Technical and Economical Evaluation of Medium Deep Borehole Thermal Energy Storages

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ABSTRACT: The utilization of medium deep borehole heat exchangers (BHEs) as seasonal thermal energy storages is expected to have benefits compared to shallow BHE storages. Medium deep borehole thermal energy storages (MD-BTES) have almost no impact on shallow groundwater resources and require less floor space. As no such system is put into practice so far, the efficiencies, the amount of heat that can be stored or extracted and the fluid temperatures that can be achieved by MD-BTES are unknown.
Therefore, 200 different models of MD-BTES were compared, using FEFLOW for modeling the heat transport processes in the BHEs and in the underground. The influence of different parameters on the storage performance was studied by varying the BHE length, the number of BHEs and the spacing between the BHEs. A simplified underground model was assumed and a simplified operation procedure was applied over a period of 30 years of storage operation.
Depending on the storage design, storage efficiencies of more than 80 % and specific heat extraction rates of more than 110 W m^{-1} could be reached with an outlet temperature of the BHE fluid of more than 30 °C during the whole extraction period.
The numerical simulations were then used to economically evaluate MD-BTES and to calculate the carbon footprint of these systems.

INTRODUCTION

The energy demand for heating of buildings and domestic water accounts for about a third of the final energy consumption in Germany (AGEB 2013). There are not synchronous seasonal and diurnal fluctuations in the heat demand and heat supply. One of the major challenges for a sustainable and effective thermal energy supply in the future is to store the heat when it is available and to recover it when it is needed. There are already several technologies available for the seasonal storage of e.g. solar thermal energy or heat from existing combined heat and power plants (CHP) (Schmidt et al. 2004, Xu et al. 2014). One concept is to store the heat in the underground in so called Borehole Thermal Energy Storages (BTES) (Gao et al. 2015). These systems consists of several BHEs arranged in a grid, which are usually not deeper than 100 m. A BHE is a closed pipe system that is installed in a borehole. The boreholes are usually cemented with a thermally enhanced backfilling material. A heat carrier fluid is circulated through this pipe system and exchanges heat with the surrounding subsurface via conductive heat transport through the pipe walls and the backfilling material.
The use of the shallow underground (less than 100 m) for heat storage results in local temperature anomalies in shallow groundwater aquifers. Changes of the groundwater temperature can affect its chemical composition and its physical properties as well as the microbiological activity in the water (Hähnlein et al. 2013). Drinking water is often produced from these aquifers. To keep the environmental impact on these aquifers low, there are, depending on the country, strict regulations for geothermal systems (Hähnlein et al. 2010).
The storage of heat via MD-BHEs with lengths of much more than 100 m to 1000 m is regarded as a possible solution to this concern. The heat will be stored in larger depths in the solid rocks below the aquifer. To minimize the thermal impact on the shallow aquifers, a thermal insulation in the upper part of the BHEs could be installed. As the BHEs in these MD-BTES are larger, less BHEs have to be installed to obtain the same heat amounts as from a comparable shallow BTES. Thus less floor space is needed. Especially in urban areas, where space is sparse and expensive, this is a further advantage of MD-BTES.
As the concept of MD-BTES has not been put into practice so far, investigations on the performance and economic considerations on these systems have to base on numerical simulations.

METHODS

The presented study examines the influence of the parameters BHE length, number of BHEs and spacing between the BHEs on the storage performance of MD- BTES. In order to achieve an optimal design, numerical models for different storage setups were created. Storage systems with different setup variations are investigated as listed in Table 1. In total 200 different systems are compared. Figure 1 illustrates the five different BHE configurations, which are considered in this study.

Table 1: Parameter variations.

Variable	Value									
BHE length [m]	100	200	300	400	500	600	700	800	900	1,000
Number of BHEs	7		13		19		28		37	
BHE spacing [m]	2.5		5		7.5		10			

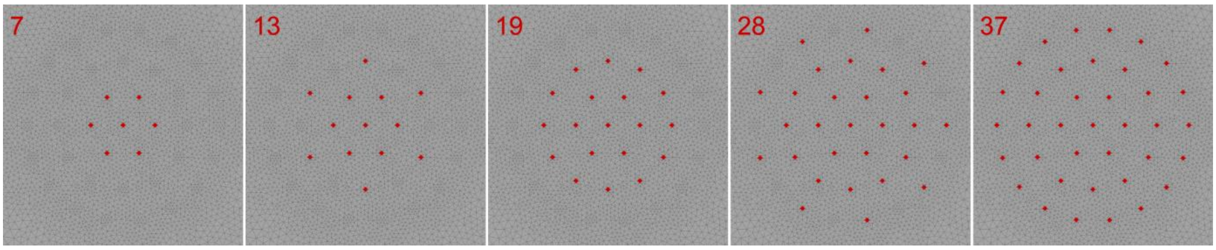

Figure 1: BHE Arrangements in top view.

