View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 76 (2015) 351 – 360
Energy Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Seasonal high temperature heat storage with medium deep borehole heat exchangers

Kristian Bär[a]*, Wolfram Rühaak[a,b], Bastian Welsch[a,b], Daniel Schulte[a,b], Sebastian Homuth[c], Ingo Sass[a,b]

[a]Technische Universität Darmstadt, Institute of Applied Geosciences, Department of Geothermal Science and Technology, Schnittspahnstrasse 9, 64287 Darmstadt, Germany
[b]Darmstadt Graduate School of Excellence Energy Science and Engineering, Technische Universität Darmstadt, Jovanka-Bontschits-Straße 2, 64287 Darmstadt, Germany
[c]Züblin Spezialtiefbau GmbH Ground Engineering, Europa-Allee 50, 60327 Frankfurt a.M., Germany

Abstract

Heating of buildings requires more than 25 % of the total end energy consumption in Germany. By storing excess heat from solar panels or thermal power stations of more than 110 °C in summer, a medium deep borehole thermal energy storage (MD-BTES) can be operated on temperature levels above 45 °C. Storage depths of 500 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 a coupled geothermal-solarthermal case study in crystalline bedrock for an office building are presented and discussed.
© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: borehole thermal energy storage, borehole heat exchanger, geothermal system, coupled renewable energy systems

* Corresponding author. Tel.: +49-6151-16-70953; fax: +49-6151-16-6539.
E-mail address: baer@geo.tu-darmstadt.de

1876-6102 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2015.07.841

1. Introduction

More than 50 % of the overall energy demand in Germany is due to heating and cooling purposes [1]. 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 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 traditional storage tanks at the surface, thermal storage in shallow aquifers and shallow borehole thermal energy storage (BTES, [2, 3]), geothermal heat storage in moderate 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 and cheaply available, the thermal energy from the geothermal storage is used for heating purposes.

The focus of the presented study is the environmentally friendly and energy efficient redesigning of a more than 50 years old office and laboratory building. A BTES system [4] as well as an energy efficient building design will help to use sustainable energy sources for the next period of the building's lifetime.

2. High Temperature Borehole Thermal Energy Storage

The proposed system of a MD-BTES [5] consists of multiple boreholes with depths of 100 m – 1,000 m. Coaxial borehole heat exchangers (BHE) are implemented in the boreholes. The surrounding rock is utilized as a heat storage, the cementation and borehole wall function as heat exchanger. Typically, water (in some cases with refrigerant or other additives to prevent corrosion) is used as heat carrier fluid.

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 1a) or the annulus (CXA, Figure 1b). 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. In the extraction phase, the cold fluid should be injected into the outer pipe to utilize the borehole wall as heat exchanger surface at full length. Furthermore, 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 (Figure 1).

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.

Deep BHEs can be constructed almost everywhere, due to the fact that neither naturally occurring thermal aquifer systems nor special geological structures are needed. The only requirement for heat storage is a location with negligible groundwater flow at reservoir depth so that the induced thermal plume is not dissipated.

In contrast to conventional shallow BTES systems the mandatory heat pump is not necessarily needed due to the higher operation temperature levels [6]. Consequently, the electric power needed to run the system is 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.

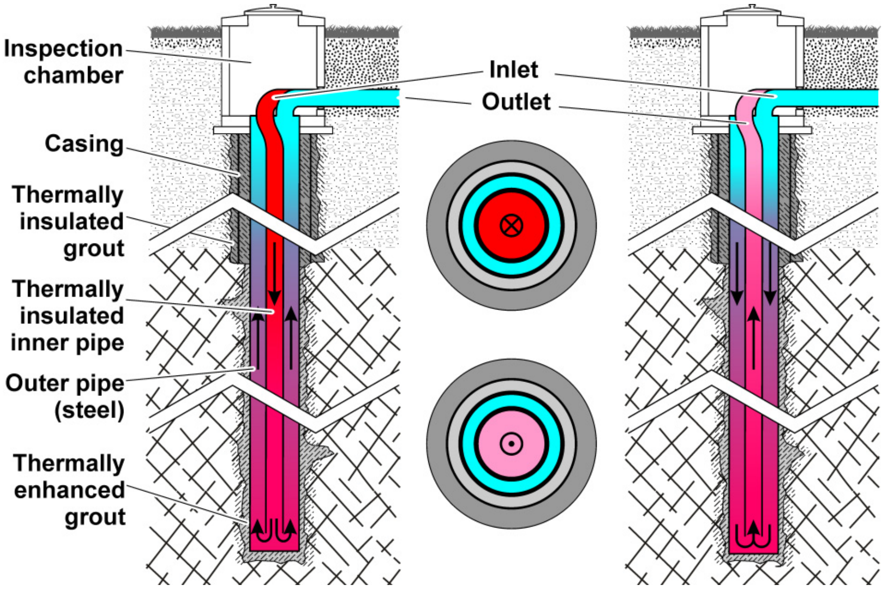


Fig. 1. Schematic horizontal and vertical cross sections of a deep coaxial borehole heat exchanger used as heat storage in summer (charge of the storage as CXC flow, left side and upper middle) and winter (discharge of the storage as CXA flow, right side and lower middle), respectively. Note that only the crystalline bedrock is used as heat storage while the caprock including possible aquifers are thermally insulated.

