Results and lessons learned from geothermal monitoring of eight non-residential buildings with heat and cold production in Germany

Dirk Bohne[1], Matthias Wohlfahrt[1], Gunnar Harhausen[1], Burkhard Sanner[2], Erich Mands[2], Marc Sauer[2], Edgar Grundmann[2]

[1] Leibniz Universität Hannover, IEK, Herrenhäuser Str. 8, 30419 Hannover, Germany

[2] UBeG Dr. Mands & Sauer GbR, Reinbergstrasse 2, 35580 Wetzlar, Germany

b.sanner@ubeg.de

Keywords: Ground Source Heat Pumps, Office Buildings, Monitoring, Seasonal Performance Factor, Design Tools.

ABSTRACT

This paper covers a study on eight office buildings using shallow geothermal technology (ground source heat pumps, with some aspects of underground thermal energy storage - UTES) for space heating and cooling via heat pumps, chillers or passive cooling. The types of ground coupling include both borehole heat exchangers (BHE) and groundwater wells; however, the main emphasis on the results in this paper is on the BHE plants. Most of the buildings are located in the West of Germany (Nordrhein-Westfalen and Hessen), with relatively mild climate.

The main goal of the monitoring was to assess the performance of the geothermal systems, their adaptation to the building systems, reliability, etc. Results show the feasibility of the general shallow geothermal concepts, with medium to high energy efficiencies. However, loss of performance and temporary breakdown of some systems as well as inconsistent concept implementation were observed. While one plant reached exceptional performance with a total (annual) SPF around 7-8, there was also a plant with total SPF below 4, which is disappointing in today standards. Some optimizations of energy efficiency and controller performance have been achieved during the process. A recurring theme is a big difference in the building demand data given during system design and the heating and cooling actually consumed once the projects were in operation – most required considerably less, rendering the systems somewhat oversized.

The monitored data were also used to validate design software. The applicability of easy-to-use programs like EED could be confirmed for large systems with a high number of BHE. For groundwater wells (incl. ATES) operation modelling, some simple methods can be used for pre-design, but numerical models are still required, in particular when groundwater flow is high enough to have a measurable influence. Thermal impact on the ground and groundwater was investigated in some cases, and all projects can be said to have either no impact at all, or at least no negative impact.

1. INTRODUCTION

Eight office buildings were subject to a multi-annual monitoring project, the targets of which were reported in Bohne et al. (2008). The basic data of the 8 plants are listed in table 1. Table 2 summarises the regional temperatures after data from the German Meteorological Service (DWD); from 2008-2011, the annual averages and maxima do not show much difference. The only project sites with slightly colder climate, obvious from the lower temperatures in table 2, are projects 3 and 7.

2. MONITORING AND ENERGY EFFICIENCY

Monitoring large, complex building energy systems (HVAC systems) can be rather complicated. Almost all modern buildings today are equipped with centralized digital control systems, which in general allows for collecting and storing data. However, sensors for digital control are located at points were they are needed for acquiring control values, and not necessarily were e.g. heat loads can be measured. Thus installation of additional, non-invasive sensors for temperatures and volume rates was required in some of the plants. Beside missing sensors, the correct data storage and transfer can be a problem. Harhausen et al (2010) and Harhausen et al (2011) provide more details on the data acquisition and monitoring aspect of the project.

The most complete set of data was recorded for project 1. For all other projects, there are either some periods with empty records, missing sensors, or intervals with inconsistencies. Concerning efficiency, the results are quite ambiguous. In table 3 the SPF-values for the three monitored plants with BHE are given. They range from a poor value of about 3 to excellent values above 6. For the low values, some causes could be identified, such as inadequate temperature control, failures of heat pump components, poor hydraulics, etc.; the basic design concept in all cases was adequate.

Table 1: Main data for the GSHPsystems within the monitoring program; thermal output as to design values

No.	Type	Ground coupling	H (kW)	C (kW)	DC (kW)	Building use
1	BHE	154 BHE, 70 m each	425	---	400	O, R
2	GW	2 extraction / 2 injection wells, 16-20 m	567	721	450	O, L
3	GW	2 extraction / 2 injection wells, 47-76 m	1014	880	1500	O, L, W
4	BHE	85 BHE, 99 m each	542	500	440	O, R
5	GW	2 extraction / 3 injection wells, 20 m	300	540	730	O, W, R
6	GW	2 extraction / 3 injection wells, 140 m	872	794	---	O, R
7	BHE	32 BHE 110 m each	160	160	280	O, L, R
8	GW	1 extraction / 2 injection wells, 26 m	156	---	550	O, R
H: heating with heat pump C: cooling with heat pump DC: direct cooling BHE: Borehole Heat Exchg. O: offices L: laboratories W: workshops R: restaurant/cafeteria GW: Groundwater wells						