Model settings

The numerical modeling was done using the finite element program FEFLOW 6.2 (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 underground parameters and the BHE parameters are listed in Table 2.

Table 2: Model parameters

Underground parameters			BHE parameters		
Parameter	Value		Parameter	Value	
Thermal conductivity of solid	2.6	$W\ m^{-1}\ K^{-1}$	Borehole diameter	0.1522	m
Volumetric heat capacity of solid	2.26	$MJ\ m^{-3}\ K^{-1}$	Outer pipe diameter	0.127	m
Thermal conductivity of fluid	0.65	$W\ m^{-1}\ K^{-1}$	Outer pipe wall thickness	0.0056	m
Volumetric heat capacity of fluid	4.2	$MJ\ m^{-3}\ K^{-1}$	Inner pipe diameter	0.075	m
Porosity	0.01		Inner pipe wall thickness	0.0068	m
Surface temperature	10	°C	Outer pipe thermal conductivity (steel)	54	$W\ m^{-1}\ K^{-1}$
Geothermal gradient	0.03	$K\ m^{-1}$	Inner pipe thermal conductivity (PE-X)	0.4	$W\ m^{-1}\ K^{-1}$
Hydraulic conductivity	10^{-8}	$m\ s^{-1}$	Grout thermal conductivity	2	$W\ m^{-1}\ K^{-1}$
Hydraulic gradient	0		Refrigerant volumetric heat capacity (water)	4.145	$MJ\ m^{-3}\ K^{-1}$
			Refrigerant thermal conductivity (water)	0.65	$W\ m^{-1}\ K^{-1}$
			Refrigerant dynamic viscosity (water)	504	$10^{-6}\ kg\ m^{-1}\ s^{-1}$
			Refrigerant density (water)	977	$kg\ m^{-3}$

Simplified single-layered box models with the dimensions 400 m x 400 m x 2000 m were created (Figure 2). The underground was assumed to consist of granodiorite. 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 (representative 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 (Figure 2).

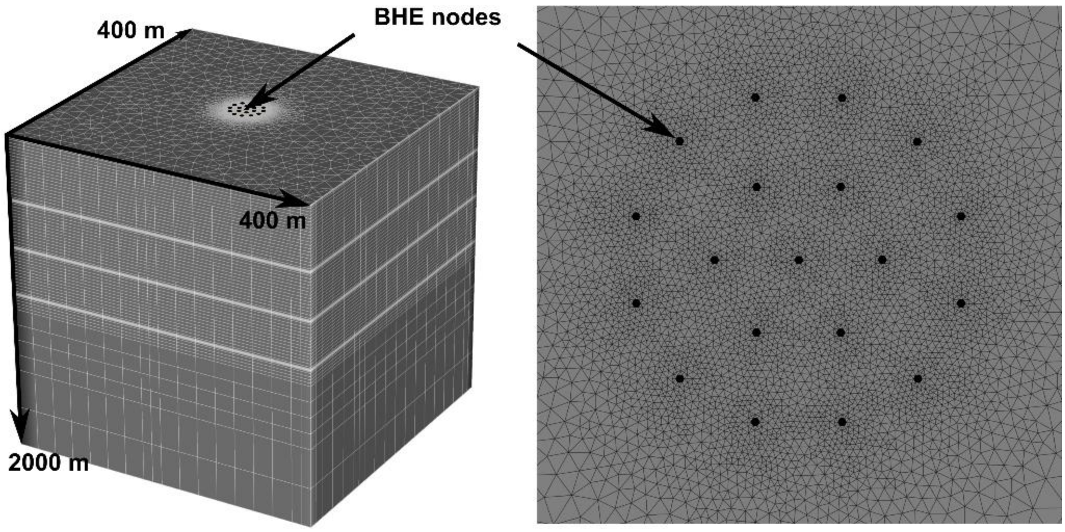

Figure 2: FEM mesh of the standard models in 3D view and in a horizontal slice around the BHE nodes.