The completion depth of about 100 m – 1,000 m 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 means a notable decrease of heat losses, which additionally enhances system efficiency.

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 [7]. 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.

For the dimensioning and operation of a BTES, 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 mandatory [8]. Additionally, important design parameters are the heat demand and the required temperature levels of the installed heating systems.

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

3. Site Description

The planned drill site (Darmstadt, Germany) for the MD-BTES system is located next to the eastern master fault zone of the Upper Rhine Graben, which divides the urban area of Darmstadt in geological and hydrogeological terms (Figure 2a). A crystalline and Permian-Carboniferous fracture controlled aquifer of the Odenwald and Sprendlinger Horst is located in the eastern part of the city whereas the western part is dominated by a Quaternary porous aquifer of the sedimentary graben fill of the Upper Rhine Graben (Figure 2b).

The northern part of the Upper Rhine Graben fault system is characterized by steep faults in N-S to NNE-SSW direction, which show up to 2,000 m of cumulative vertical displacement. Especially in the inner city area a turn in strike direction to NE – SW results in a complex block mosaic structure [9, 10].

The lithology of the proposed MD-BTES site consists from top to bottom of a 4 - 5 m thick Quaternary soil layer, underlain by some 30 – 60 m thick intercalation of Permo-Carboniferous coarse to fine grained siliciclastic sediments, volcanoclastics and partly altered basaltic to andesitic volcanics [11]. Those unconformably overly the crystalline basement with an up to 30 m thick weathered zone at its top (Figure 2, [12]).

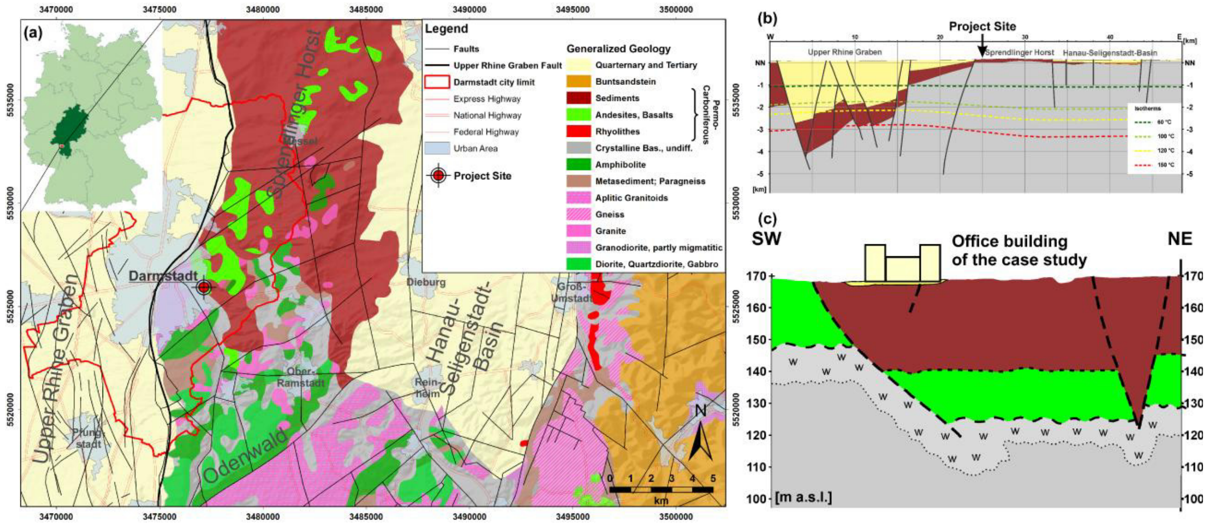


Fig. 2. (a) Simplified geological map of the project site at the eastern Upper Rhine Graben fault, after [13]. (b) Schematic W-E-cross section of the northern Upper Rhine Graben and accompanying graben shoulders including major isotherms [14]. (c) Schematic SW-NE-cross section of the project site, modified from [11], symbol w indicates weathered zone at the top of the crystalline bedrock.

The basement is mainly composed of granodiorite. Additionally, at this northern end of the Odenwald complex amphibolites, diabase, gneiss, granite, diorite, gabbro and hornfels occur [15, 16]. These varying, mostly NE-SW trending, formations are intruded by basic to acidic dyke rocks [17]. The basement is the target of the MD-BTES.

