Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Coupled Renewable Energy Systems for Seasonal High Temperature Heat Storage via Medium Deep Borehole Heat Exchangers

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Keywords: borehole thermal energy storage, borehole heat exchanger, geothermal heating,

ABSTRACT

Heating of buildings requires more than 50% of the overall energy consumption in Germany (German Ministry of Economics and Technology, 2012). Worldwide many people live in a comparable climate. Therefore, especially in this sector, new techniques are needed to save energy and reduce greenhouse gas emissions. Shallow geothermal systems for indirect use as well as shallow geothermal heat storage systems like aquifer thermal energy storage (ATES) or borehole thermal energy storage (BTES) typically provide low temperatures only. The temperature levels and ranges usually require a coupling with heat pumps.

Based on a case study of an office building at the University of Darmstadt (Germany) the feasibility and design criteria of a coupled renewable energy system, designed to store and supply high temperature heat, which is needed for a conventional heating system, are assessed. By storing hot water, which is provided from solar panels installed on the building's roof and from the combined heat and power station (CHP) of the campus with temperatures of 90 °C to 110 °C, a medium deep high temperature heat storage (MDHTS) can be operated on high temperature levels of 50 °C to 90 °C. Thus, it is possible to avoid the use of heat pumps or at least to significantly reduce their energy costs for the operation of conventional radiator based high temperature heating systems. Furthermore, target depths of more than 400 m below the surface typically avoid conflicts with groundwater use. In addition, the temperature difference between the storage system and the surrounding rocks decreases with increasing depth, which results in a reduction of thermal losses.

Recently a demonstration project is realized. A more than 200 m deep exploration borehole into the crystalline basement is drilled with a hydraulic down the hole hammer (DTH), which promises high verticality of the borehole and low drilling costs. A coax BHE will be installed and used for testing different operation modes. One aim is to calibrate the existing numerical models with these operational data.

Especially the coupling of different renewable energy sources – solar thermal and geothermal – with already existing district heating systems – e.g. combined heat and power stations (CHP) – as presented here, proves to be a very promising approach to cover the heating demand of renovated or old buildings at higher temperature levels with renewable energies.

1. INTRODUCTION

More than 50% of the overall energy demand in Germany is due to heating and cooling purposes (German Ministry of Economics and Technology, 2012). Therefore, especially in this low exergy sector groundbreaking techniques are needed to save energy and reduce greenhouse gas emissions. The combination of different renewable energy sources – solar thermal and geothermal – with already existing district heating systems – combined heat and power station (CHP) – is a very promising new approach to do so.

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 in terms of thermal storage to cope with the seasonal shift. Besides traditional storage tanks at the surface, thermal storage in shallow aquifers and shallow borehole thermal energy storage (Hellström, 1991; Diersch et al., 2011), geothermal heat storage in moderate depths is an innovative and yet under scientific considerations 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 for the building or at the time when surplus energy from nearby sources is available. In winter when other sources of energy are not sufficiently and cheaply available without using heat pumps the thermal energy from the upgraded geothermal reservoir is used for space heating and hot water supply.

The focus of the study presented here is the environmentally friendly and energy efficient redesigning of a more than 50 year old office building. The introduction of a geothermal space heating system and heat storage system (Homuth et al., 2012) as well as an energy efficient building design (energy efficient envelope) will help to facilitate the use of sustainable energy sources for the next period of the building's lifetime.

2. HIGH TEMPERATURE BOREHOLE HEAT STORAGE

The proposed system of a medium deep borehole high temperature heat storage (MDHTS) (Homuth et al., 2013) consists of one or multiple boreholes with depths of 500 m – 1,500 m. A coaxial pipe is implemented in the borehole. The surrounding rock is therefore utilized as a heat carrier and heat storage, the cementation and borehole wall function as heat exchange surface. Typically water (in some cases with refrigerant or other additives to prevent corrosion) is used as heat carrier fluid.

For the design of a medium deep borehole heat storage two separate phases have to be considered. These phases are the charging phase and the extraction phase. During the charging phase hot water is pumped into the coaxial BHE in order to heat up the reservoir. Alternately in the extraction phase, cold water is pumped into the coaxial BHE in order to exchange energy with the relatively hot formation and bring that energy back to the surface as heat. During the design of the MDHTS it is important to consider the different options of flow in a coaxial BHE. The inlet can either be the center pipe (CXC, Figure 1a) or the annulus (CXA, Figure 1b) of the coaxial pipe. For the storage of a maximum amount of heat energy at a high temperature level, both the temperature gradient between the subsurface and the fluid of the inlet as the surface area of heat transport have to be considered to optimize heat transfer both in the charging and extraction phase. In the charging phase hot water needs to reach the bottom of the wellbore in the inner pipe before exchanging the bulk of its heat with the surroundings. In the extraction phase cold water flowing down in the outer pipe must have as much heat transferred as possible at the bottom of the wellbore where charged formation temperatures are the highest. Therefore, depending on the thermal properties of the piping, a seasonal change of flow direction in the BHE might be beneficial (Figure 1).