Operating procedure

To compare their performance, a very simplified identical charging and discharging procedure had to be applied on all the different storage designs. FEFLOW 6.2 offers three different kinds of operation modes to control 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.

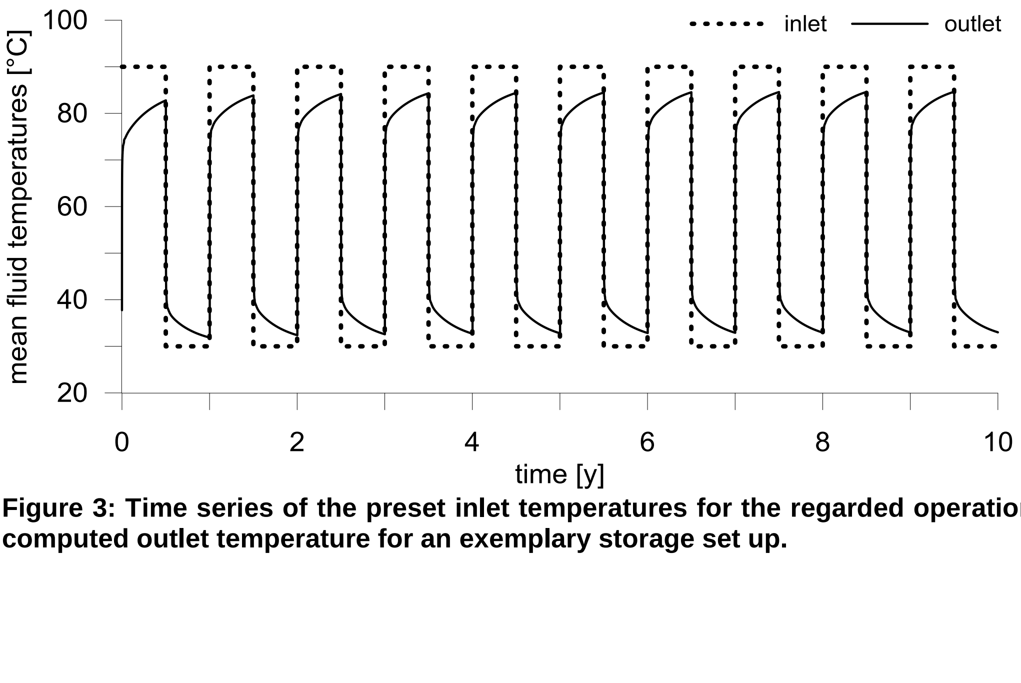

Figure 3: Time series of the preset inlet temperatures for the regarded operation scenario and computed outlet temperature for an exemplary storage set up.

Following the results of some preliminary optimization studies, the flow rate through each BHE of an array was set to 4 l s^{-1} for the whole simulation time. The operation of the arrays was controled by a time series, giving the preset inlet temperature of the storage system over a time span of 30 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.
To compare the different storage setups reference values were calculated from the inlet and outlet temperature time series:

The storage efficiency η, which is the ratio of extracted heat Q_E to stored heat Q_S in a certain year of operation:

$$\eta = \frac{|Q_E|}{Q_S} \tag{1}$$

and the specific heat extraction rate $\dot{q}$, which is the mean heat extraction rate for each meter of borehole during a certain year of operation:

$$\dot{q} = Q_E \cdot \frac{1}{\Delta t \cdot L_{tot}} \tag{2}$$

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. In the regarded operating procedure Δt corresponded to the time span of half a year (4380 h).