The upper 30 – 40 m of granodiorite are intensely weathered. This is due to its surface exposure during the Permian-Carboniferous, the Upper Cenozoic and the Lower Pleistocene. Near the fracture zone of the Upper Rhine Graben fault systems, weathering is most intensive and results in gravelly layers partially acting as porous aquifers. The hydraulic conductivity of these weathered and fresh rocks are in the range of 10^{-4} – 10^{-5} m/s and 10^{-6} – 10^{-7} m/s, respectively [12, 17, 18]. Dykes can be either permeable or impermeable [17]. Nonetheless, at depths of more than 100 m the permeability is supposed to be very low making it suitable for a MD-BTES system.

Information about the subsurface temperature result from the 3D geothermal model of Hesse, Germany [19]. Nearby deep drilling sites show that the geothermal gradient ranges between 2.6 and 3.9 °C/100 m.

4. Assessment of Different Heating Scenarios

For this case study two different heat supply scenarios (Figure 3 and 4) were assessed for the office building currently being redesigned in an environmentally friendly and energy efficient way compared to its current system:

1. The use of excess heat from a CHP to charge the MD-BTES system during summer and retrieving all required heat directly from the storage in winter,
2. The combination of scenario 1 with solar thermal collectors on the roof of the building charging the MD-BTES during summer and providing partial direct heat supply during winter. Additional heat demand for charging the MD-BTES is covered by the CHP.

The typical design of a project such as this would not include deep BHEs. Normally a multiple BHE array would be drilled and completed to a depth of not more than 100 – 200 m. At the project site, the boreholes will be placed in a parking lot next to the building. Because of space availability, an array of shallow BHEs large enough to cover the heat demand is not possible due to the spatial restrictions. Therefore, a layout with a few deeper boreholes and a small surface footprint instead of a multiple borehole array is chosen.

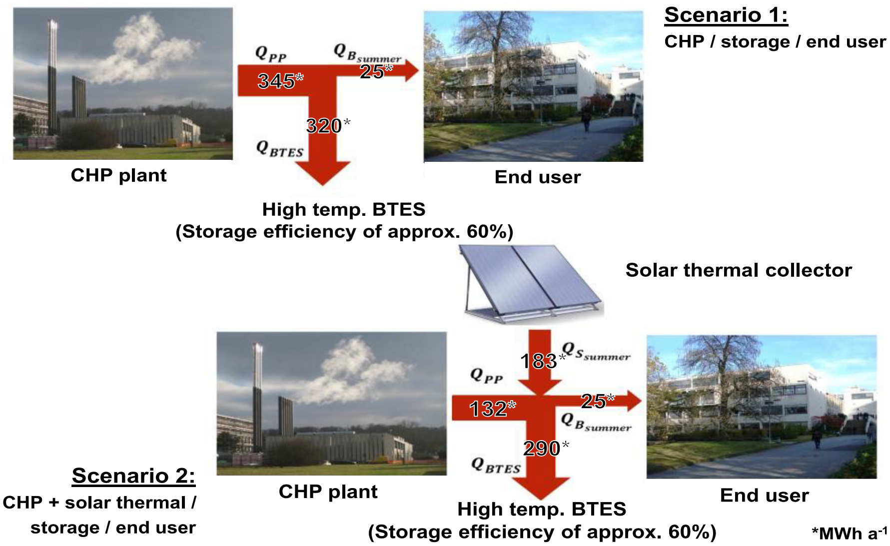


Fig. 3. (top): summer operation mode of scenario 1 with the combined heat and power (CHP) plant covering both the heat demand of the building and the MD-BTES. (bottom): summer operation mode of scenario 2 with the coupling of the CHP and solar thermal collectors to cover the heat demand of the building and the MD-BTES. Numbers are annual heat flows in MWh assuming a storage efficiency of 60%.

