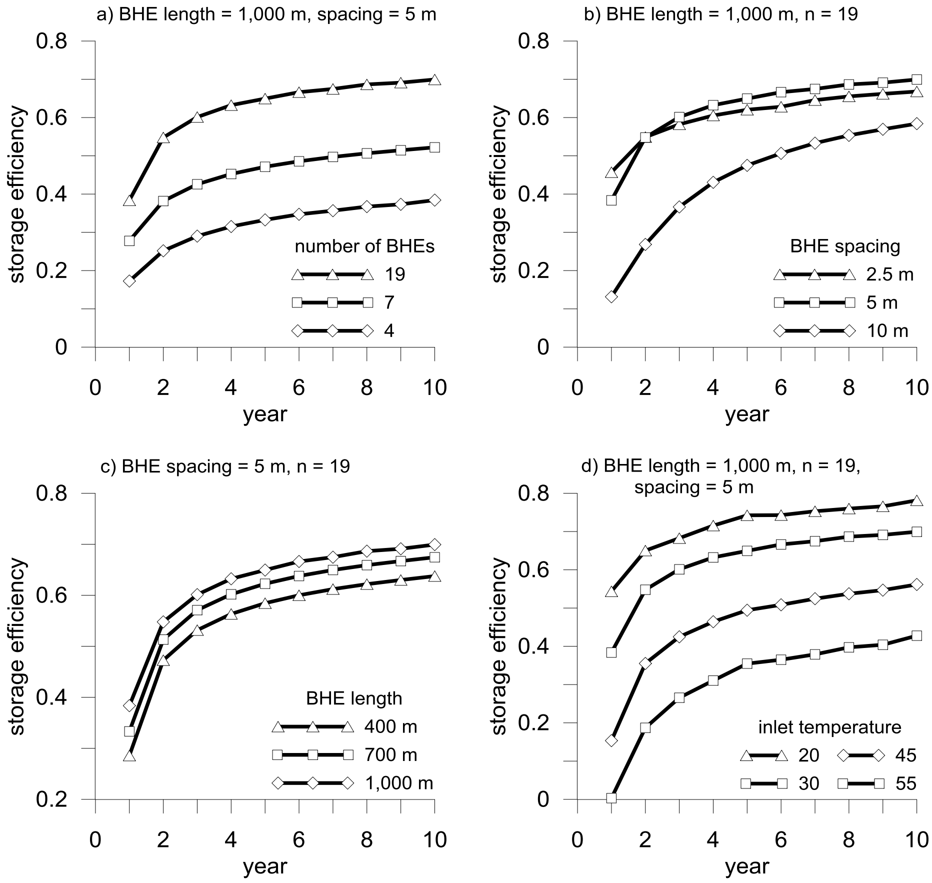

Figure 5: Development of storage efficiency over 10 years of operation for selected storage setups and variations of a) the number of BHEs, b) the spacing between the BHEs, c) the length of the BHEs and d) the inlet temperature.

Figure 5 shows the increase of the storage efficiency over the time frame of ten years for selected storage setups and variations. All regarded storages undergo an increase of efficiency with time. In the first year of operation, the largest increase of efficiency can be observed, whereas in the following years it lowers continuously. In Figure 5a three storage systems that consist of 4, 7 and 19 BHEs with the same length of 1,000 m and the same BHE spacing of 5 m are plotted. The higher the number of BHEs, the higher the initial value and the higher the increase of storage efficiency over the years. Figure 5b illustrates storage systems that consist of 19 BHEs with a length of 1,000 m and BHE spacings of 2.5, 5 and 10 m. The system with a spacing of single BHE of 10 m has the lowest storage efficiency during the whole time span of 10 years, nevertheless all systems with a BHE spacing of 10 m and a number of 19 BHEs show the highest increase of efficiency of all considered systems. The system with a BHE spacing of 2.5 m has a slightly higher storage efficiency in the first year of operation than the system with a BHE spacing of 5 m. Due to a higher increase of efficiency of the latter system, this proportion changes after the second year of operation. From that time, the efficiency of the system with a BHE spacing of 5 m has the higher efficiency. In Figure 5c different BHE lengths are compared for the storage setup with 19 BHEs and a BHE spacing of 5 m. While the initial storage efficiency slightly increases with length of the BHEs, the increase of efficiency is more or less equal for the regarded systems. Figure 5d demonstrates the strong influence of inlet temperature on the efficiency of the systems. The considered storage system consists of 19 BHEs with a length of 1,000 m and a spacing of 5 m. While the absolute values of the efficiency show a clearly recognizable decrease with increasing inlet temperatures, the systems with lower inlet temperatures show a lower increase of efficiency with time than the systems with higher inlet temperatures. After 10 years of operation, still there are no steady-state conditions reached. The storage efficiency is further increasing.