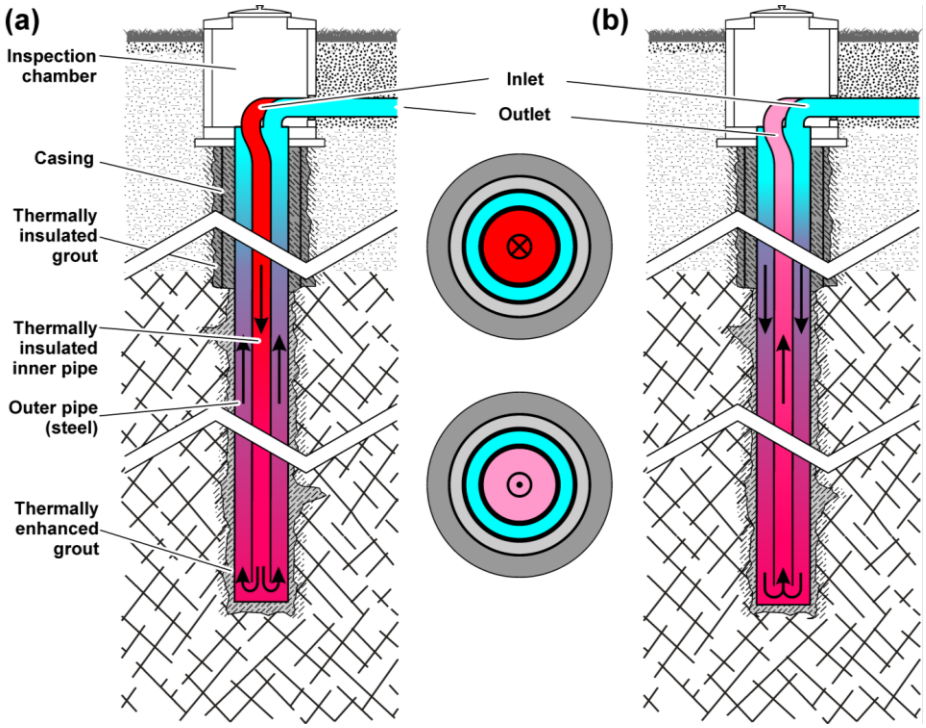

Figure 1: Schematic example of a deep coaxial borehole heat exchanger used as heat storage in summer (charge of the storage as CXC flow, left side) and winter (discharge of the storage as CXA flow, right side), respectively. Note that only the crystalline bedrock is used as heat storage while the caprock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

The advantage of BHE storage 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 processes like solution and mineralization in the surrounding rock and a direct hydrochemical or biological influence on the groundwater will be prevented. Furthermore, auxiliaries like pumps, etc. on the surface are protected against scaling and corrosion since no mineralized thermal waters are used. Consequently the life time of the system is expected to be higher and the system can be operated more constantly and therefore more economically.

In general deep BHEs can be constructed everywhere, due to the fact that neither naturally occurring thermal aquifer systems nor special geological structures are needed. Only in terms of heat storage a location with negligible groundwater flow is required so that the induced thermal plume in the vicinity of the deep boreholes is not dissipated.

In contrast to conventional shallow BHE storages the mandatory heat pump is not necessarily needed due to the higher operation temperature levels (e.g. Kuntz et al., 2013). Consequently, the electric power which is needed to run a heat pump is not required which increases the economic feasibility. Furthermore, deep BHEs have a much smaller surface footprint than shallow BHEs with the same capacity would have and is therefore a viable option in densely urbanized areas.

The completion depth of about 500 m – 1,500 m with higher underground temperatures compared to shallow systems results in lower temperature differences between the heat carrier fluid and surrounding rock. This means a significant decrease of heat losses of the system which additionally enhances system efficiency.

Operating the storage with high temperatures of up to 110 °C supplied by solar heating and/or industrial processes/thermal power plants in combination with greater depths can, after an initial charging phase of 3 to 5 years, allow backflow temperatures of the geothermal storage of 45 °C – 75 °C depending on the setup of the storage and utilization scenarios. The supply of constant heating preflow temperatures of 55 °C – 65 °C allows for a feed in to conventional radiator based high temperature heating systems, which

are commonly installed in older office buildings. This makes geothermal direct heating even an option for old buildings without low temperature heating systems which are not on the actual energy efficiency levels. Another option is to directly feed in to district heating distribution systems and supply heat for multiple uses possibly even at cascading temperature levels.

To ensure a reliable prognosis for the dimensioning and operation of a geothermal heat storage a detailed knowledge of the petrophysical (conductive heat transfer) as well as the geometrical and hydraulic properties (convective heat transfer) of the subsurface temperature regime is mandatory (Mielke et al., 2014). Additionally, the heat demand and the required temperature levels of the heating systems installed in the buildings are important design parameters.

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 as well as local heat sources or sinks which could be incorporated. Specific user profiles and economic frameworks are necessary to consider. Figure 4 shows possible coupled system configurations for summer and winter operation for the proposed system.

3. SITE DESCRIPTION

The planned drill site (Darmstadt) for the MDHTS 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 roughly located in the eastern part of the city where the proposed drill site is located, whereas the western part is dominated by a Quaternary porous aquifer of the sedimentary graben fill of the Upper Rhine Graben (Figure 2b).

