# Modelling of seasonal borehole thermal energy storages and integration into a power plant simulation environment

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## ABSTRACT

This paper presents an analytical method for calculating the thermal behaviour of borehole heat exchangers and borehole thermal energy storages under the boundary condition of a constant inlet temperature. An analytical model based on the use of dimensionless temperature response functions, so-called g-functions, is set up for this purpose. Due to the small difference in g-functions for different boundary conditions within short observation times, the analytical model can be verified by a two-dimensional numerical borehole heat exchanger model with prescribed thermal power input. In addition, the numerical model is used to evaluate the thermal capacity of a borehole thermal energy storage with 80 boreholes. The analytical model is coupled to the *EBSILON® Professional* power plant simulation environment. In future, this connection enables the simulation of borehole thermal energy storages in combination with heat generators or heat pumps in district heating applications.

**Keywords:** borehole heat exchangers, borehole thermal energy storage, analytical model, numerical simulation, storage capacity, power plant simulation.

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## 1. INTRODUCTION

In its strategy for transition to renewable energies, the European Commission has stated that the share of solar thermal and geothermal energy should be at least tripled to achieve the EU targets for 2030 [1]. Therefore, it is necessary to identify and evaluate possible thermal underground storage capacities in addition to installing further geothermal heat exchangers. The European Geothermal Energy Council has also called for the consideration of thermal underground storages in a 9-point action plan [2].

Thermal underground storage systems, in particular the borehole thermal energy storages (BTES) considered in this study, are used to cover peak loads and the shift between seasonal heat demand and supply. BTES consist of several boreholes at comparatively short distances from each other. During summer, BTES are often charged with surplus solar or waste heat from high temperature processes and discharged during the heating period, e.g. in conjunction with high-temperature heat pumps.

In order to model a borehole heat exchanger (BHE) in such a system, it makes sense to set the boundary conditions to a predefined inlet temperature instead of a constant heat flow. This article describes an analytical approach for calculating the thermal behaviour of BTES for predefined inlet temperature. A verification with numerical simulations shows that the analytical solution is valid at least for short periods of times. The numerical model is also used to analyse the thermal storage capacity of BTES.

The overall aim of the analytical model is to interact with the *EBSILON® Professional* power plant simulation environment (*EBSILON*). *EBSILON* deals with the simulation of high-temperature heat pumps. The interface between the analytical model and *EBSILON* is also described.

## 2. ANALYTICAL MODEL

This section describes an analytical model to calculate the thermal reaction in a BHE with prescribed and over a considered time step constant fluid inlet temperature. The goal is to calculate the fluid outlet temperature of a single BHE or a BHE field.

Eskilson showed that the temperature at the borehole wall $\bar{T}_b$ can be evaluated by the help of so-called g-functions $g$, describing the time-dependent dimensionless thermal response of a corresponding BHE [3]:

$$\bar{T}_{b,n} = T_0 + \sum_{i=1}^{n} \frac{\dot{q}_i}{2\pi\lambda}(g_{n-i+1} - g_{n-i}) \tag{1}$$

Depending on the injected or extracted heat flux $\dot{q}$ and the thermal conductivity of the ground $\lambda$, the temperature drop or rise between the undisturbed ground and the borehole wall temperature can be superimposed and accumulated to the initial ground temperature $T_0$ for an amount of equidistant time steps $n$.

By definition $g_0$ is equal to zero, and therefore equation (1) can be expressed as

$$\bar{T}_{b,n} = T_0 + \dot{q}_n R_{g,n} + S_{g,n-1} \quad (2)$$

with the thermal resistance $R_{g,n}$ as

$$R_{g,n} = \frac{g_1}{2\pi\lambda} \quad (3)$$

and the summation term $S_{g,n-1}$ as

$$S_{g,n-1} = \sum_{i=1}^{n-1} \frac{\dot{q}_i}{2\pi\lambda}(g_{n-i+1} - g_{n-i}) \quad . \quad (4)$$

Considering the inside of the borehole, two more heat transportation processes have to be accounted. First, the injected or extracted heat flux has to cross the grouted borehole and the wall of the pipes until it reaches the fluid. The effective thermal borehole resistance $R_{b,eff}$ includes these influences as well as the thermal short circuit between the upward and downward fluid flows in the pipes:

$$\dot{q}_n = \frac{1}{R_{b,eff}}\left(\bar{T}_{f,n} - \bar{T}_{b,n}\right) \quad (5)$$

