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GSHP DESIGN: DESIGN METHODS, CALCULATIONS, SOFTWARE DEMO

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SUMMARY/ABSTRACT

Design of borehole heat exchangers using tables or graphs for small systems are presented as well as software for larger installations. For the software EED, an example with validation of this software is given.

INTRODUCTION

In the early days of GSHP, design of Borehole Heat Exchangers (BHE) used to be done by "rules of the thump" or empirical values. However, first design calculations based on the use of Kelvin´s line source theory date back to the late 1940s [Ingersoll & Plass, 1948]. In the 1970s/80s, in Europe in particular a group around Prof. Claesson of Lund University in Sweden worked on design calculations for BHE; the basic publication is [Claesson et al., 1985]. In the 1990s, some basic calculation methods from that group have been implemented into the design software "Earth Energy Designer" (EED), first published in [Hellström & Sanner, 1994]. Today, existing methods and tools range from simple tables and graphs, over simple software tools as EED, to detailed numerical simulation using FE or FD methods-

1 BOREHOLE HEAT EXCHANGERS

A borehole heat exchanger (BHE) is meant to carry a fluid inside the underground and allow for exchange of heat from the underground into the fluid (heat extraction, heating mode of the system) or for exchange from the fluid into the underground (heat injection, cooling mode of the system). The BHE consists of pipes containing the fluid; because it needs to be installed down to a certain depth, it is typically long and slim. The BHE must include a design for the return of the fluid from the deepest point in the hole back to the surface.

There are different methods of coupling the fluid circuit inside the BHE to the heat pump as shown in figure 1. Because of the need to circulate a fluid down into the earth and up again, there are only few basic options for BHE:

- Coaxial (or concentric) pipes, a.k.a. pipe in pipe
- U-pipes (two or more simple pipes connected at the bottom)
- Only for heat pipes, a single pipe is sufficient, as the vapour can rise upwards in the centre of the pipe while the condensate flows down alongside the pipe walls

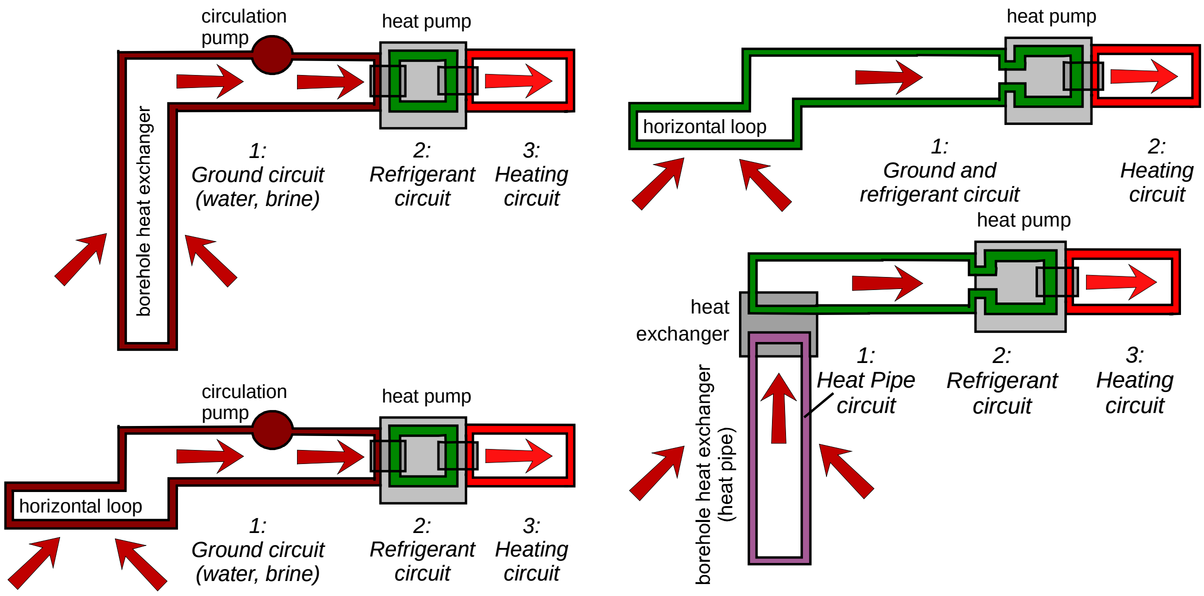


Figure 1: Possible ground loop circuits: fluid (brine) circuit for vertical and for horizontal loops (left), direct expansion (DX) circuit for horizontal loop (upper right) and heat pipe circuit for vertical loop (lower right)