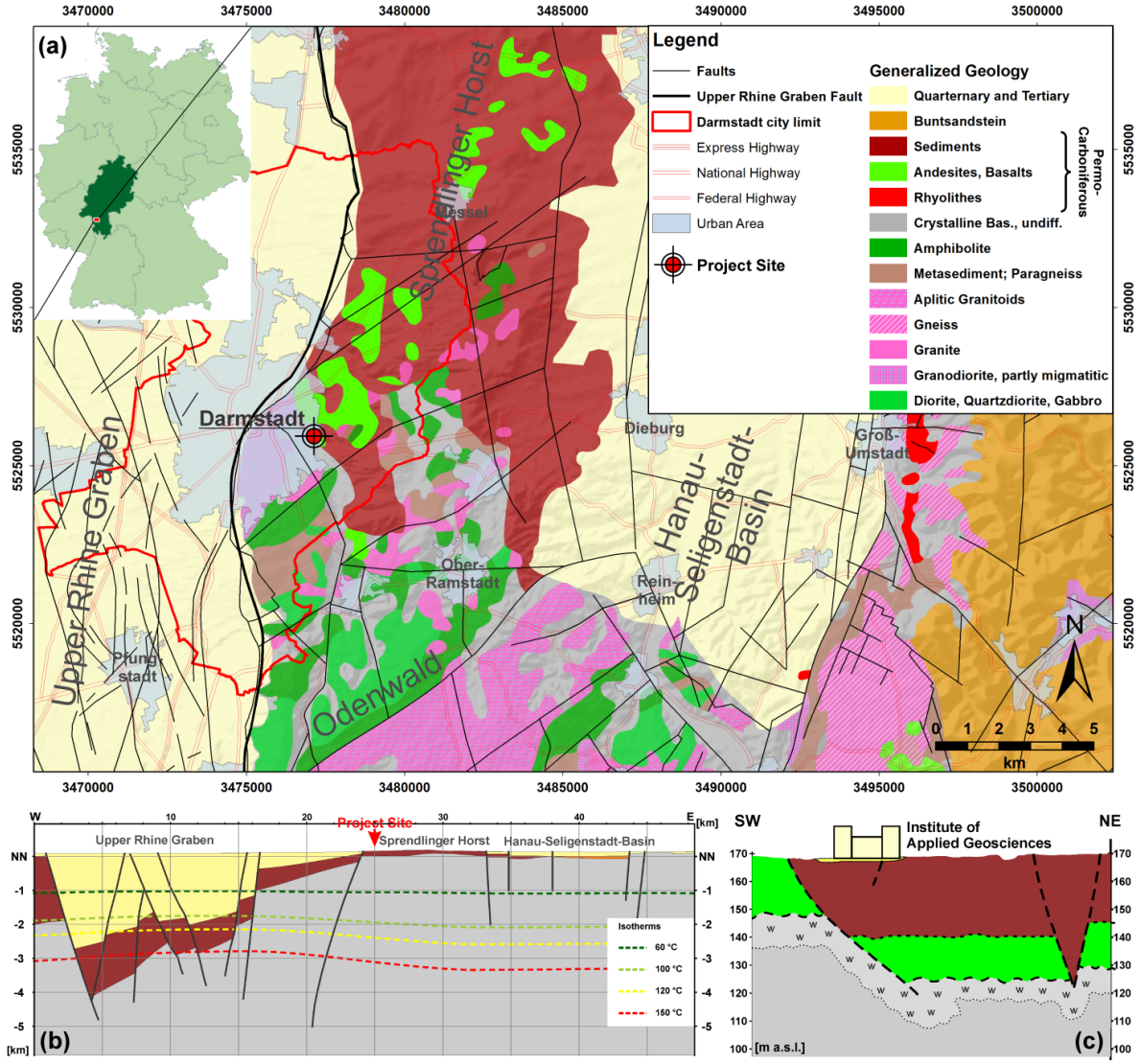

Figure 2: (a): Simplified geological map of the project site in the eastern part of Darmstadt at the eastern fault of the Upper Rhine Graben (after Voges et al., 1993); (b): Schematic W-E-cross section of the northern Upper Rhine Graben and accompanying graben shoulders including major isotherms (Bär, 2012); (c): Schematic SW-NE-cross section of the project site (modified from Backhaus, 1965), legend as above, signature w indicates weathered zone at the top of the crystalline bedrock.

3.1 Structural Geology

The northern part of the Upper Rhine Graben fault system is characterized by steep faults in N-S to NNE-SSW direction, which show a displacement of up to 2,000 m. Especially in the inner city area where the fault turns to a NE – SW direction, the main fault is accompanied by a complex block mosaic structure (Fahlbusch, 1979, 1974, 1980; Hoppe and Lang, 2007).

3.2 Lithology

The lithology of the proposed MDHTS site consists from top to bottom of a Quaternary soil layer, which is about 4 - 5 m thick and is 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 (melaphyre in local nomenclature, see Backhaus (1965) for detailed descriptions) which unconformably overly the crystalline basement (Figure 2c) with a weathered zone of up to 30 m thickness at its top (Matthess, 1964).

The crystalline at the project site is mainly composed of granodiorite (Nickel, 1985). Additionally at this northern end of the Odenwald complex amphibolites, diabase, dark slate gneiss, granite, diorite, gabbro and hornfels occur (Stein, 2001; Mezger et al., 2013) in an alternating sequence with the granodiorite. These varying mostly NE-SW trending formations are intruded by basic to acidic dyke rocks (Beier, 2008). The crystalline is the target formation of the MDHTS site and a few kilometers to the west in the adjacent Upper Rhine Graben especially the weathered zone at its top is a reservoir horizon for several planned and existing deep geothermal projects (e.g. Landau and Insheim).

3.3 Hydrogeology

The upper parts of the granodiorite are intensively weathered to a depth of about 30 - 40 m. This is due to its surface exposure during the Permian-Carboniferous, the Upper Tertiary and the Lower Pleistocene. Near the fracture zone of the Rhine Graben fault systems weathering is the most intensive resulting in gravelly layers which partially act as porous aquifers. The hydraulic conductivity of these weathered and unweathered rocks are in the range of $10^{-4} – 10^{-5}$ m/s and $10^{-6} – 10^{-7}$ m/s respectively (Matthess, 1964; Greifenhagen, 1997 and 2000). Layers of secondary clay, products of weathering, can act as aquicludes. Dykes can be either permeable or impermeable (Beier, 2008). Nonetheless, at depths of more than 100 m where weathering influence ceases the permeability is supposed to be very low (Stober and Bucher, 2007), so that it is a suitable formation for a MDHTS system.

3.4 Subsurface Temperature Distribution

The temperature distribution used for the planning is extracted from the 3D geothermal model of the federal state of Hesse (Bär et al., 2011; Arndt et al., 2011), which includes all available temperature datasets (Figure 3). The data from different nearby deep drill sites shows that the geothermal gradient ranges between 2.6 and 3.9 °C/100 m (Fritsche et al., 2012), depending on the distance and location of the drill site to the Upper Rhine Graben and its fault zones. The geothermal gradient obviously has a significant influence on the temperature in the subsurface.