In Figure 6 characteristic values for all 27 case examples are illustrated for the 10th year of storage operation. Attention should be paid to that the x-axis is a discontinuous one. Figure 6a and b show the total heat stored and extracted during the 10th year of operation for the different storage setups. As mentioned before, the increase of BHE length results in an increase in the amount of heat stored as well as in an increase in the amount of heat extracted, due to an enlargement of the heat-exchanger surface. For the storage systems with 4 BHEs, the influence of the BHE spacing on the heat storage and extraction is low. Only the setups with a spacing of 10 m show a slightly higher amount of heat stored. For the storage setups with more than 4 BHEs, regardless of the BHE lengths, the storage systems with BHE spacing of 2.5 m store and extract the lowest amount of heat during the year. The systems with a BHE spacing of 10 m are able to store a larger amount of heat than the systems with a BHE spacing of 5 m, however less heat can be extracted from the systems with a BHE spacing of 10 m.

The storage efficiency, which describes the ratio of extracted to stored heat, is illustrated in Figure 6c. A significant influence of the storage design on the storage efficiency can be observed. Depending on the system, the efficiency varies from about 20 % for the worst system to about 70 % efficiency for the best of the modeled systems. With increasing BHE length, the efficiencies of the systems increase. Increasing the number of BHEs has a strong positive influence on the storage efficiency. The systems with a BHE spacing of 10 m have the lowest storage efficiencies for all variations of length and number of BHEs. The systems with BHE spacing of 2.5 and 5 m show equal storage efficiencies in the case of 4 BHEs. Regarding systems consisting of a higher number of BHEs, the setups with a BHE spacing of 5 m show about 3 to 5 % higher efficiencies than the setups with a spacing of 2.5 m.

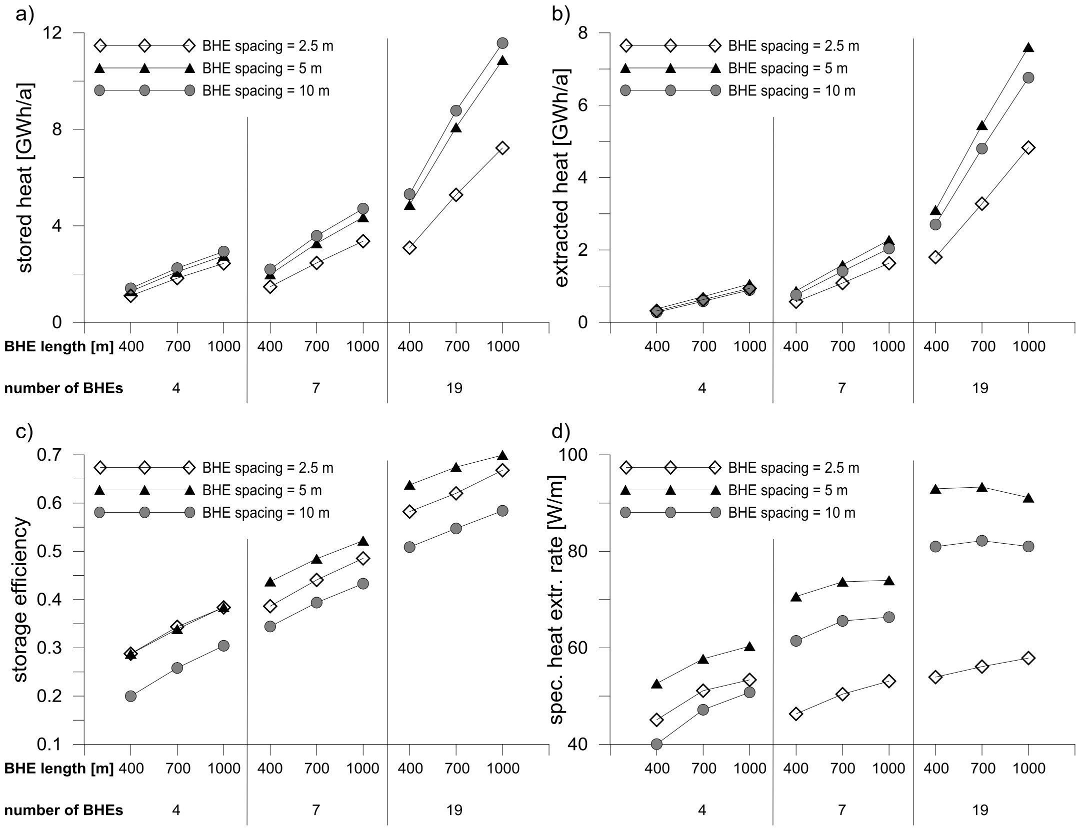

Figure 6: Comparison of a) stored heat, b) extracted heat, c) storage efficiency and d) specific heat extraction rate of different BTES setups during the 10th year of operation. X-axis is discontinuous.