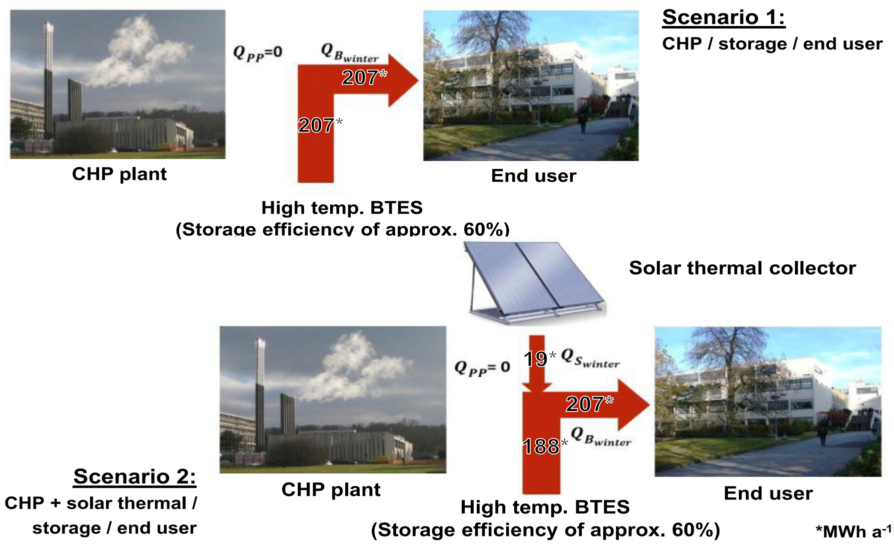
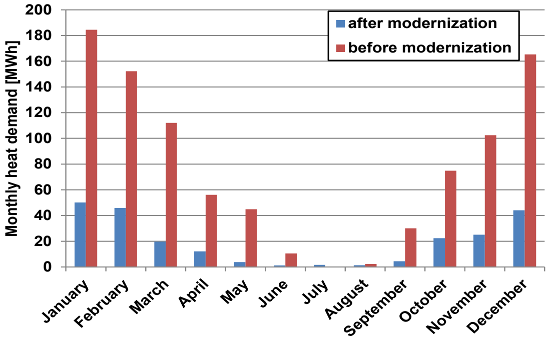


Fig. 4. Winter operation modes for scenarios (1) and (2) respectively with coupling of combined heat and power (CHP) plant, solar thermal collectors and MH-BTES. Numbers are annual heat flows in MWh assuming a storage efficiency of 60%.

In a first step, the building's heat demand and the heat gains of different solar installations were assessed according to national or international standards and requirements. Based on the results, the energy flow demand between the different heat sources and sinks of the three proposed scenarios were evaluated.

4.1. Heat Demand

The building's energy consumption was modelled using a standard software package for precise calculation of 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 [20, 21]. All parameters influencing the energy use are defined in the software. The calculations of the required heating load are done according to the standards [22] and [23].



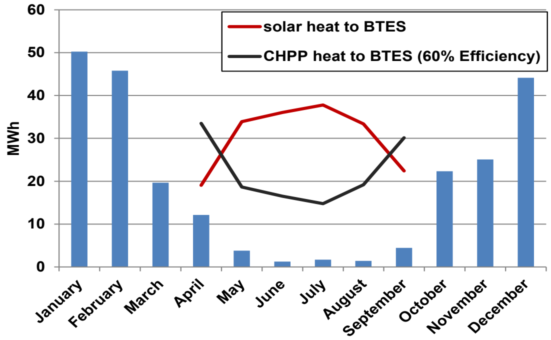


Fig. 5. (left): comparison of the modelled monthly heat demand of the project building before and after the modernization in 2012. (right): amount of solar heat available from the evacuated tube collectors which can be stored in summer and amount of heat needed from the CHP to cover the heat demand of the storage assuming a storage efficiency of 60%.

Both the heat demand of the building as build in the 1960's and after modernization in 2012 were calculated. Therefore, design construction parameters, the geometry, building service engineering and different space usage were considered. The model of the building was positively validated against measured energy usage in the building with its conditions before modernization. Unfortunately, the modernization is split into two phases. Therefore, a comparison of the actual to the modeled heat demand of the completely modernized building is not yet possible.

The results of the heat demand calculations show a significant reduction after modernization. The modeled value is 232 MWh/a, which represents a reduction of 75 % compared to the measured demand for 2009 of 935 MWh/a (modeled: 916 MWh/a) before the modernization (Figure 5). The calculated characteristic heating energy consumption of the modernized building is 37 kWh/(m²·a) compared to 148 kWh/(m²·a) before modernization, making it one of the most energy efficient buildings for teaching and research purposes of the University.

4.2. Solar Thermal Collectors

For scenario 2 the available roof top area for solar thermal collectors had to be assessed. The building has a flat roof (1,796 m²) 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 were calculated after [24] for three different types of solar installations: flat plate collectors with an optimized inclination angle of 39º, flat plate collectors with seasonally changing optimized inclination angles of 21º and 57º and evacuated tube collectors situated flat on the roof with tubes tilted 25º. The design arrangement of the solar collectors was based on the limits set by [25] as well as the shading areas of existing construction elements (elevator shafts, ventilation systems) and the solar collectors itself [26].