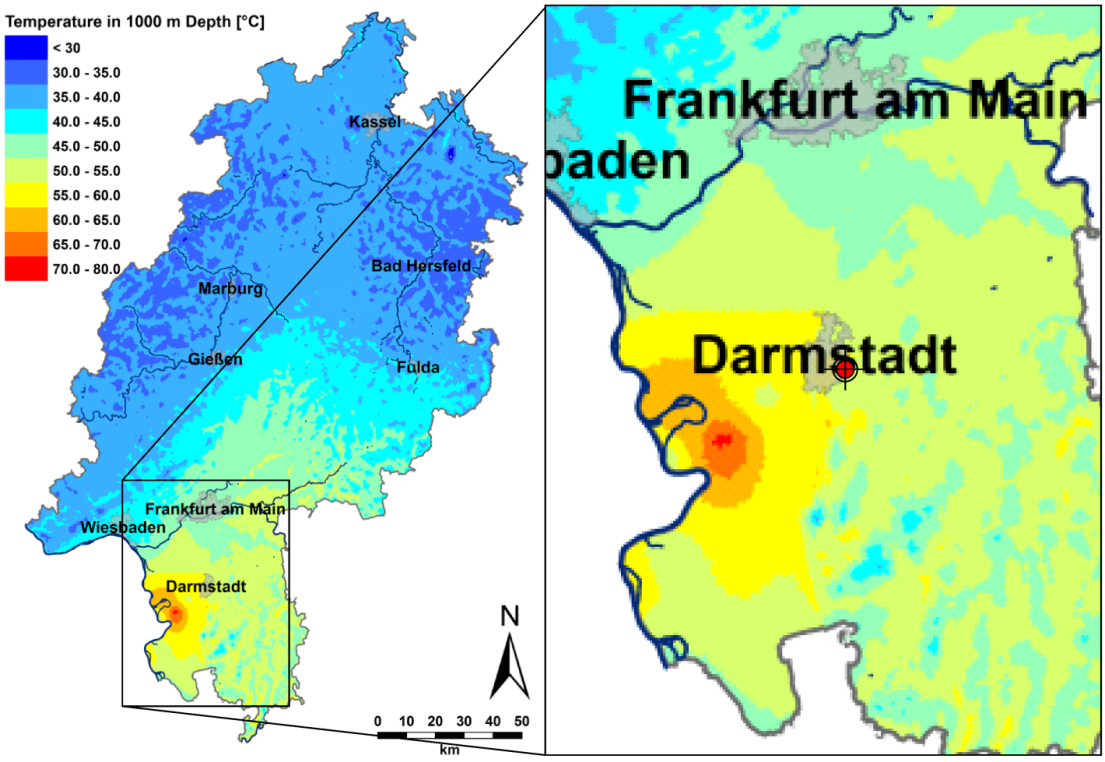

Figure 3: Temperature distribution of the federal state of Hessen (left) and the Darmstadt region (right) in 1,000 m depth (Bär, 2012)

4. ASSESSMENT OF DIFFERENT HEATING SCENARIOS

4.1 Project Description and Heating Scenarios

For the more than 50 years old office and laboratory building, which is currently redesigned in an environmentally friendly and energy efficient way, three different heat supply scenarios (Figure 4 and 5) were evaluated and compared with each other:

1. A traditional all year heat supply from the combined heat and power plant (CHP) of the University,
2. The use of the industrial waste heat from this CHP (90 ºC) for a medium deep high temperature heat storage system (MDHTS) during summer and withdrawing that heat directly without the use of a heat pump during winter,
3. The combination of scenario 2 with a solar thermal installation on the roof of the building, which is intended for charging the MDHTS during summer and partial direct heat supply during winter. Additional demand of scenario 3 is be covered by the CHP.

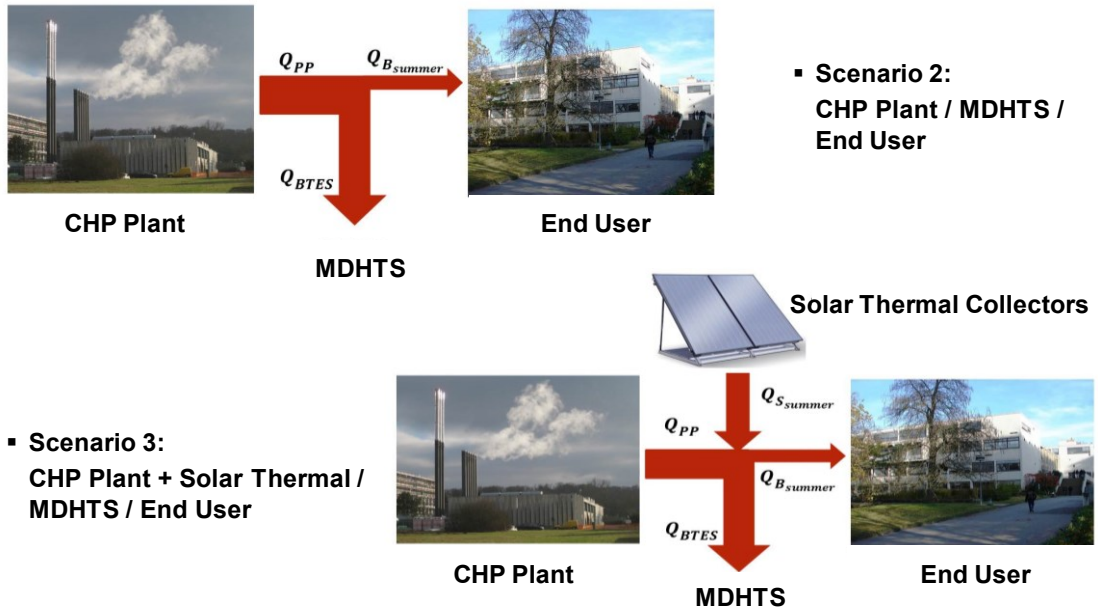

Figure 4: Summer operation modes of scenario 2 with the combined heat and power (CHP) plant as supply for the heat demand and to charge the medium deep high temperature heat storage and scenario 3 with the coupling of the CHP and solar thermal collectors as heat supply and to charge the medium deep high temperature heat storage (modified after Homuth et al., 2013). Scenario 1 is not shown due to its simple layout.