Over the course of >60 years of BHE development, various design alternatives have been developed and tested. Due to cost effectiveness, only a few rather simple designs prevail (figure 2). These BHE are inserted in boreholes, and the remaining annulus between the pipes and the borehole wall is either filled with a special grouting material, or with water if the borehole is stable (limited to Scandinavia).

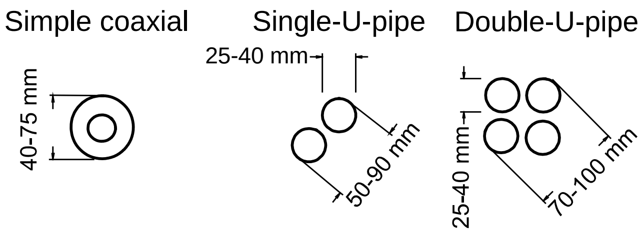


Figure 2: Cross sections of three most frequent BHE types

The effectiveness of a BHE can be described using a summary parameter, the borehole thermal resistance R_b. This parameter includes all the heat transfer phenomena from the ground outside the borehole right into the fluid inside the pipes (figure 3). For BHE design, only these parameters can be influenced by engineering, as the ground outside the borehole cannot be changed.

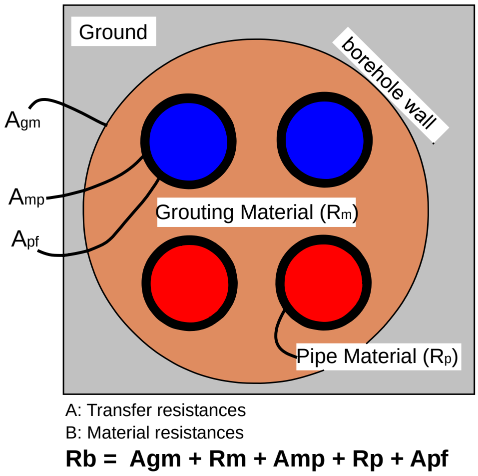


Figure 3: The components of R_b shown in the cross sections of a double-U-BHE

For sizing of BHE to a given heating and/or cooling load, different methods are available both for smaller and larger projects. For smaller systems such as in single-family-houses, design is done using tables or nomograms (e.g. VDI 4640 or SIA 384/6), or calculations with easy-to-use software. For larger systems, design calculations with simple software like EED or even with numerical simulation is required. The boundary between small and large typically is set at about 30 kW thermal capacity. The procedures are described in chapter 2.

2 BOREHOLE HEAT EXCHANGER DESIGN EXAMPLE – SMALL BUILDINGS

For small buildings, normally the design is done by using a specific extraction rate in W/m. For using this simple design method, certain limits need to be observed (list according to VDI 4640, 2001):

- Valid only for heating (incl. DHW), no cooling
- Length of individual BHE not less than 40 m and not exceeding 100 m
- Smallest distance between BHE, 5 m for depth down to 50 m, 6 m for depth exceeding 50 m
- Double-U-pipes or coaxial pipes
- Not applicable to a larger number of small plants in a limited area

The values given in VDI 4640 can only give a rough estimate and will prevent the design to be completely out of any meaningful sizing. Compared to calculated values for specific cases, this rudimentary resolution becomes obvious (4). In any case, the VDI values can give an idea of the range of BHE heat supply possible under Central European conditions. Some rules of thumb used in the past were much more arbitrary; statistics from BHE in some German states show that the vast majority of BHE for smaller projects are sized for ca. 50 W/m extraction rate!