The biggest amount of solar heat (422 MWh/a) of all considered installations was obtained in the installation with evacuated tube collectors. This is 72 % more than from flat plate collectors with inclination angles of 21º and 57º (114 MWh/a) and 75 % more than from those with an inclination angle of 39º (106 MWh/a). This large contrast between the systems is mainly caused by differences in efficiency of the collectors and in total collector surface area considering the required minimum spacing between collectors. The efficiency used for further calculations of the flat plate collectors was 25 %, where the efficiency of the evacuated tube collectors was 62 %. The total surface area of evacuated tube collectors was 292 m², 181 m² for the flat plate collectors with 21º/57º inclination angle and 195 m² for those with an inclination angle of 39º (195 m²).

During the winter months, the only time when it's possible to obtain heat from the solar installation is from 12 to 3 pm. This means that the solar installation will be able to provide only a small fraction of a building's heat demand. The solar heat gains for minimum solar insulation (conservative approach) obtained for evacuated tube collectors were used for the calculations.

For the further calculations of the energy flow between the sources and sinks the year was divided into two parts. Charging of the MD-BTES in summer included the months April till September. Extracting heat in winter took place from October till March. The storage efficiency was assumed to be 60 % according to comparable projects [8].

4.3. Results

For scenario 1, the heat demand of the system resulting from the buildings summer heat demand (25 MWh/a) and the energy needed to charge the MD-BTES (345 MWh/a) to meet the buildings winter heating energy demand (207 MWh/a) amounts to 370 MWh/a. This is higher than the annual heat demand supplied by the CHP directly, but still 2.5 times less than what was delivered directly to the building before modernization.

For scenario 2, it was assumed that solar heat is able to meet only about 8 % (17 MWh/a) of the buildings winter heat demand directly because of its short availability and time lag in relation to the buildings heating energy demand. During summer the considered solar thermal installation was able to deliver all of the buildings summer heat demand (25 MWh/a) and supply the MD-BTES with 182 MWh/a of thermal energy. The additional amount of heat from the CHP, which is needed to charge the MD-BTES, was calculated to be 84 MWh/a.

These preliminary results, which do not consider any analytical or numerical analysis of the systems behavior, show that the solar thermal installation is able to deliver 68 % of the required heat of scenario 2. The rest of the heat (84 MWh/a) can be delivered by the CHP and amounts to only 58 % of the heat which was delivered to the building during summer months by the CHP (144 MWh) before its modernization and only 36 % of the total heat demand of the building. The proper design of the solar thermal installation combined with the MD-BTES should therefore be able to significantly reduce or exclude heat provided by the CHP to the project building and will therefore be responsible for a reduction in the CO_2 emissions compared to the current system.

4.4. Drilling Technology

Another important factor for the economic feasibility of MD-BTES systems are the drilling costs. Competitive and cheap drilling technologies are a prerequisite. Because of depth considerations and the geological setting the boreholes for the proposed MD-BTES (100 - 1,000 m b.g.s) shall be drilled with down the hole (DTH) hydraulic hammer drilling technology. Improved cutting transport, increased hole stability and enhanced deviation control (less than 5 to 10 % vertical deviation angle compared to 10 to 40 % with pneumatic hammer [27]) are reasons for the hydraulic hammer. Especially a minimized deviation from the vertical is a crucial prerequisite in BHE fields, where usually less than 10 m spacing between single BHEs is applied. Additionally, CO_2 emission reduction can be achieved since [28] showed that for an equivalent hole of 220 m a pneumatic drilling requires 2.9 l/m of diesel fuel in comparison to 0.7 l/m for the hydraulic hammer drilling process.

5. Design and Numerical Simulation of the System

The BHE completion design has an important influence on the thermal performance of the system. Stainless steel as outer casing material with a thermal conductivity of 54 W/m·K is used to ensure a higher efficiency of heat exchange between the subsurface and the heat carrier fluid in the outer pipe. For the inner pipe pre-insulated steel is recommended to reduce the effective thermal conductivity and thermal bypassing. A 10 mm thick PE foam insulator has a thermal conductivity of 0.026 W/m·K.

The deeper section of the granodiorite is suitable for heat storage whilst the caprock and the weathered zone locally and temporarily may act as an aquifer. Therefore, a thermally and hydraulically insulating backfill material for the shallow wellbore section is required as indicated in Figure 1.

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 BHE and amount of heat and frequency of storage phases, etc. These factors affect the level of average output heat during 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.

5.1. Numerical Model

Numerical modeling of the MD-BTES was carried out using FEFLOW [29, 30] to describe the transient behavior of the subsurface and the production characteristics of the system with the set up given in Figure 6. It delivers information about the capacity and sustainability of the BHE system for a given size, depth, flow rate, heat extraction intervals and other factors.