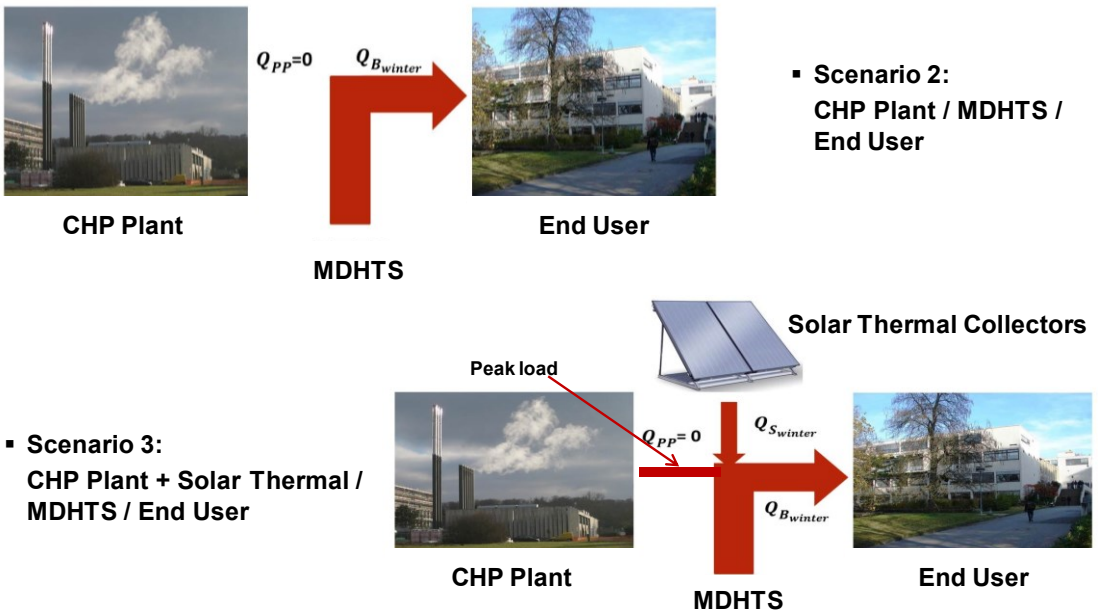

Figure 5: Winter operation modes for scenarios (2) and (3) respectively with coupling of combined heat and power (CHP) plant, solar thermal collectors and medium deep high temperature heat storage (MHDTS) (modified after Homuth et al., 2013). Scenario 1 is not shown due to its simple layout.

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 was chosen.

In a first step, the buildings 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.

4.2 Heat Demand

The calculations of the building energy consumption were done with the 'BUBI' software (Thaller, 2004; Siegel, 2009), for every hour in the modeled year 2009 based on the meteorological data of the Test Reference Years (TRY) provided by Germany's National Meteorological Service (Deutscher Wetterdienst (DWD), 2004 and 2011).

The 'BUBI' software is a complex tool which allows for precise calculation of energy consumption of every single room inside a building. All of the parameters which have an influence on the energy use are defined in the software. The calculations of the required heating load are done according to the standard VDI 2067 part 11 (2006) and DIN 18599-100 (2009), (see Woronowski, 2011 for more details).

Both the heat demand of the project building as build in the 1960's and the demand after rehabilitation measures carried out 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 tested against measured energy usage in the building with its conditions before the rehabilitation. Unfortunately, the rehabilitation of this object is split into two construction phases. Therefore, the actual heat demand of the partly modernized building cannot yet be compared to the modeled demand of the completely modernized building.

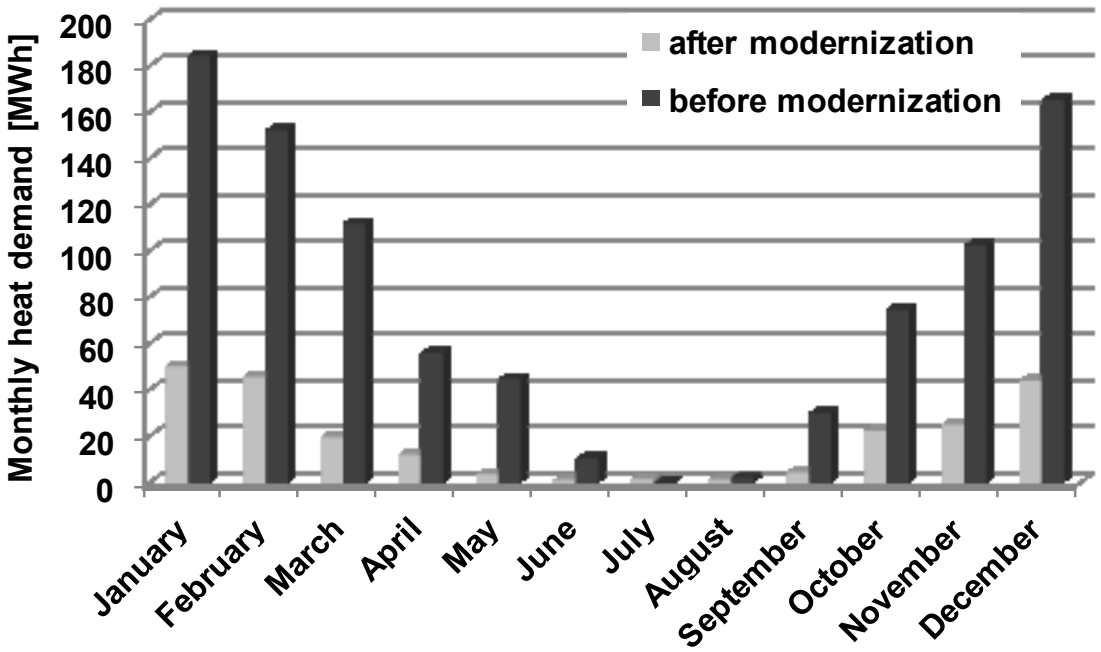

Figure 6: Comparison of the modelled monthly heat demand of the project building before and after the modernization in 2012 (after Woronowski, 2011).