Assuming the mean fluid temperature $\bar{T}_f$ to be the arithmetic mean between the inlet ($T_{f,in,n}$) and outlet fluid temperature ($T_{f,out,n}$), equation (5) can be expressed as follows:

$$\dot{q}_n = \frac{1}{R_{b,eff}}\left(\frac{T_{f,in,n} + T_{f,out,n}}{2} - \bar{T}_{b,n}\right) \quad (6)$$

The second heat transportation process within the borehole is the heat flux carried by the fluid flow within the pipes. The total pipe length $L$ of one pipe circuit in the borehole is two times the borehole depth $H$.

$$\dot{q}_n = \dot{V}_n \varrho c_p \left(T_{f,in,n} - T_{f,out,n}\right)\frac{2}{L} \quad (7)$$

The corresponding fluid parameters as the volume flow $\dot{V}$, the density $\varrho$ and the specific heat capacity $c_p$ are related to the total volume flow supplied to a single BHE.

Equations (7) and (2) can be inserted in equation (6):

$$\dot{q}_n = \frac{1}{R_{b,eff}}\left(T_{f,in,n} - \frac{\dot{q}_n L}{4\dot{V}_n \varrho c_p} - T_0 - \dot{q}_n R_{g,n} - S_{g,n-1}\right) \quad (8)$$

For better clarity the thermal resistance $R_f$ is introduced:

$$R_f = \frac{L}{4\dot{V}_n \varrho c_p} \quad (9)$$

Further parsing of equation (8) under consideration of equation (9) leads to:

$$\dot{q}_n = \frac{T_{f,in,n} - T_0 - S_{g,n-1}}{R_{b,eff} + R_f + R_{g,n}} \quad (10))$$

Also, equation (7) can be reinterpreted with equation (9) in order to calculate the fluid outlet temperature:

$$T_{f,out,n} = T_{f,in,n} - 2\dot{q}_n R_f \quad (11)$$

Inserting equation (10) in (11):

$$T_{f,out,n} = T_{f,in,n} - \frac{T_{f,in,n} - T_0 - S_{g,n-1}}{R_{b,eff} + R_f + R_{g,n}} 2R_f \quad (12)$$

Equation (12) can be used to calculate the fluid outlet temperature at time step $n$ with regard to the temperature responses in the past. The thermal influence of the past can be evaluated by the superposition of g-function values. The *Python* tool *pygfunction* is used here to calculate g-functions [4,5]. It is open source, free to use and fits well to the presented approach, which is also implemented in the *Python* programming language. Using *pygfunction*, it is possible to calculate g-functions for different boundary conditions, including the boundary condition of a specified inlet temperature required here [6,7].

Fig. 1 shows an example of calculated g-functions with *pygfunction* for a BHE field of 6 x 4 BHEs (example is delivered with the *pygfunction* toolbox). The g-function values differ depending on the given boundary condition, but they are almost equal until a logarithmic value of the dimensionless expression $ln\left(\frac{t}{t_s}\right) = -2.5$ is reached. As stated by Cimmino, these are several years for conventional BHE dimensions [8].

As a consequence of these almost equal g-function values, short time considerations of BHEs and the surrounding ground are therefore independent of the given boundary condition. In the next chapter, a numerical model is presented, which serves to verify the analytical solution.

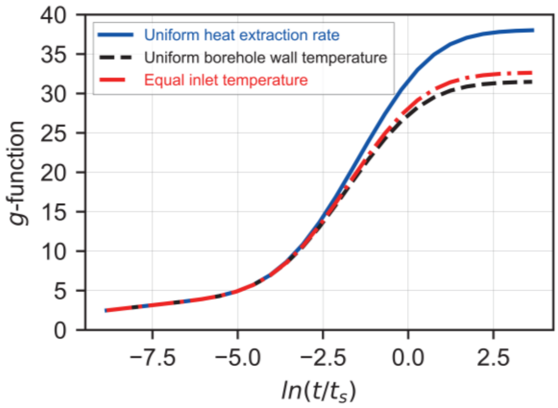


*Fig. 1: Example g-function values calculated with pygfunction for a 6 x 4 BHE field and different boundary conditions [5]*

## 3. NUMERICAL SIMULATION AND VERIFICATION

For verifying the analytical model described in the previous section, a simplified numerical BHE model is simulated with *COMSOL Multiphysics®* (software Version 6.1). In the following, a BHE field with 80 boreholes is considered. The arrangement of the BHEs in the field is based on the real system in Crailsheim [9] and shown in Fig. 2. The distance between the boreholes is 3 m and the depth of each BHE is 55 m.