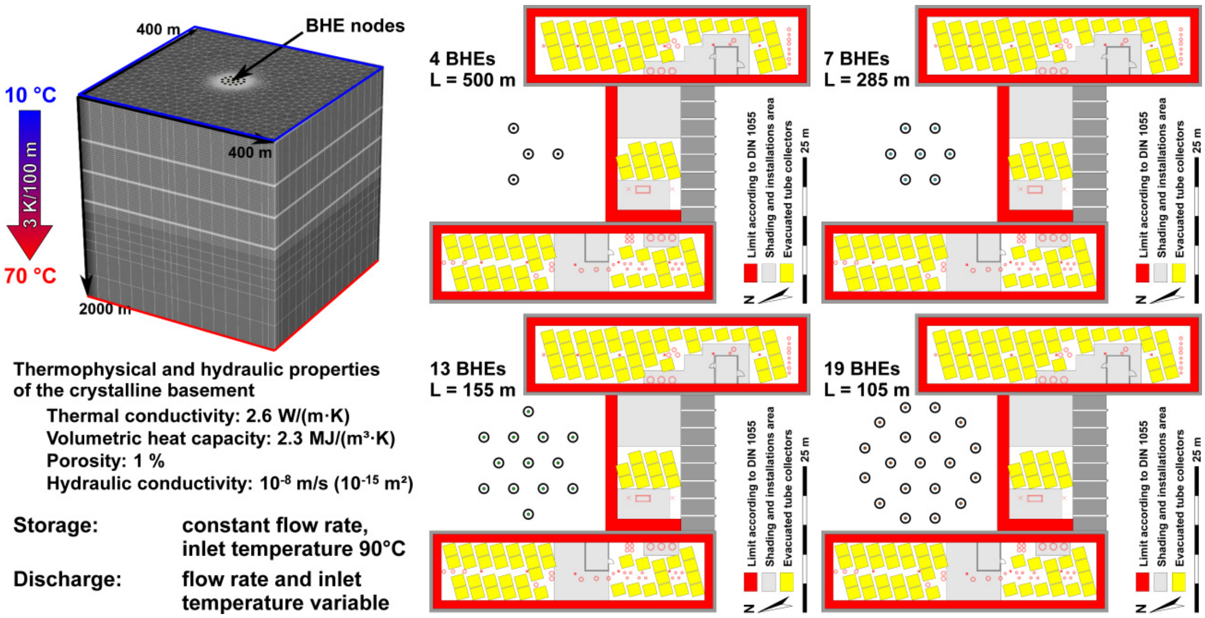


Fig. 6. (left): General set up, parameters, boundary conditions and flow rates and temperature during storage and extraction of the numerical FEFLOW models. (right): Layout of the BHEs in top view of the modelled office building including the position of the evacuated tube collectors installed on the building's roof for the four different preliminary set ups: 4, 7, 13 and 19 BHE's with the same total BHE length for the BTES.

Depending upon the depth of the proposed MD-BTES a vertical extent of the model is defined. The vertical extent is set such that the boundary parameters are kept considerably far from the MD-BTES. For a 1.0 km deep BHE a vertical model extent of 2.0 km has been set so that the 1st kind (temperature) boundary condition or other heat flux boundary conditions may not directly influence the BHEs. Boundary conditions have been set as shown in Figure 6. A subsurface temperature distribution with a geothermal gradient of 3 °C/km is set as initial condition. This model is now used incorporating 4th kind (BHE) boundary conditions at the BHE nodes with the BHE parameter setting and loading cycles for an operation period of 30 years.

5.2. Results

The simulation results (Figure 7) illustrate that the storage efficiency and the outlet temperature are higher if more BHEs can thermally interact with each other. Minimum outlet temperatures range from 40 °C to 60 °C after 30 years of operation. Thus, heat pumps are only needed during the coldest days of the heating period. Storage efficiencies are rather low, illustrating that either the heat demand of the building is too low for the chosen sizes of the different storage set ups and that more heat could be discharged from the storage in winter or that the heat input during summer was too high.

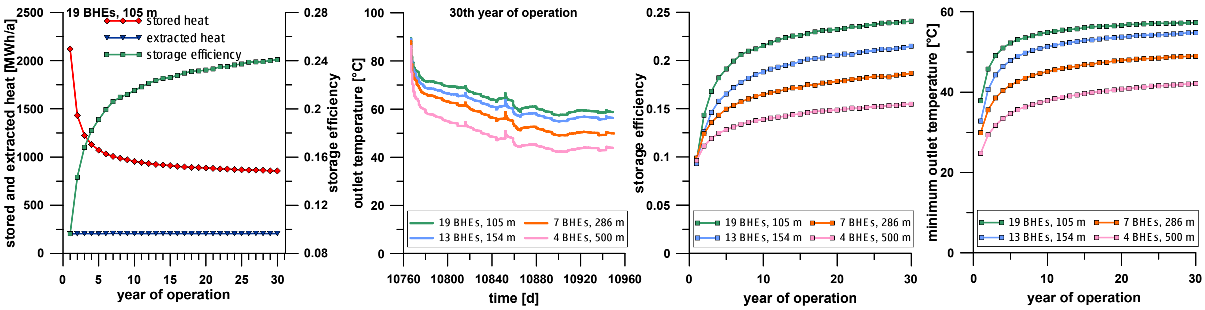


Fig. 6. (From left to right): Stored heat, extracted heat and storage efficiencies of the set up with 19 BHEs; comparison of the outlet temperatures in the 30th year of operation and of the storage efficiencies and minimum outlet temperatures (right) for the four different preliminary set ups.