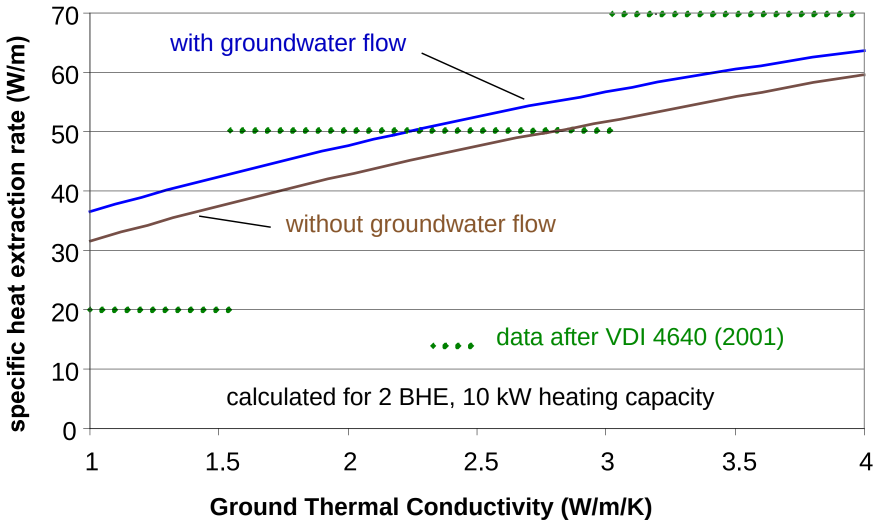


Figure 4: The components of R_b shown in the cross sections of a double-U-BHE

A comparison of the various methods is provided for a single family house and a heat pump for heating only. The basic assumptions are:

• Maximum building heat load	12 kW
• Average full-load hours of heat pump	1800 h/a (typical for systems without DHW)
• Heat distribution system	floor heating (slab heating)
• Heat supply temperature	max. 35 °C
• Expected average SPF	3,8
• Underground geology	Sandstone
• Mean ground surface temperature	9,5 °C

Using the following formula, the evaporator capacity (which in heating mode is equal to the heat to be supplied from the ground) can be calculated from heating capacity and SPF:

$$P_{ground} = \frac{P_{heating}}{SPF} \cdot (SPF - 1)$$

$$P_{ground} = \frac{12}{3,8} \cdot (3,8 - 1) = 3,16 \cdot 2,8 = 8,8$$

with P_{ground} heat pump evaporator capacity in W or kW
$P_{heating}$ heat pump heating capacity in W or kW
SPF Seasonal Performance Factor (COP over heating season)

The resulting ground heat supply (evaporator capacity) is 8,8 kW or 8800 W.

As the plant is inside the constraints given in VDI 4640, the specific heat extraction rate can be used for BHE design ("loop sizing"). The basic formulas are:

$$P_{ground} = n_{BHE} \cdot l_{BHE} \cdot P_{BHE}$$

respectively:

$$l_{BHE} = \frac{p_{ground}}{n_{BHE} \cdot P_{BHE}}$$

with P_{ground} heat pump evaporator capacity in W
P_{BHE} specific heat extraction rate in W/m
l_{BHE} (average) length of one BHE in m
n_{BHE} number of BHE

2.1 VDI 4640

A value for the thermal conductivity of the sandstone on site has to be estimated; the recommended value for sandstone as to VDI 4640 is used, which is $\lambda = 2{,}3$ W/m/K. Then the relevant value for specific heat extraction rate can be taken from the table within VDI 4640 (see table 1).

Table 1: Specific heat extraction rate for the example, as to table in VDI 4640 (column for 1800 h/a)

Method	**Range**	**Specific heat extraction rate P_{BHE}**
General Values	1,5-3,0 W/m/K	60 W/m
Values for specific rock types	Sandstone	65-80 W/m

Now the required borehole length can be calculated with the formula given above (the heat pump evaporator capacity has to be converted from kW to W):

From general values

$$l_{BHE} = \frac{8800}{2 \cdot 60} = 73{,}4\ m$$

From specific rock values

$$l_{BHE} = \frac{8800}{2 \cdot 65} = 67{,}7\ m \quad \text{to} \quad l_{BHE} = \frac{8800}{2 \cdot 80} = 55{,}0\ m$$

As a result, 2 BHE of 55.0 m – 73.4 m length would be required – quite a range! The designer now has to judge from experience to size the design closer to the lower or to the upper limit of the range, according to the rock type (fractures, weathering) and the presumed accuracy of the heat load data.