The positions of the BHEs are symmetrical to the $x$-and $y$-axis, which means that only a quarter of the borefield needs to be simulated. The simulated quarter therefore consists only of 20 BHEs, which are highlighted with black points in Fig. 2.

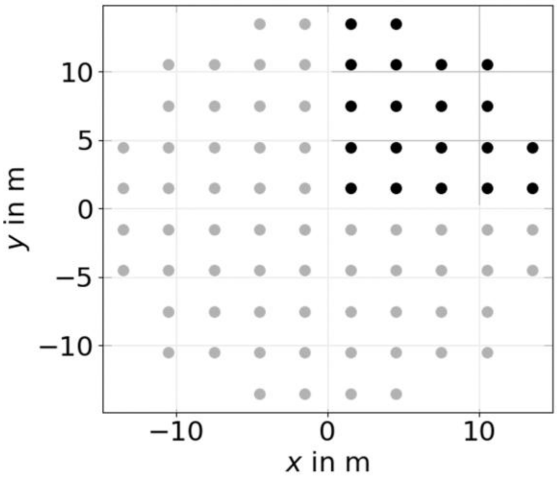


*Fig. 2: Arrangement of the borefield in Crailsheim with 80 BHEs*

The numerical BHE model is simplified in that only a 2D region is modelled, which thus corresponds to an infinite line source. In the simulation of the BHEs, as shown in Fig. 3, each BHE is therefore regarded as a simple point source in the 2D space that extends to infinity in the ordinate of the drawing plane. The dimensions of the simulated area are equal in $x$ and $y$ direction with a value of 20 m. In *COMSOL Multiphysics®* it is possible to expand the physically investigated area with so-called infinite boundary layers. In the model used here, the infinite boundary layers are applied to the last metre at the top and right edge, which is extended by a factor of $10^3$. At the end of the infinite boundary layers, the boundary condition of a constant temperature is applied.

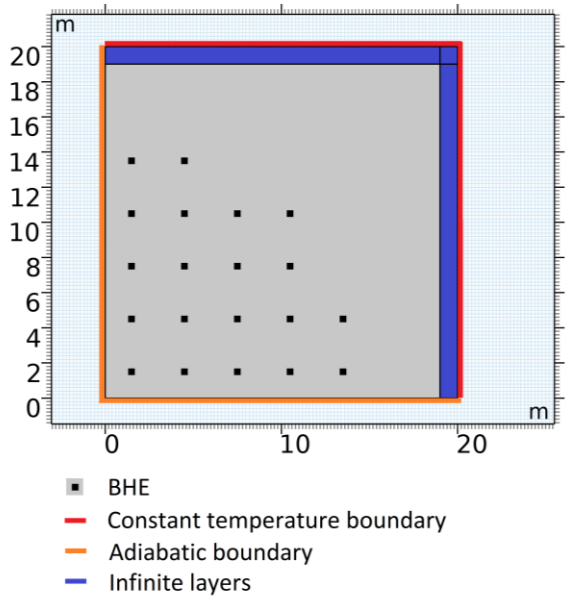


*Fig. 3: Construction of the 2D model of the single BHE with adiabatic boundary conditions at the symmetry axes x=0 and y=0 and constant temperature conditions at the end of the infinite boundary layers*

In the following verifications, a specific heat load of 40 W/m is injected through the BHEs to the surrounding ground. The simulation period is one month. In order to analyse the heat distribution in the area under investigation with sufficient accuracy, the mesh near the BHEs is significantly refined. The size of the grid cells increases with increasing distance from the BHEs as shown in Fig. 4. In addition to the mesh settings, the time step width of the simulation is limited to one hour, so that calculation errors are minimised.