The results of the heat demand calculations after modernization show a significant reduction of the heat demand. The modeled value is 232.01 MWh/a, which represents a reduction of 75% compared to the measured demand for 2009 of 935.2 MWh/a (modeled demand of 915.6 MWh/a) before the modernization (Figure 6). Such a significant reduction is possible due to the high standard of insulation of the building construction elements and new argon filled triple glazing windows.

The calculated characteristic heating energy consumption of the modernized office building was 36.6 kWh/(m²·a) (compared to 147.66 kWh/(m²·a) before modernization), which makes it (according to VDI 3807, 2013) one of the most energy efficient buildings for teaching and research purposes of the University.

4.3 Solar Thermal Collectors

For scenario 3 available roof top area for solar thermal collectors had to be assessed. The building has a flat roof (1,796.01 m²) easily adaptable for solar installations, which can be used for charging the MDHTS during summer and for direct heat supply during winter. The amount of energy produced varies depending on the location, manner of installation and type of the solar collectors. Different collectors' modes of installations were considered in calculations of the solar heat gains after Honsberg and Bowden (2011).

The heat gains of the solar thermal system were calculated 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 standard DIN 1055 (2005) as well as the shading areas of existing construction elements (elevator shafts, ventilation systems) and the solar collectors itself (after Viessmann 2006).

The biggest amount of solar heat (421.75 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 seasonally changing inclination angles of 21º and 57º (114.30 MWh/a) and 75% more than from the installation with a fixed inclination angle of 39º (105.45 MWh/a). This large contrast between the systems is mainly caused by the big differences in the efficiency of the collectors and the differences in the total collector surface area which can be installed on the roof due to different required minimum spacing between the 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 tubes collectors was 292 m² which is 61% bigger than flat plate collectors with 21º/57º inclination angle (181 m²) and 66% bigger than those with an inclination angle of 39º (194.88 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 values of heat gains for the minimum solar insulation (conservative approach) obtained for the installation with evacuated tube collectors were used for the calculations of the energy flow in the considered energy supply system.

For the further calculations of the energy flow between the sources and sinks the year was divided into two parts for which the individual months were assigned:

• Summer (charging of MDHTS): April till September.

• Winter (withdrawing the heat from MDHTS): October till March,

The efficiency of the MDHTS was assumed for 60% (conservative approach: Homuth et al., 2011, Mielke et al., 2014).

4.4 Results

For scenario 1 the amount of the heat which needs to be supplied to the system is equal to the building heat demand of 232.01 MWh/a.

For scenario 2 the amount of the heat which needs to be delivered to supply the building with summer heating energy demand (24.75 MWh/a) and to charge the MDHTS (345.43 MWh/a) to meet the buildings winter heating energy demand (207.26 MWh/a) was calculated as 370.18 MWh/a. This is higher than the heat demand supplied by the CHP in scenario 1 but still 2.5 times less than the amount of heat which was delivered directly to the project building by the CHP before modernization.

For scenario 3 it was assumed that solar heat because of its short ability and time lag in relation to the buildings heating energy demand is able to meet only up to 10% (16.57 MWh/a) of the building winter heating energy demand (207.26 MWh) directly. During summer time the considered solar thermal installation was able to deliver all of the building summer heating energy demand (24.75 MWh/a) and supply the MDHTS with 182.49 MWh/a of thermal energy. The additional amount of heat which will need to be delivered to the MDHTS from the CHP was calculated as 84.04 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 amount of heat which needs to be injected to the MDHTS in summer to meet the buildings winter heating demand. The rest of the heat (84.04 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 (143.9 MWh) before its modernization and only 36% of the heat which would be delivered for scenario 1. The proper design of the solar thermal installation combined with the MDHTS should therefore be able to significantly reduce or exclude heat provided by the CHP to the project building and will therefore be responsible for less CO_2 emissions than the current system.

4.5 Future Modelling Approach

For the precise thermodynamic analysis of the energy flows within the systems the simulation of the heat gains from the solar thermal system and the simulation of the MDHTS system have to be done. All of the simulations, together with simulation of the heating energy demand made with 'BUBI', need to be combined in a MATLAB toolbox which incorporates all system components (Schulte et al., 2015). The result will present the precise behavior of the overall energy supply system, not only of the MDHTS system but also of the interaction with the in house system and the solar thermal installations.

4.6 Drilling technology

Another important factor for the economic feasibility of MDHTS systems are the drilling cost. Competitive and cheaper drilling technologies than currently established on the market are needed. The wells necessary for the proposed MDHTS (500 - 1,500 m b.g.s) shall therefore be drilled with down the hole (DTH) hydraulic hammer drilling technology because of depth considerations

and the geological setting. Pneumatic hammer drilling is not nearly as efficient as hydraulic hammer drilling at depths greater than around 300 m. Improved cutting transport, increased hole stability and enhanced deviation control (less than 5 to 10% deviation angle compared to more than 10 to 20% with pneumatic hammer (up to 40% after Wittig and Bracke, 2011)) are all reasons to prefer the hydraulic hammer. Especially a minimized deviation from the vertical is a crucial prerequisite in BHE fields where the spacing between single BHEs is usually lower than 10 m. In a study conducted by Riechers (2010) the pneumatic hammer drilling process required 2.9 l/m of diesel fuel for an equivalent hole of 220 m whereas the hydraulic hammer drilling process only required 0.7 l/m of diesel fuel.

5. DESIGN, ANALYTICAL AND NUMERICAL SIMULATION OF THE MDHTS

5.1 BHE setup

The BHE completion design has important influence on the thermal performance of the system. Stainless steel as outer casing material with higher thermal conductivity of 54 W/m·K in comparison to plastic pipes is used to ensure a higher efficiency of heat exchange between the subsurface and the heat carrier fluid in the outer pipe. High pressure casing is also necessary to sustain the effective fluid pressure due to grouting procedure or hydraulic pressure at all and also to bear pressure due to its own weight. For the inner standpipe of the BHE pre-insulated steel pipe is recommended to reduce the effective thermal conductivity of the inner pipe so that thermal bypassing is reduced. A 10 mm thick PE foam insulator has a thermal conductivity of 0.026 W/m·K. So, using a steel pipe with this insulator can help to enhance the heat transfer efficiency from BHE bottom to its outlet.