2.2 SIA 384/6

In SIA 384/6, the design for smaller projects is given in annex D3. Here some curves are provided for a standard BHE and for various correction factures. The process is shown using the same example as above. First, the specific heat extraction rate of a standard 100 m BHE as to SIA 384/6, D3, figure 7 (pipe diameter 32 mm) is read: 37 W/m

The same formula as above can be used for calculating required standard BHE length:

$$l_{BHE} = \frac{8800}{2 \cdot 37} = 119\ m$$

The resulting value of 2 BHE each 119 m deep (more than twice the smallest sizing according to VDI 4640!) now has to be adjusted with different correction factors.

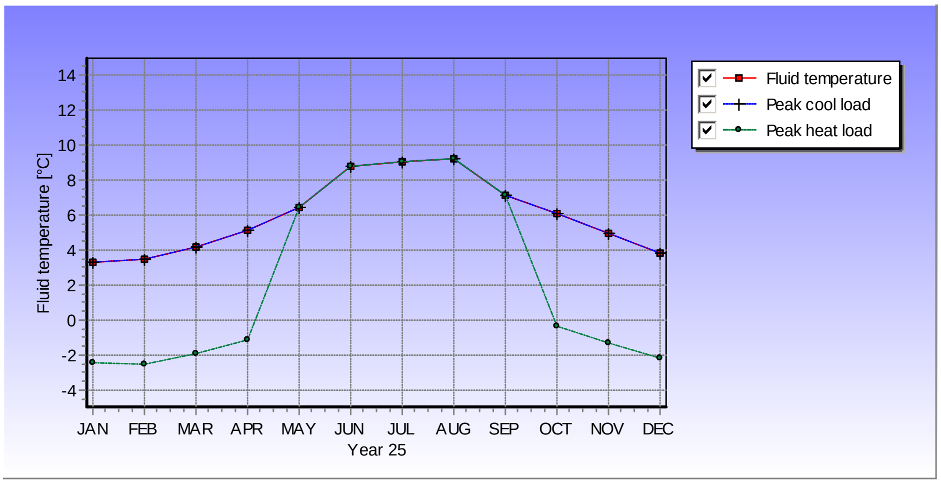
As for the standard BHE an operation time (full-load hours) of 1850 h/a is assumed, a correction for differing values is required. In figures 11-19 of annex D3 SIA 384/6 provides graphs showing curves for different full-load hours, BHE patterns and BHE distances. The correction factors can be obtained from these curves. For the example, no correction for the operation time is required, but the fact that 2 BHE are used would lead to a required increase in BHE length of 3 % if the BHE distance is not below 7.5 m (the value for 5 m distance would be 5 %, however, this distance is to short as to VDI 4640). The interim design for 7.5 m distance would be 2 BHE each 122,5 m deep.

In the last step, the correction for temperatures in the ground and desired extraction temperatures has to be made, using formulas (19) and (20) given in annex D3 of SIA 384/6. For the current example, the result of this correction is negligible, so a depth of 123 m for each BHE is selected.

2.3 Calculation with EED

With EED, also small projects can be calculated in a speedy way. The annual heating work is calculated (12 kW x 1800 h = 21,6 MWh), and the default monthly distribution used for base load. For peak load, the heat pump heating capacity of 12 kW is given, and a reasonable number of hours per day (e.g. 18 h in Jaunary).

The calculation is done for a period of 25 years, and for 2 BHE each 110 m deep at 7,5 m distance, the temperatures figure 5 were found. These are quite suitable (albeit slightly lower than the 0/-3 °C limits of SIA 384/6, which would be -1,5 °C in EED).