Economic evaluation

To economically assess a complete heating system that is equipped with an MD-BTES, several cost factors have to be considered: Investment costs for the storage and further installations like for example solar thermal collectors, pipes to connect the installations, circulating and heating pumps and the running costs like for example the gas costs to run the CHP, electricity costs for the pumps and the maintenance costs for all the installations. As opposed to this there are earnings for example in terms of discharged heat from the storage in winter, which also have to be included in the calculations.
The assessment was done for all the different storage configurations that were modeled with FEFLOW and was based on the simulation results.
Two scenarios were compared. In scenario 1 all of the heat that was used to charge the storage was supplied by an existing CHP, so that the operation time of the CHP in summer could be increased. In scenario 2 a large part of the heat from the CHP to charge the storage was substituted by heat from newly installed solar thermal collectors. The costs for both scenarios were compared to a conventional scenario without an MD-BTES, where all the heat in winter was supplied by the CHP directly. So the additional heat available in winter from the discharge of the storage and in scenario 2 also from the solar thermal collectors can be seen as earnings of the system.

RESULTS

Simulation results

Figure 4 shows the temperature distribution in an exemplary storage after a charging period. After the discharge of the storage, there is still some heat left in the underground from the storage cycle as not all of the stored heat can be extracted. As a result, the temperature rises in the storage rocks from year to year. The warmer the storage gets, the less heat can be stored in summer and the more heat can be extracted in winter. This leads to a continuous increase in the storage efficiency with the time of operation (Figure 5).

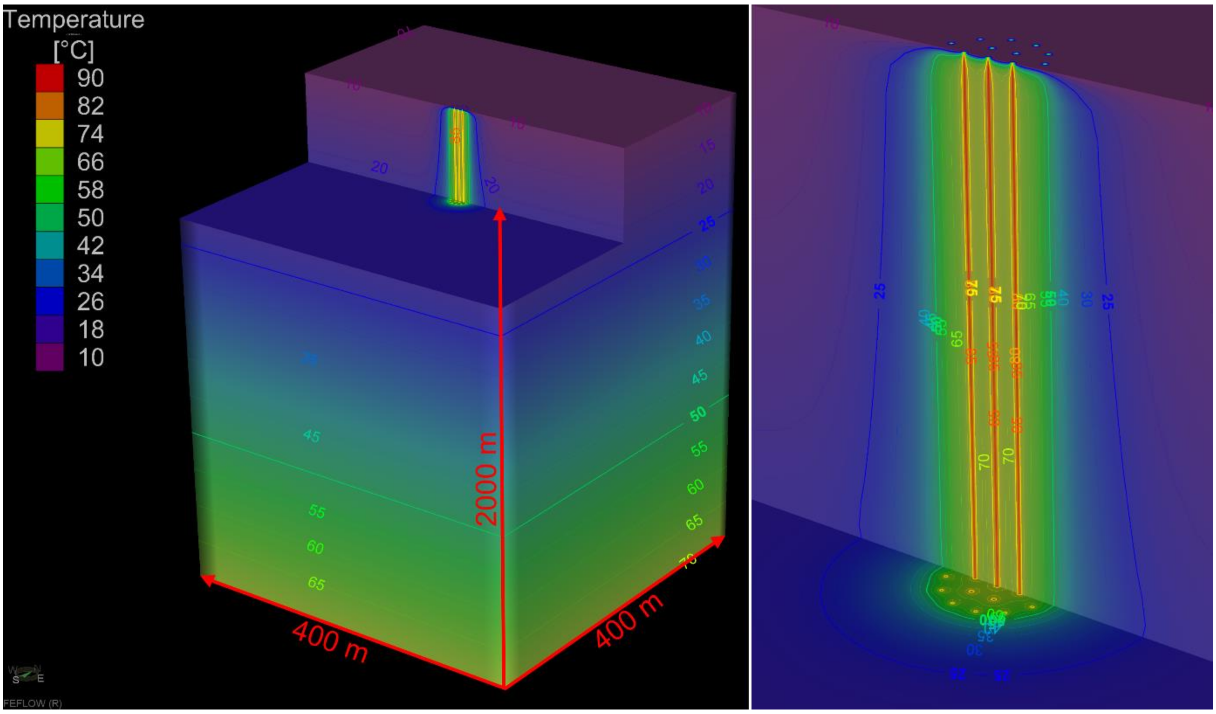

Figure 4: Temperature distribution in the subsurface around an exemplary MD-BTES after charging with heat.