Hydrogeological consideration was to utilize the deeper section of the granodiorite for the storage whilst the caprock and the weathered zone locally and temporarily may act as an aquifer. Therefore, a thermal and hydraulical insulation of the shallow wellbore section was required as indicated in Figure 1.

In designing a vertical closed loop BHE, 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 a certain degree of steady state heat transfer from the surrounding subsurface. But due to long term and peak power extraction, during the operation time, the heat flow may change into transient nature. In this stage, either the power level may decrease or the injection temperature relative to the outlet temperature has to be reduced to get the desired heat level.

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 upon the actual heat demand scenario. . So, consideration of those parameters while designing a BHE system is necessary to find a best fit BHE scenario but also results in more computation time. Here, best fit scenario means the BHE system with higher efficiency and higher production capacity at minimum BHE length and economical heat storage conditions. To identify a best fit scenario using computer based modeling, a large number of models with different BHE scenarios need to be simulated and compared.

5.2 Analytical Model

In a first assessment the basics of the thermodynamics of the BHE were evaluated and a one dimensional heat transfer distribution in the crystalline basement was calculated for a single BHE (Thompson, 2011). This temperature distribution calculation assumed steady state conditions calculated at the point in which the reservoir was fully charged to an acceptable thermally affected radius of 100 m.

Applying the analytical approach of Claesson and Eskilson (1988) the extractable heat transfer rate per meter of wellbore of the BHE as described above, results to a maximum of 150.7 W/m. When the average formation temperature is considered (18.75 °C) the heat transfer calculates to 128.5 W/m of meter wellbore. This average number divided by the 300 kW of required power, calculated for the heating systems of the project, equals to a total of 2,334.5 m of wellbore meters required. This could be obtained with an installation of three 800 m wellbores.

Verification of the temperature distribution along the borehole wall calculated with the analytical solution was done via FEFLOW showing an error range of only 6%. With acceptable accuracy these first calculations, based on conductive heat transfer, were able to match the underground temperature distribution of the FEFLOW result. The calculation, when done for depths ranging from the bottom of the insulated layers of the cap rock and weathered crystalline at about 100 m (simplified) to a depth of 900 m gave a theoretical temperature profile in the reservoir. The temperature at the grouted borehole wall was used to calculate an average initial heat transfer rate of approximately 130 W/m of wellbore. Transient analysis is needed to calculate the regression of this value. However, based on this value it was decided that at least 3 BHE with lengths of 800 to 1,000 m would be needed in order to supply the building with 300 kW of peak load heat extraction.

5.3 Numerical Model

Numerical modeling of the MDHTS was applied to describe the transient behavior of the subsurface and the production characteristic of the system. It delivers information about the capacity and sustainability of the BHE system in a geothermal reservoir for a given size, depth, flow rate, heat extraction intervals and other factors.

The mesh element around the BHE node must be discretized in such a way that the nearest peripheral nodes around the BHE node should be at some specific distance far from the BHE node (Figure 7). This specific distance is called nodal distance and can be calculated using the Nillert method (Diersch et al., 2010). The specific nodal distance is used to create virtual radii of BHEs equivalent to the real radius. The virtual radius is the radius of the borehole considered by the model during BHE simulation. This virtual radius is always greater than the real radius of the borehole.

Depending upon the depth of the proposed MDHTS a vertical extend of the model is defined. The height is set such that the boundary parameters are kept considerably far from the borehole heat exchanger. For 1,000 m deep BHE a model height of 2,000 m

has been set so that the 1st kind (temperature) boundary condition or other heat flux boundary condition may not directly influence the BHE.

For heat transport, a 1st kind (Dirichlet) temperature boundary condition of 10 °C was set on the top slice (average surface temperature) and certain temperature boundary values at the bottom slice of the model based on geothermal gradient of 40 °C/km are applied. The model is first simulated in steady flow and steady transport scenario and the resulting model is a primary model in which subsurface temperature and hydraulic head throughout the model domain are established as an initial condition.