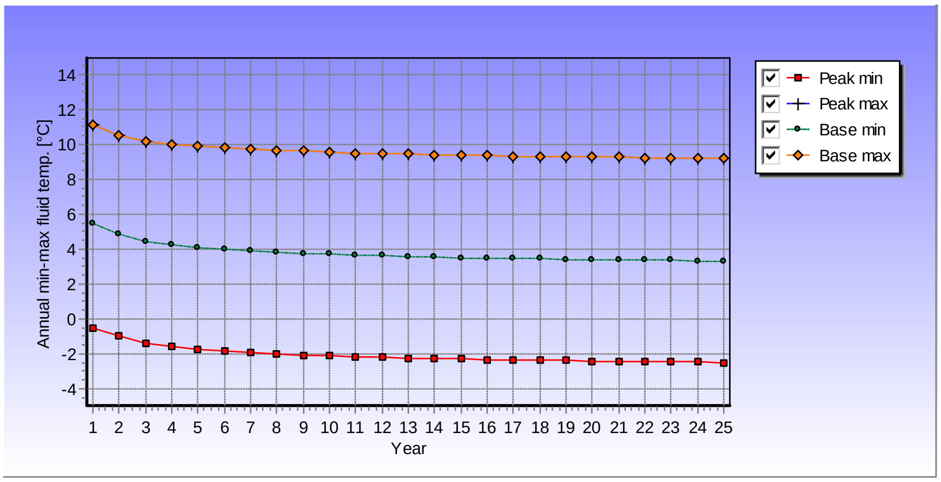


Figure 5: EED-calculation with BHE 2 x 110 m, temperature variation over the 25th year of operation and minima and maxima over 25 years

Table 2 gives a summary of the various design methods. There are large variances from the smallest VDI 4640 sizing to the largest SIA 384/6 sizing; boundary conditions and methods differ, and for VDI 4640 a new version with revised calculation is due in close future.

Table 2: Comparison of results for small project, 12 kW heating capacity

Method	Number BHE	Length BHE	Total length
VDI 4640, general	2	73,4 m	147 m
VDI 4640, specific	2	55-68 m	110-136 m
SIA 384/6	2	123 m	246 m
EED	2	110 m	220 m

3 DESIGN SOFTWARE AND ITS VALIDATION

Design of a geothermal heat pump system requires provision of sufficient heat extraction capacity from the ground for heating, or heat injection capacity (for cooling). With groundwater wells, this will be the well yield, to be determined by classical hydrogeological methods (well test / pumping test), and some calculation of the thermal influence zones.

For systems with borehole heat exchangers (BHE), the temperature development in the BHE in response to heat extraction or injection is the key issue. To calculate this response, the Earth Energy Designer (EED) is a typical software. Being around for quite some years [Sanner & Hellström, 1994], EED now is in version 3.16 from 2010, and can be considered one of the standard tools for design of BHE.

A monitoring project [Bohne et al., 2012] provided an opportunity for validation of geothermal design tools with actual measured data. A large office building with GSHP and BHE in Langen, Germany, built in 2000 [Sanner et al., 2003], was used for reference. For the use of EED, the measured heat loads had to be summarised into monthly values (figure 6). The values in table 3 and figure 6 are those actually extracted from or injected into the underground, not the loads on the building side.

Table 3: Measured ground-side heat loads in the Langen project

	design	2008	2009	2010	2011
Heat extraction (heating, MWh/a)	658	575	533	594	469
Heat injection (cooling, MWh/a)	572	461	480	423	432
Ratio extract./inject.	1.15 (1 : 0.87)	1.25 (1 : 0.80)	1.11 (1 : 0.90)	1.40 (1 : 0.71)	1.09 (1 : 0.92)

EED is programmed for calculation of the same heat/cold loads recurring every year. Using EED for calculating annually differing heat loads is only possible in plants with quasi-balanced energy flows at the ground side. In such cases, the surrounding ground temperature will be stable over the years. Long-term decreasing or increasing ground temperatures could not be addressed as input parameters within EED. For the ground thermal parameters of the Langen project, values from first Thermal Response Tests (TRT) in Germany in 1999-2000 could be used. The undisturbed ground temperatures, however, under the greenfield in 1999 were about 1 K lower than those measured today in some observation wells outside the BHE field. This can be attributed to a general heating up of the underground from the buildings etc. over the past decade.