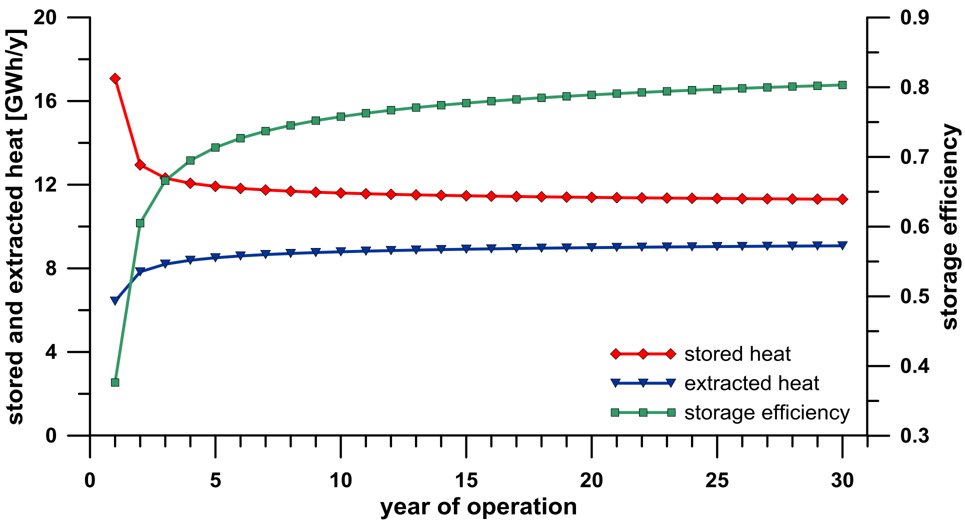

Figure 5: Temporal evolution of an exemplary MD-BTES.

The variations of the BHE configurations showed, that the storage systems with a BHE spacing of 5 m reach the highest storage efficiencies and specific heat extraction rates. Figure 6 shows the stored and extracted heat amounts as well as the storage efficiency and the specific heat extraction rates for the variations of the BHE length and the variation of the number of BHEs for all systems with a BHE spacing of 5 m. The larger the systems get, the more heat can be stored and extracted from the storages. Increasing the BHE length as well as increasing the BHE number have both a positive effect on the storage efficiency. The deeper the storage reaches into the ground, the higher are the natural ground temperatures and the lower are the thermal losses into the surrounding rocks. In storage systems that consist of a higher number of BHEs, more BHEs can interact with each other. Parts of the heat, which is stored in one BHE, migrate away and can be extracted in an adjacent BHE.

The specific heat extraction rate also increases with an increase in the number of BHEs. It also shows an increase with the BHE length until a maximum specific heat extraction rate is reached at a BHE length of about 300 to 400 m. A further increase in the BHE length leads to a slight decrease in the specific heat extraction rate again. Depending on the storage dimensions several GWh of heat can be stored and extracted from the systems per year, storage efficiencies of more than 80 % and specific heat extraction rates of more than 110 W per meter of borehole can be reached.