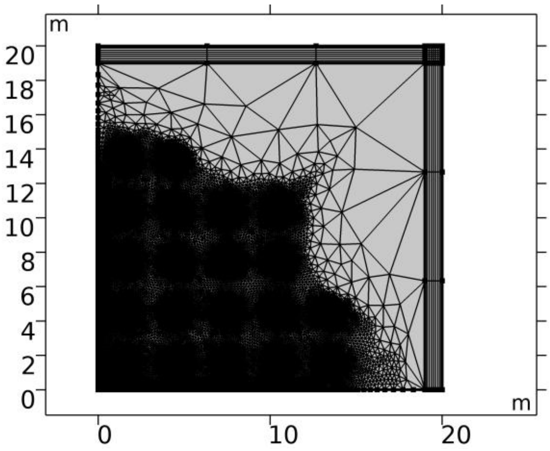


*Fig. 4: Generated mesh for the investivation of 20 BHEs within the BHE field*

In order to use the analytical equations shown in section 2 and to compare the results with the solutions obtained with the numerical simulations, the injected heat load of 40 W/m must be converted to an inlet temperature. This can be calculated using equation (7) based on the given heat load and a given mass flow rate. The mass flow rate is set to 0.2 kg/s per BHE. To calculate the fluid inlet temperature, however, the fluid outlet temperature must also be specified. In the first time step, the fluid outlet temperature is therefore set to the undisturbed ground temperature. All subsequent values of the fluid inlet temperature can then be calculated using the fluid outlet temperature of the previous time step. The undisturbed ground temperature is set to 0 °C in the following considerations. The g-function for individual arrangement of the 80 BHEs is created by *pygfunction*.

The comparison focuses on the temperature at the borehole wall, i.e. at a distance of 0.075 m from the heat source. This is the only comparable temperature due to the fact that the g-functions are calculated for this radius. Conclusions about the fluid inlet and outlet temperature cannot be drawn with the simplified numerical model.

Fig. 5 shows the results of the analytical and the numerical solutions for the mean borehole wall temperature over all boreholes ($\bar{T}_b$ and $\bar{T}_{b,Comsol}$). In addition, the temperature curves for the outermost and innermost borehole are shown ($\bar{T}_{b,Comsol,o}$ and $\bar{T}_{b,Comsol,i}$), i.e. the boreholes at position $x_o, y_o = (1.5{,}1.5)$ and $x_i, y_i = (10.5{,}10.5)$ according to Fig. 3.

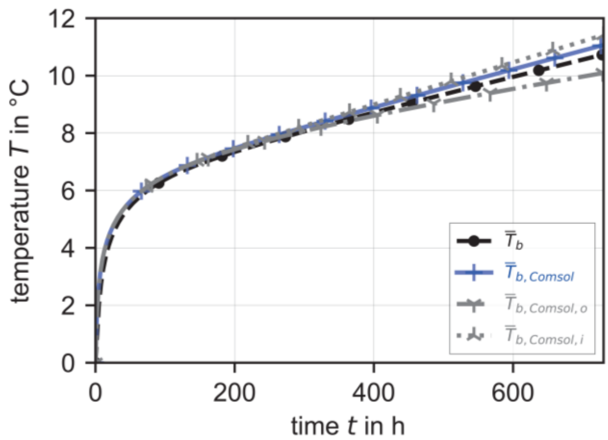


*Fig. 5: Comparison of different borehole wall temperatures in a BHE field calculated with the numerical model and compared to the overall borehole wall temperature of the analytical model*

For the short time of one month, the difference between the analytical and numerical solution with regard to the mean borehole wall temperature over the entire field is small. The deviation at the end of the calculation period is below 5 % ($\bar{T}_b = 10.74\,°C$ and $\bar{T}_{b,Comsol} =$

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$11.07\ °C$). The temperature difference at the innermost and outermost BHE shows the influence of the BHEs on each other. BHEs at the outer edge of the field are less influenced by neighbouring BHEs and therefore have a lower temperature rise than BHEs in the centre of the field.

The comparison between the numerical and analytical model shows a good agreement of the average borehole wall temperatures over short periods of time. However, further investigations are required to verify the temperature values over longer periods. This is particularly difficult with numerical models, as a detailed model of the borehole interior must be provided to represent the correct boundary condition (constant inlet temperature). Symmetries can also no longer be used for the investigation of U-probes and double U-probes, which significantly enlarges the calculation area and makes it three-dimensional.