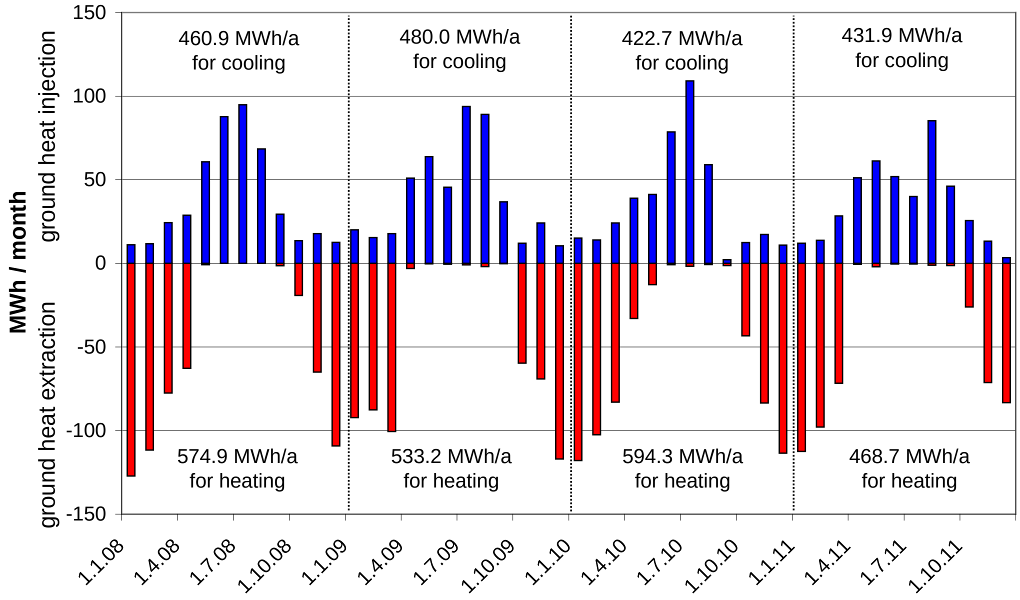


Figure 6: Monthly heat extraction from the ground (for heating) and injection into the ground (for cooling) in Langen GSHP

Using the measured temperature from the wells of 12.7 °C as the mean value over BHE depth, the comparison of EED-calculation with the measured values as given in figure 9 and 10 can be drawn. The measured values are taken at two points, at the forward/return pipes from the mechanical room, and in a sensor chain inside one BHE in the field. For comparison with EED, the mean value between forward and return was used, and the sensor at 35 m depth (half of the BHE depth) in the field. The monthly averaged values from the BHE match well with the EED base load curve (which represents the monthly average as well). There is a deviation in summer 2008 and January-March 2009, which can be attributed to a substantial number of BHE isolated from the system in the search for a leakage. The percentage of active BHE was considered in the load input for EED, however, there might be some inaccuracy of representation of the actual situation. Since autumn 2009, the system is operating normally again, with just 2 BHE isolated permanently (i.e. 98.7 % of total BHE length available). Another deviation is with the values at the building during summertime. While these values match well in autumn and winter, they are substantially higher in summer (and also higher than those measured at the BHE). This discrepancy still needs to be explained; most probable reasons comprise influences of ambient room temperature, from ground-side circulation pump, or from external sources (e.g. heat emissions of pumps etc. near sensors).

Beside the monthly averages shown in figure 7, EED allows also for calculating the maximum and minimum temperatures to be expected during full-load operation of the BHE system. However, this is not given as an actual temperature, but as a kind of envelope within which the temperature will swing according to actual load patterns. The design just has to make sure that the extremes of this envelope are within allowed ranges for temperature both concerning the technical operation constraints as well as environmental issues in the underground. In figure 8 this min-max-envelope is shown for 2008-2011, for which consistent values for the hourly temperatures at the BHE in 35 m depth during the period May 2008 – October 2011 could be used for comparison. The prediction given by EED is rather well matching the actual temperature development.