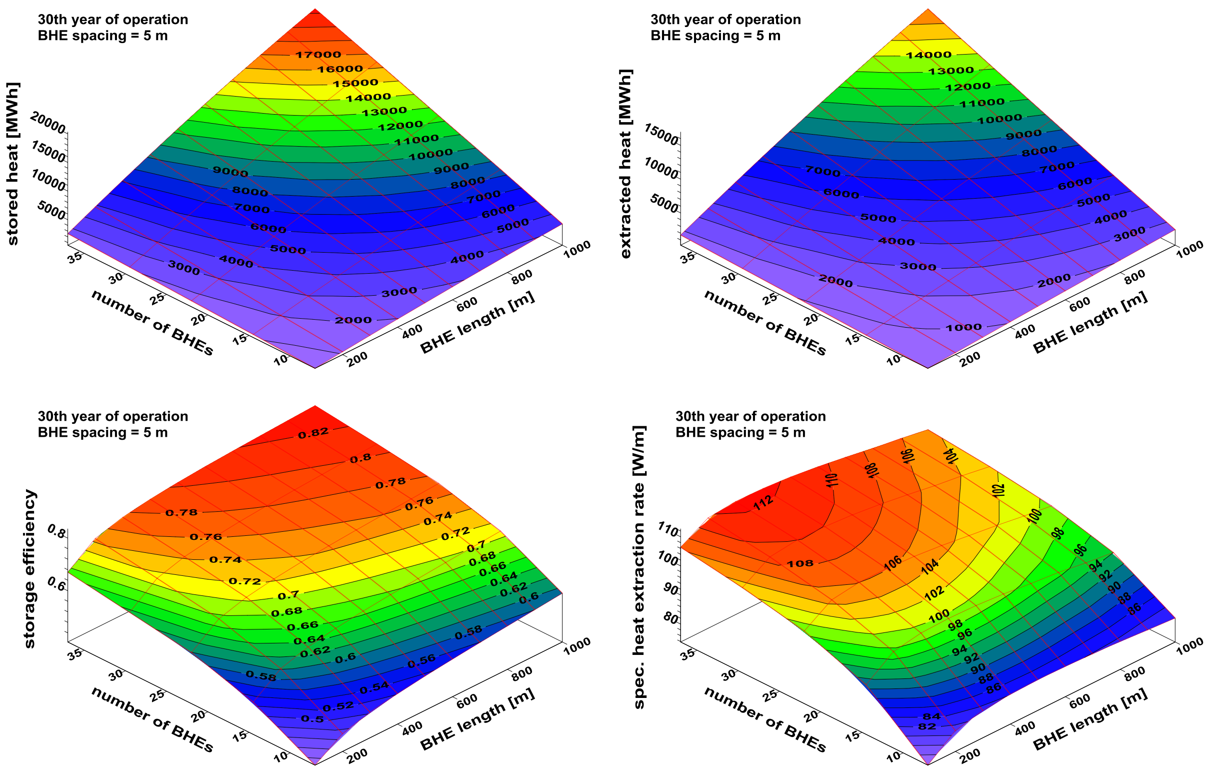

Figure 6: Comparison of different MD-BTES configurations.

Economic assessment and carbon footprint

The results of the economic assessment and the calculations of the carbon footprint of the MD-BTES systems with a BHE spacing of 5 m are shown in Figure 7. The results are in relation to the conventional heating scenario, in which all the heat in winter is supplied by the CHP directly. The calculated values are mean values for the whole regarded time span of 30 years. Scenario 1, in which the storage system is charged with heat from the existing CHP only, shows earnings of up to 10 ct per kWh of heat that is discharged from the current MD-BTES system. MD-BTES systems with a high specific heat extraction rate show the highest earnings. The investment costs can be amortized in less than 10 years. However, the main earnings in this scenario result from the selling of additionally produced electricity in summer. As the CHP produces more heat in summer, compared to the conventional scenario, more electricity is produced as well. In Scenario 2 the heat is in a large part supplied by additionally installed solar thermal collectors. Compared to scenario 1, less heat is needed from the CHP to charge the storage and thus less electricity can be sold. In combination with the additional investment costs for the solar collectors, expenses are higher than the earnings of the systems. In the best case about 1 ct per kWh of heat has to be paid additionally to the heat price in the conventional scenario. In return the carbon footprint of scenario 2 is much better than both the carbon footprint of the conventional scenario as well as the carbon footprint of scenario 1. The latter is even worse than that of the conventional scenario. As MD-BTES show notable heat losses, more heat is needed to charge the storage than later can be discharged to heat buildings and as a result, more fossil fuel has to be burnt. Whereas an MD-BTES in combination with solar thermal collectors can save about 160 g of CO_2 per kWh of heat. Another option to deal with the increased carbon emissions might be the use of a biofuel powered CHP.