To optimize the design and completion of the MD-BTES to maximize storage efficiency and to reach the desired temperature and power outputs as well as to evaluate the best economic scenario for such a coupled system two approaches are used in ongoing studies. The first approach [7] uses the software FEFLOW to model a variety of different geometrical scenarios as accurately as possible. For the second approach a MATLAB Toolbox [31] is designed to simulate a BHE heat storage system with similar numerical codes as used by FEFLOW but with other gridding and coupling algorithms, supposed to enable much shorter processing times. Furthermore, this toolbox incorporates mathematical optimization algorithms, which allow for an automatic optimization within predefined boundary conditions of each scenario. These parallel approaches are expected to define the best MD-BTES scenario for the project building.

6. Conclusions and Outlook

The largest energy consumer in industrial countries is building infrastructure with its heating and cooling demand. Innovative energy saving concepts in this field will have the biggest impact in terms of reducing CO_2 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) – as presented here, seems to be a very promising approach to cover the heating demand of renovated or old buildings at higher temperature levels with renewable energies. 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 heating supply system without the application of a heat pump or specialized heat-pumps with increased coefficients of performance are needed. However, storage configurations like the MD-BTES systems can also be utilized for low temperature heating systems.

The design and completion of MD-BTES systems as described here are strongly depending on the knowledge about 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 needs some iterative procedures. Coupled numerical-analytical modeling of the whole system combined with mathematical optimization algorithms will be used in future studies to estimate the optimal geometrical setup and depth of the MD-BTES.

Acknowledgements

The presented work is part of the research project “Simulation and evaluation of coupled systems and storage concepts for different renewables energies to supply space heating” (HA project no. 375/13-14) funded in the framework of Hessen ModellProjekte, Energietechnologieoffensive Hessen. We thank Michael Thompson, Marcin Wronowski and Bishnu Prasad Koju for their work on this project. This work is also financially supported by the DFG in the framework of the Excellence Initiative, Darmstadt Graduate School of Excellence Energy Science and Engineering (GSC 1070) and by the Förderinitiative interdisziplinäre Forschung (fif) of the TU Darmstadt.