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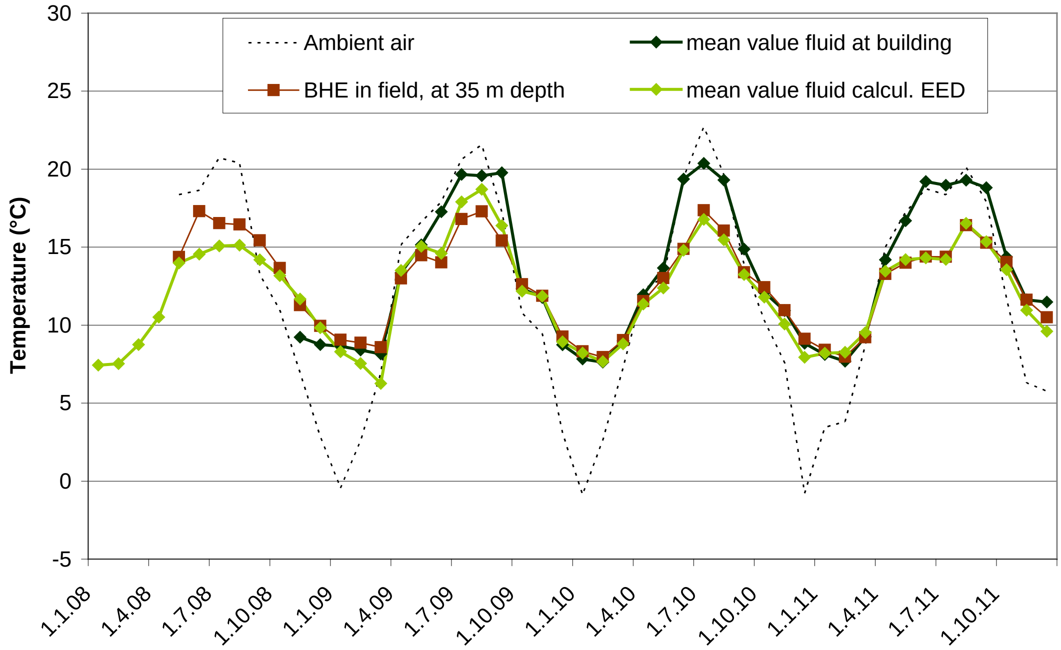

Figure 7: Measured temperatures in ambient air and in the Langen BHE (monthly averages), compared with EED-calculation of BHE

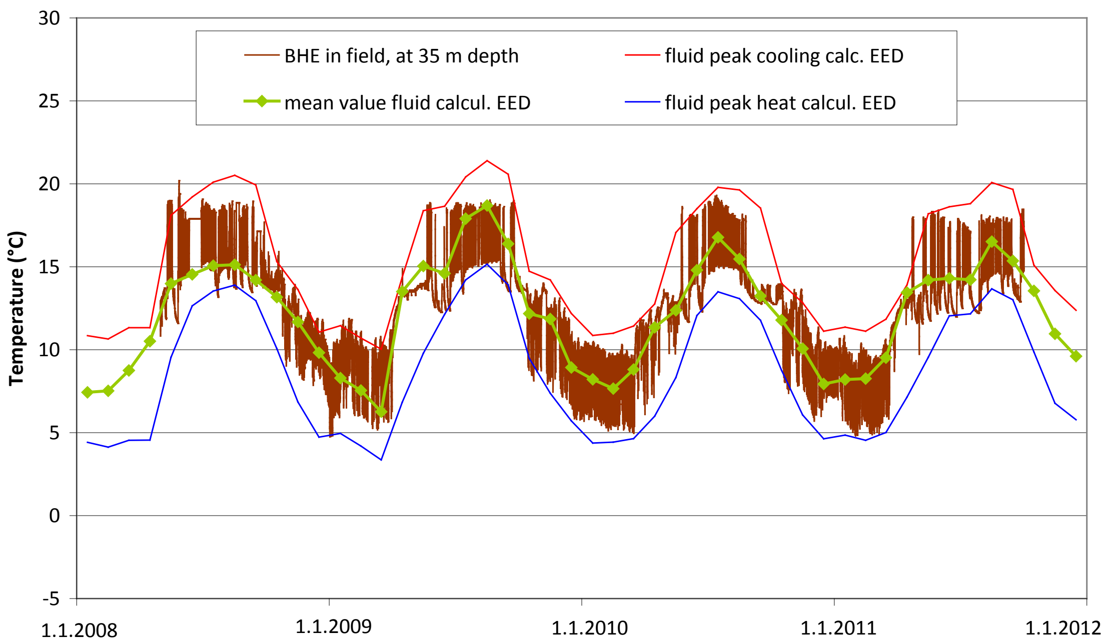

Figure 8: EED-calculation showing the development of monthly averages of mean fluid temperature on the ground side in Langen and minimum and maximum values for temperature during peak-load conditions, compared with the annual averages of temperature at a BHE in the field

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