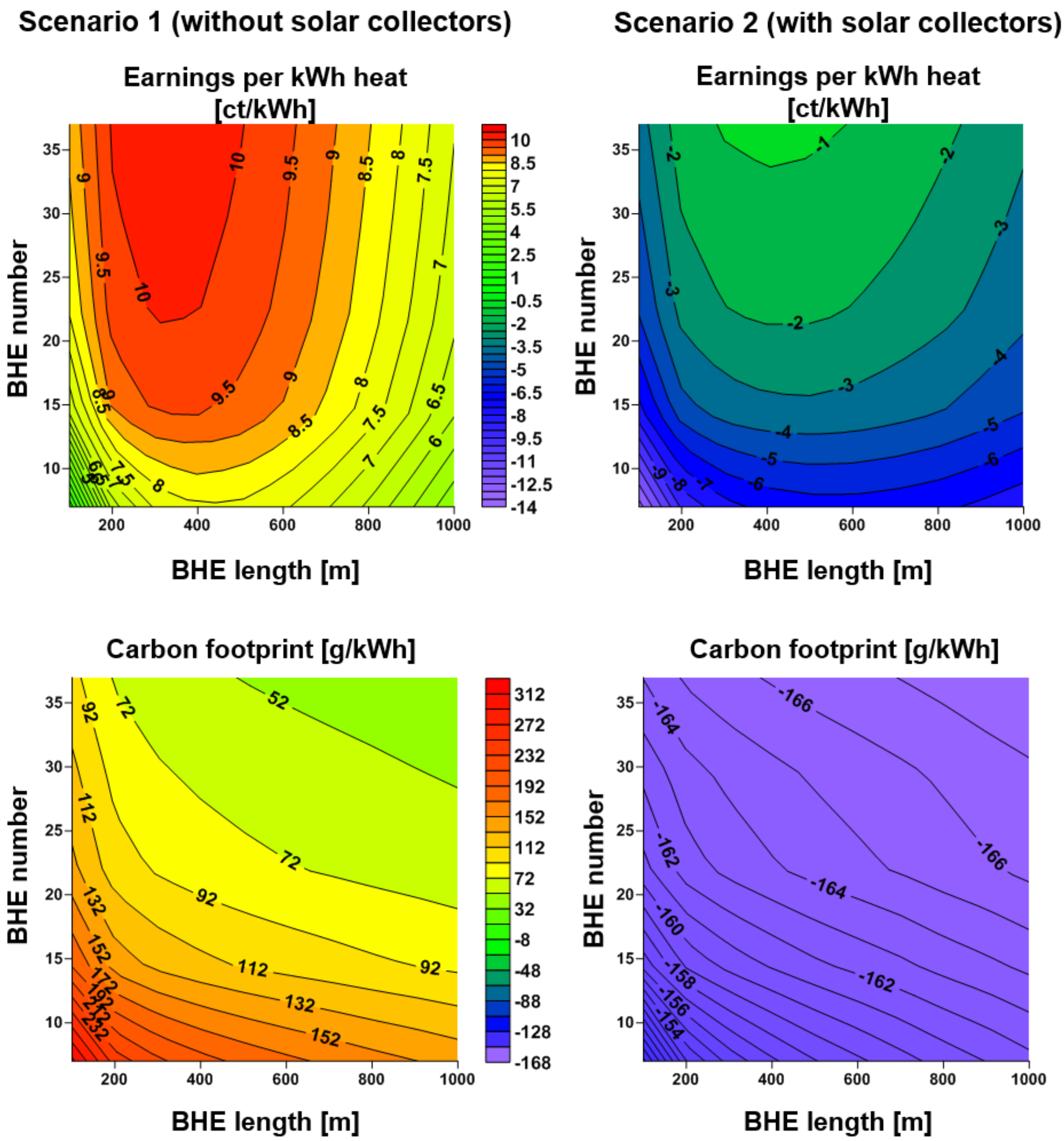

Figure 7: Additional earnings/expenses per kWh of heat and additional CO_2 emissions/savings per kWh of heat for heating systems with different MD-BTES configurations, compared to the conventional heating system.

SUMMARY

The modeling results showed, that in practical terms MD-BTES are eminently suitable for seasonal heat storage. All the regarded storage systems show an increase of storage efficiency with time. A strong influence of the design parameters BHE length, BHE spacing and the number of BHEs on the storage performance was observed. High storage efficiencies can be reached as well as high heat extraction rates, supplying outlet temperatures of more than 30 °C. Depending on the design parameters, in the 30th year of operation more than 80 % of the stored heat could be recovered during the extraction period and the average specific heat extraction rate reached more than 110 W m^{-1} assuming 4380 operating hours.

Furthermore the study showed, that MD-BTES also can be suitable from an economic point of view. In combination with an existing CHP the investment costs for the storage could be amortized in less than 10 years. In combination with a solar thermal device the investment costs are larger and compared to a conventional heating scenario, the heat price is slightly increased. In return about 160 g/kWh of CO_2 could be saved.

In the next step, the FEFLOW storage models will be coupled with models of the surface facilities including heat pumps, buffer storages, heat sources and heat consumers, which are modeled with MathWorks Simulink. The coupling of FEFLOW and Simulink shall enable a more precise evaluation and optimization of an integrated heating system combined with an MD-BTES.

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