However, the numerical model with 80 BHEs shown here is suitable to assess the temperature development not only at the wall of the borehole, but also at any point in the field. In the next section, this flexibility is used to estimate the storage capacity of such BTES.

## 4. EVALUATION OF STORAGE CAPACITY OF BTES

In contrast to the analytical model, the numerical model allows to assess the temperature at any point within the simulated area. This makes it possible to evaluate the temperature development, e.g. along the symmetry axes of the BHE field, and thus easily calculate the stored thermal energy. In contrast, only the average borehole wall temperature over the entire field can be considered in the analytical model, which makes it difficult to determine the stored thermal energy. Therefore, the thermal storage capacity is only evaluated with the numerical model in this work.

The numerical model from section 3, which represents 20 of 80 BHEs, is used to determine the storage capacity as an example. This model reflects the real BTES installed in Crailsheim, Germany. Fig. 6 shows a picture during the drilling of the boreholes. Since the numerical model includes the simplified assumption that the length of the BHEs is infinite (2D model), the storage capacity can only be determined without losses in the depth of the ground.

*Fig. 6: Installation of the 80 BHEs at the BTES in Crailsheim, Germany [9]*

For this reason, the storage capacity is related to the BHE length in the following considerations (as depicted in Fig. 7). In addition, the capacity is also considered in several sections along the radius of the BTES (see Fig. 3, symmetry axis $x_c, y_c = (0,0 \dots 20\mathrm{m})$) in order to recognize the distribution along the BHE field.

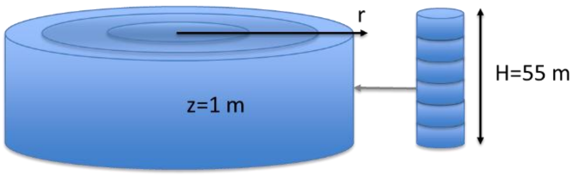


*Fig. 7: Splitting the BTES into several layers of the same size*

Fig. 8 shows the ground temperature determined at the symmetry axis as well as the thermal storage capacity per borehole length calculated with the temperature rise from 0 °C after one month of simulation. The influence of the neighbouring BHEs on the temperature at the symmetry axis can be seen from the fluctuating temperature line. Beyond the outermost borehole, which is located at a distance of 13.5 m from the centre of the BTES, the temperature drops very quickly. The thermal energy stored initially rises with increasing diameter as long as the temperature remains almost constant, and then decreases. This is due to the fact, that the storage capacity is calculated here with the volume of each ground section along the radius, which becomes larger with greater distance to the centre.

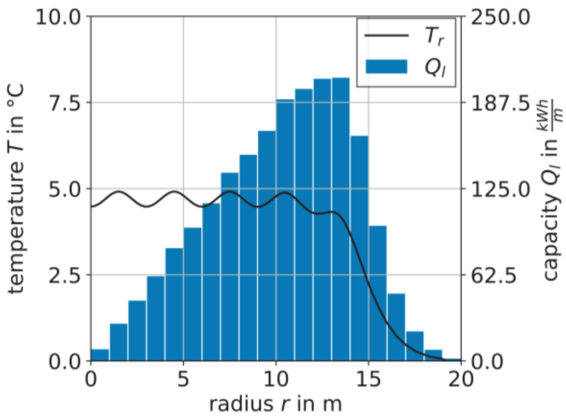


*Fig. 8: Temperature and thermal capacity distribution over the radius of the simulated BTES after one month of constant heat injection*

The example shown serves primarily to illustrate the distribution of the temperature and the stored thermal energy, i.e. thermal storage capacity. Building on this, a method for determining the capacitance with the analytical model is to be developed in further work.

## 5. INTERACTION WITH EBSILON® PROFESSIONAL

Within the HeatSHIFT research project, the analytical model presented in this paper is being further improved [10]. The analytical model is already being used in combination with *EBSILON* to calculate the thermal interaction between high-temperature heat pumps and the ground. Extra interfaces were programmed on the *EBSILON* and *Python* side for this purpose. The function of the interfaces and an overview of the interaction between the two tools is shown in Fig. 9.