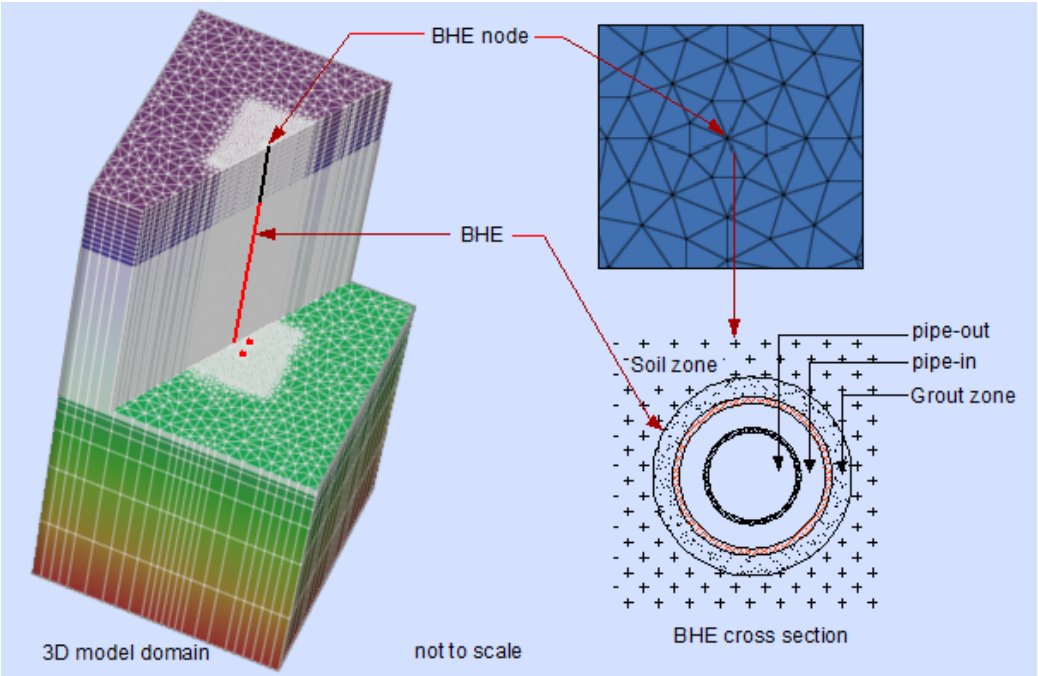

Figure 7: Example of a simulation model of one deep coaxial BHE heat storage during discharge with three drillings (Koju, 2012)

For modeling a BHE system using the FEFLOW software, 4th kind (BHE) boundary conditions are assigned in the primary model over the BHE nodes with the relevant BHE parameter setting. The initial model has been simulated for 10 years with 211 days/year of thermal charging of the geothermal storage continually in the summer period and 154 days/year of heat extraction continually in winter period. The heat carrier fluid flow was set to 120 m³/d, loading injection temperature to a maximum of 90 °C and unloading injection temperature to 45 °C.

In this preliminary attempt three model scenarios of 1,000 m, 1,250 m and 1,500 m deep BHE systems were modeled in FEFLOW 6.1 each containing corresponding three equal BHEs. Each model was simulated up to 10 years for geothermal heat storage with 100 kW thermal power (369.60 MWh) input from each BHE for 154 days/year (summer charging period) and unloading with real heating demand (77.33 MWh from each BHE = 232 MWh) for the remaining 211 days/year (winter discharge period).

5.4 Results

The obtained production temperature was more than 55 °C in the 1,500 m deep BHE scenario from the 7th year on, while it was still below 50 °C in the 1,000 m and 1,250 m deep BHE scenarios. By simulating 1,000 m and 1,500 m deep BHE models without geothermal heat storage, average production temperatures of 35 °C and 48 °C were obtained respectively. To raise the production temperature in the 1,000 m and 1,250 m deep BHE scenarios, re-simulation was done by increasing thermal storage to 175 kW and 150 kW thermal input from each BHE in both scenarios respectively. The production temperature was observed to be more than 55 °C for these scenarios as well from the 7th year of heat extraction.

To keep the power production within desired levels of production temperature, the suitable BHE depth has to be estimated. This can be done by simulating various computer based numerical or analytical BHE models with different geometrical scenarios and different BHE depths in the given geological setting. Based on the output power and production temperature a best fit scenario can be selected. Figure 7 displays a first approach of the box model, which simulates a three borehole thermal energy storage system with a 1,000 m deep coaxial borehole completion.

To optimize the design and completion of the MDHTS 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 (Welsch et al., 2015) uses the software FEFLOW to model a variety of different geometrical scenarios as accurately as possible. For the second approach (Schulte et al., 2015) a MATLAB Toolbox is designed to simulate a BHE heat storage system with similar numerical codes as used by FEFLOW but with other gridding and coupling algorithms, enabling much shorter processing times for each model. 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 MDHTS scenario for the project building.

6. CONCLUSIONS

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 greenhouse gas emissions. A coupling of solar thermal, geothermal and power-heat-cogenerations plants in combination with tailored underground storage systems can be a huge benefit and cost saving factor and energy efficiency trigger. Low temperature heating systems cannot be applied everywhere, due to the need of costly renovation measures. 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 MDHTS systems can also be utilized for low temperature heating systems.

The design and completion of MDHTS systems as described here are depending strongly on the knowledge about the subsurface and the energy flows from the source (solar thermal/thermal power plant/geothermal) to the storage system to the building and back. The estimation of the BHE depth and completion design needs some iterative procedures. Numerical modeling combined with mathematical optimization algorithms can be used to estimate the optimal geometrical setup and depth of the BHE system by simulating different mathematical models with different BHE depth and BHE parameters.

7. OUTLOOK

The result of the parallel calculations as described above will enable the presentation of the best scenario under ecological and economic considerations at the WGC in 2015. The realization of this optimized MDHTS system and the CO_2-neutral heating system of the office building will be the focus of a separate research proposal following the research project presented here as well as by Welsch et al. (2015) and Schulte et al. (2015).

Within this proposed research project the MDHTS will be constructed using the hydraulic DTH and be charged, tested and monitored with in well optical cables for continuous temperature profiles (Sass et al. 2014) during the operation of the system. Furthermore, the software tools developed within the research project for the preliminary design will be adapted so that they can be used as general design tool for the coupling of different renewable energy sources – solar thermal and geothermal – with already existing district heating systems – e.g. combined heat and power stations (CHP) to cover the heating demand of renovated or old buildings at higher temperature levels with renewable energies.

In upcoming projects related with the project presented here, the hydraulic down the hole hammer (DTH), which promises high verticality of the borehole and low drilling costs will be tested in the crystalline basement. The results of these drillings will show whether this technology proves to be as efficient as expected and will also be presented at the WGC2015. A coax BHE will be installed together with optical fibre cables. The system will be used for testing different operation modes. One aim is to calibrate the existing numerical models with these operational data.

ACKNOWLEDGEMENTS

The presented work is part of the research project “Simulation und Evaluierung von Kopplungs- und Speicherkonzepten regenerativer Energieformen zur Heizwärmeversorgung” [Simulation and evaluation of coupled systems and storage concepts for different renewables energies to supply space heating]. This project (HA project no. 375/13-14) is funded in the framework of Hessen ModellProjekte, financed with funds of Energietechnologieoffensive Hessen – Projektförderung in den Bereichen Energieerzeugung, Energiespeicherung, Energietransport und Energieeffizienz. 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).

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