To compare the total extracted amounts of heat of the different systems, the influence of the total BHE length has to be taken into account. Thus the specific heat extraction rate $\dot{q}$, which gives the mean value of the heat extraction rate for a single meter of the BHE array over a certain time span, is calculated by

$$\dot{q} = Q_E \cdot \frac{1}{\Delta t \cdot L_{tot}} \tag{3}$$

where Q_E is the heat extracted from the storage during the considered year, L_{tot} is the total BHE length of the considered storage system and Δt are the hours of heat extraction, which correspond to a time span of half a year (4380 h) in the regarded operating procedure. The results for the 10^{th} year of operation are shown in Figure 6d. Dependent on the storage setup, the specific heat extraction rates vary from about 40 W/m for the system with 4 BHEs of 400 m in length and a spacing of 2.5 m between the BHEs to about 93 $W \cdot m^{-1}$ for the system with 19 x 700 m BHEs and a spacing of 5 m. For the systems with a BHE spacing of 2.5 m an increase of the specific heat extraction rate with increasing BHE length can be observed for all numbers of BHEs. For the systems with 5 and 10 m of BHE spacing this effect is observable as well for the systems with 4 BHEs, but it minimizes for the systems of 7 and for 19 BHEs. For these systems the effect turns around, which means, that the heat extraction rates even decrease from systems with 700 m to systems with 1,000 m of depth. A significant increase in the specific heat extraction rate with the increase of the number of BHEs can be observed, apart from the systems with a spacing of 2.5 m, where the effect is low. For all regarded BHE numbers and lengths, the systems with 5 m of BHE spacing have the highest specific heat extraction rates. Apart from the systems with 4 BHEs, the systems with a BHE spacing of 2.5 m have a distinctly lower specific heat extraction than the other systems.

4. CONCLUSIONS

All the regarded storage systems show an increase of storage efficiency with time. Every year more heat needs to be stored into the underground than can be extracted. This leads to an increase of temperature in the storage rocks. The warmer the underground gets, the less heat can be stored and the more heat can be extracted from the storage.

A strong influence of the BHE length, BHE spacing, the number of BHEs and the inlet temperature of the heat transfer fluid on the storage performance can be observed. The storage efficiency increases with BHE length. The increase of underground temperatures with depth causes lower thermal losses, as the temperature gradients between the heated storage and the surrounding underground are reduced. In systems with a lower number of BHEs, the specific heat extraction rate also increases with depth. For larger arrays, this effect is reduced and for some systems even a slight reduction of the specific heat extraction rate can be observed with increasing BHE depths. Increasing the BHE spacing from 2.5 m to 5 m leads to an increase of storage efficiency and to an increase of the specific heat extraction rates. However, further increase to 10 m of spacing between the BHEs causes a decrease of storage efficiency and a decrease of the specific heat extraction rates. There must be an optimum of BHE spacing in the range of the regarded values, where the highest storage efficiency can be reached. This optimum spacing is probably highly dependent on the thermal properties of the underground. The variation of the number of BHEs shows a strong positive influence on the storage efficiency as well as on the specific heat extraction rates. This might be explained by the increasing ratio of storage volume to the imaginary envelope surface of the storage resulting in lower heat losses to the surrounding rocks.

The study shows, that with all the simplifications, which were made, medium deep storage systems in crystalline rocks can be suitable for the storage of heat with temperatures of 90 °C. High storage efficiencies can be reached as well as high heat extraction rates, supplying outlet temperatures of more than 30 °C. Among the studied storage setups, the systems with 19 BHEs and a BHE spacing of 5 m show the highest storage efficiencies as well as the highest heat extraction rates. In the 10^{th} year of operation, between 64 and 70 % of the stored heat can be recovered during the extraction period and the average specific heat extraction rate reaches more than 90 $W \cdot m^{-1}$assuming 4380 operating hours. The mean outlet temperature during the extraction period is up to 35.4 °C in the 10^{th} year of operation. The storage systems consisting of only 4 BHEs show much lower efficiencies and extraction rates. In the 10^{th} year of operation, these systems only reach efficiencies of about 20 to 38 %, depending on the BHE length and the BHE spacing. The average specific heat extraction rate does not exceed 60 $W \cdot m^{-1}$. For this systems the mean outlet temperatures during the extraction period are in the range of 31 °C to 33.6 °C.

In the continuation of the study, realistic heat loads have to be applied on a selection of model setups, to show, that the technique not only works under simplified assumptions, but also could work under real-life operation conditions. An alternating operation of the coaxial heat exchangers between centered inlet (CXC) during storage periods and annular inlet (CXA) during extraction periods shall be applied, as there may be a potential to enhance the storage performance. An improved scheme of how the BHEs are linked in serial arrangement to each other could also bring an enhancement of the storage efficiency and has to be studied in further simulations. A variation of underground properties will be done, in order to gather information on their influence on the storage behavior. In a further step, groundwater flow should also be taken into account, as it could have strong influences on the storage properties of the underground. Convective heat transport could significantly decrease the storage efficiency, as the stored heat might be carried away from the BHEs. The thermal disturbance of shallow aquifers also has to be quantified.

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Graduate School of Energy Science and Engineering

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