References

[1] AGEB (ed). Anwendungsbilanzen für die Endenergiesektoren in Deutschland in 2011 und 2012 mit Zeitreihen von 2008 bis 2012. Berlin; 2013
[2] Hellstöm G. Ground Heat Storage, Thermal Analysis of duct Storage Systems. Department of Mathematical Physics, University of Lund; 1991.
[3] Bauer D, Marx R, Nußbicker-Lux J, Ochs F, Heidemann W, Müller-Steinhagen H. German central solar heating plants with seasonal heat storage. Solar Energy 2010:84(4):612-623.
[4] Homuth S, Bär K, Rühaak W, Sass I. Mitteltiefe kristalline Hochtemperaturspeicher – Dimensionierungsgrößen – Übertragbarkeit nördlichen Oberrheingraben (ORG). Proceedings Der Geothermiekongress 2012, Geothermische Vereinigung (GtV-BV e.V.), Essen; 2012.
[5] Homuth S, Rühaak W, Bär K, Sass I. Medium Deep High Temperature Heat Storage. Proceedings, European Geothermal Congress, Pisa, 2013.
[6] Kuntz D, Kübert M, Walker-Hertkorn S, Reisig O.A. Saisonale geothermische Wärmespeicher zur Direktheizung – ein Praxisbeispiel. Geothermische Energie 2013:76.
[7] Welsch B, Rühaak W, Schulte DO, Bär K, Homuth S, Sass I. A Comparative Study of Medium Deep Borehole Thermal Energy Storage Systems Using Numerical Modelling. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 2015:7 p.
[8] Mielke P, Bauer D, Homuth S, Götz AE, Sass I. Thermal Effect of a Borehole Thermal Energy Store on the Subsurface. Geothermal Energy 2014:2,5. Springer, DOI 10.1186/s40517-014- 0005-1 .
[9] Fahlbusch K. Die geologischen Grundlagen der alten Wasserversorgung Darmstadts. Geol. Jb. Hessen 1980:108:223-240.
[10] Hoppe A, Lang S. The eastern master fault of the Upper Rhine Graben below the Science and Conference Centre in Darmstadt (Germany). Z. dt. Ges. Geowiss., 2007:158(1):113-117.
[11] Backhaus E. Die randliche „Rotliegend“-Fazies und die Paläogeographie des Zechsteins im Bereich des nördlichen Odenwaldes. Notizbl. Hess. L.-Amt Bodenforsch. 1965:93:112-140,
[12] Matthess G. Zur Vergrusung der magmatischen Tiefengesteine des Odenwaldes. Notizbl. Hess. L.-Amt Bodenforsch. 1964:92:160-178.
[13] Voges A, Toloczyki M, Trurnit P, Wittekindt H. Geologische Karte der Bundesrepublik Deutschland 1:1.000.000. BGR, Hannover; 1993.
[14] Bär,K. Untersuchung der tiefengeothermischen Potenziale von Hessen. PhD Thesis, TU Darmstadt, 2012:XXVI and 265 p.
[15] Stein E. The Geology of the Odenwald Crystalline Complex. Mineral. Petrol. 2001:72(1-3):7-28.
[16] Mezger JE, Felder M, Harms F-J. Crystalline rocks in the maar deposits of Messel: key to understand the geometries of the Messel Fault Zone and diatreme and the post-eruptional development of the basin fill. Z. dt. Ges. Geowiss. 2013:164(4):639-662.
[17] Beier M. Urbane Beeinflussung des Grundwassers: Stoffemissionen und-immissionen. PhD Thesis, TU Darmstadt; 2007.
[18] Greifenhagen G: Untersuchungen zur Hydrogeologie des Stadtgebietes Darmstadt mit Hilfe eines Grundwasserinformationssystems unter Verwendung von einer Datenbank, Datenmodellierung und ausgewählten statistischen Methoden. PhD Thesis, TU Darmstadt, (2000), 221 p.
[19] Bär K, Arndt D, Fritsche J-G, Götz A E, Kracht M, Hoppe A, Sass I. 3D-Modellierung der tiefengeothermischen Potenziale von Hessen – Eingangsdaten und Potenzialausweisung. Z. dt. Ges. Geowiss. 2011:162(4):371–388.
[20] Deutscher Wetterdienst (DWD), 2004: Testreferenzjahre von Deutschland, viewed 13th December 2010.
[21] Deutscher Wetterdienst (DWD), 2011: Climate data from selected German stations, viewed 13 December 2010.
[22] VDI-Gesellschaft Bauen und Gebäudetechnik, VDI-Fachbereich Facility-Management, VDI Richtlinie 2607 - Wirtschaftlichkeit gebäudetechnischer Anlagen - Blatt 11 - Rechenverfahren zum Energiebedarf beheizter und klimatisierter Gebäude; 2006.
[23] Deutsche Industrie Norm: Energy efficiency of buildings – Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting – Part 100 (18599-100), Deutsches Institut für Normung (DIN), Berlin; 2009.
[24] Honsberg C, Bowden S. Solar Radiation on a tilted Surface. http://pvcdrom.pveducation.org/SUNLIGHT/MODTILT.HTM; 2011.
[25] Deutsche Industrie Norm: Actions on structures - Part 4: Wind loads (1055-4:2005-03). Deutsches Institut für Normung (DIN), Berlin; 2005.
[26] Viessmann: VITOSOL technical guide, Author: Telford; 2006.
[27] Wittig V, Bracke R. Innovative Hydraulic DTH Drilling Technology based on Coiled Tubing for deep, hard rock Geothermal Drilling. Proceedings, European Geosciences Union (EGU) Kongress, Vienna / Wien; 2011.
[28] Riechers J. Wohin bohren wir? Masshaltigkeit konventioneller und innovativer hydraulischer GeoJEtting Bohrtechnik. unpublished BSc Thesis, Internationales Geothermiezentrum, Hochschule Bochum; 2011.
[29] Diersch H-JG, Bauer D, Heidemann W, Rühaak W, Schätzl P. Finite element modeling of borehole heat exchanger systems - Part 1: Fundamentals. Computers & Geosciences 2010a:37(8), DOI:10.1016/j.cageo.2010.08.003.
[30] Diersch H-JG, Bauer D, Heidemann W, Rühaak W, Schätzl P. Finite element modeling of borehole heat exchanger systems - Part 2. Numerical simulation. Computers & Geosciences 2010b:37(8):1136-1147.
[31] Schulte DO, Rühaak W, Chauhan S, Welsch B, Sass I. A MATLAB Toolbox for Optimization of Deep Borehole Heat Exchanger Storage Systems. Proceedings World Geothermal Congress 2015, Melbourne, Australia; 2015:5 p.