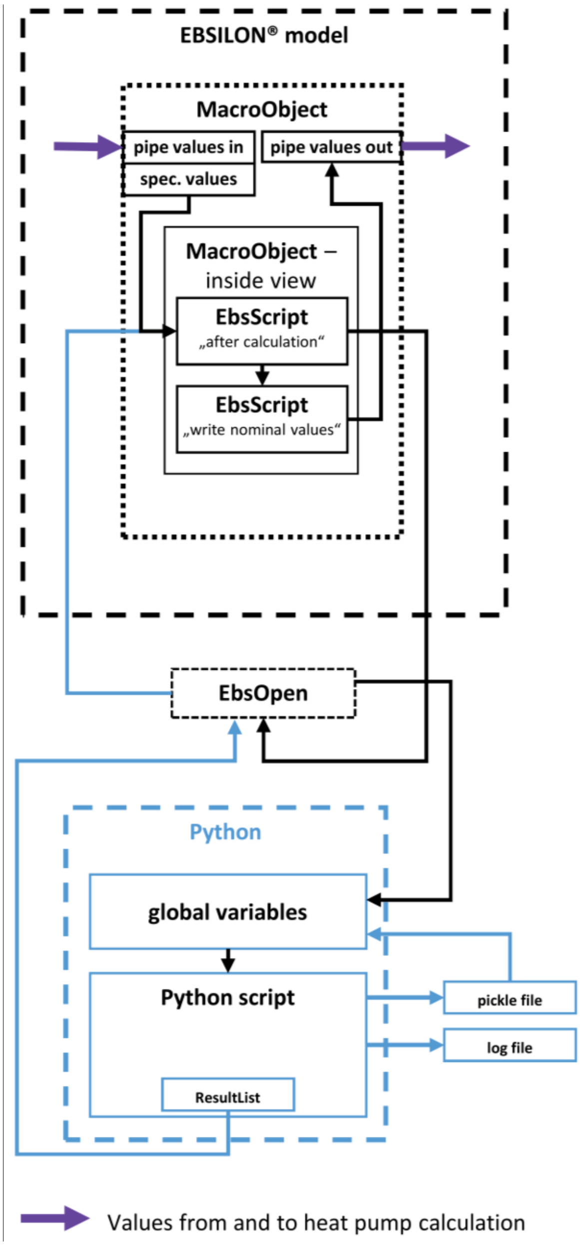


*Fig. 9: Overview of the interface between the EBSILON and python model*

*EBSILON* executes the *Python* script for calculating the BHEs via an *EbsOpen* interface. Relevant parameters such as the volume flow and the BHE inlet temperature are transferred to the *Python* script. The *Python* script calculates the reaction of the ground and passes values such as the BHE outlet temperature back to *EBSILON* (Result list). At the same time, *Python* creates pickle and log files to retrieve the values already calculated for the calculations in the next time step. These values from the previous time steps are required for the temporal superposition. *EBSILON* uses the returned values to calculate the thermal behaviour of the heat pump.

The interaction between *Python* and *EBSILON* works very reliably via the described interface. However, the calculation speed is dependent on read and write processes in the log and pickle files. Further work on the interface is planned in order to eliminate this bottleneck.

## 6. SUMMARY AND CONCLUSIONS

The present paper shows an analytical method to calculate the thermal response of single BHEs as well as multiple BHEs summarized in a BTES with prescribed fluid inlet temperature. Based on g-functions, this method is verified using numerical simulations with predefined heat flux for short times. When considering a BTES with 80 BHEs for the period of one month, the difference between the analytical and numerical solutions in terms of the temperature increase is less than 5 %.

As the evaluation of the thermal storage capacity still has to be worked out using the analytical model, an initial exemplary analysis was carried out using the numerical model. This made it possible to visualise the temperature curve and the storage capacity as a function of the storage radius.

By using the analytical model in conjunction with *EBSILON*, the interaction between high-temperature heat pumps and BTES is to be investigated. The implemented interface is shown and further tests will also provide information on the thermal behaviour of BTES.

The results shown are based on the observation of only short periods of time. However, in order to verify the analytical solution for longer time periods, the numerical simulation has to be extended to a three-dimensional model with heat flux from the surface and deeper ground layers as well as a detailed borehole heat exchanger model to meet the influences due to the specific boundary conditions (also recognisable in Fig. 1). In addition, a method still needs to be identified with which the analytical model can also calculate the storage capacity of BTES. As the numerical simulations have shown, the consideration of the temperature distribution over the radius of the storage tank is relevant here.

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## 8. ACKNOWLEDGMENT

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