Table 2: Annual averages, minima and maxima of daily means of ambient air temperature 2008-2010 for four regions where the projects are located (after public data from DWD)

values in °C	2008			2009			2010			2011		
Region of:	min	**av**	max	min	**av**	max	min	**av**	max	min	**av**	max
projects 1,4,6	-4.3	**11.0**	26.3	-12.8	**11.0**	27.6	-8.4	**9.8**	28.7	-5.1	**11.5**	26.2
projects 2,5,8	-4.2	**10.6**	24.5	-12.6	**10.7**	25.8	-13.0	**9.4**	28.9	-6.5	**11.3**	26.9
project 3	-5.8	**9.8**	24.1	-12.5	**9.5**	23.2	-6.9	**8.3**	25.8	-5.2	**9.6**	25.2
project 7	-6.5	**9.6**	24.6	-14.6	**9.5**	24.9	-10.0	**8.4**	26.9	-5.8	**10.0**	23.8

Table 3: Annual performance (SPF) and geothermal share of the heating and cooling energy supplied to the building, for the three BHE plants monitored

No		design	2009	2010	2011
1	**SPF total H/C**	---	**8.2**	**7.1**	**7.9**
	SPF heating	5	6.5	5.6	6.1
	SPF cooling	> 8	9.9	9.9	12.0
	geoth. share heat	75 %	23.1 %	25.3 %	26.3 %
	geoth. share cold	82 %	53.6 %	54.0 %	49.5 %
4	**SPF total H/C**	---	**4.4**	**3.3**	**5.3**
	geoth. share heat	75 %	72.3 %	55.8 % *	83.7 %
7	**SPF total H/C**	**> 4**	---	**3.5**	**3.7**
	geoth. share heat	100 %	ca. 50% *	100 %	100 %

* heat pump failures

From 2009-2011, the system with BHE in project 1 achieved a SPF of ca 6 for heating and about 10-12 for cooling (direct cooling). The efficiency in direct cooling is somewhat hampered by the system design and control, using two circulation pumps on the ground side in cooling mode where one might be sufficient. A much higher SPF for direct cooling of >19 would be possible that way. The high SPF in heating mode is due to the relatively high temperature on the ground side (cf. figure 6) and the low-temperature distribution inside the building.

Systems with groundwater wells might generate high SPF especially in direct cooling mode, provided that the drilling depth is less than about 50 m, and that the pump(s) on the ground side are dimensioned correctly and controlled efficiently by demand (e.g. variable frequency drive, VFD). The performance of ground-side pumps can be assessed by calculating “SPFpump” or “COPpump”, as heat/cold extraction from the underground divided by the electricity consumption of the pumps. In optimum design and settings, measurements show monthly COPpump for direct cooling as high as almost 50. Ground-side pumps have great influence on total system efficiency; in some cases, these pumps work constantly, as in project 6 and 7 in table 4. For project 6 the SPFpump is remarkably poor, an additional cause for this is the considerable drilling depth of 140 m.

Table 4: Efficiency of ground-side pumps and influence of control strategy, values for the year 2011

No	1	2	3	6	7
Type	BTES	ATES	ATES	ATES	BTES
control strategy	on/off	VFD	VFD	const. on	const. on
SPFpump (see text)	18.3	28.6	28.9	5.0	10.6

As the geothermal system in most of the projects was not the only source for heat and cold, the whole building system had to be considered for evaluation and the geothermal share to be determined. Figure 1 shows the total specific heating and cooling loads for project 1 and the part covered by the geothermal plant, in comparison to project 7, where the BHE and heat pump are intended to cover all heating and cooling loads (however, due to a heat pump failure, for some time before 2010 an additional heat source had to be provided temporarily).

In figure 1 also the electricity consumption of the building and the share of electric power used by the UTES system (ground-side pumps and heat pumps) can be seen. The specific energy loads are calculated using the net floor area (NFA) of the buildings. Notwithstanding different size, type and age (12 and 8 years) of the buildings, the specific loads are in a narrow range between 40 and 60 kWh/m²/a for heating and 15-20 kWh/m²/a for cooling.

In project 1 (wellfield with 154 BHE), some constraints are given from a number of drinking-water wells less than 1 km away in the direction of groundwater flow. Heating up of the groundwater was not allowed, and thus heat extraction must be higher than heat injection on the long term. Table 5 shows that this goal (given with a ratio 1 : 0.87 in the design) was achieved in all years covered.

3. COMPARISON OF DESIGN LOADS AND MEASURED LOADS

During design of a geothermal system, both the ground parameters (controlling the supply potential) and the heating and cooling demand of the building need to be known. With conventional technology, the main target is to cover the maximum heating and cooling loads, while the duration of these loads is of less importance. In geothermal energy, however, the annual amounts of heat and cold as required are of great importance; best would be a typical load profile over the year. The problem is that most building designers do not provide this load profile.

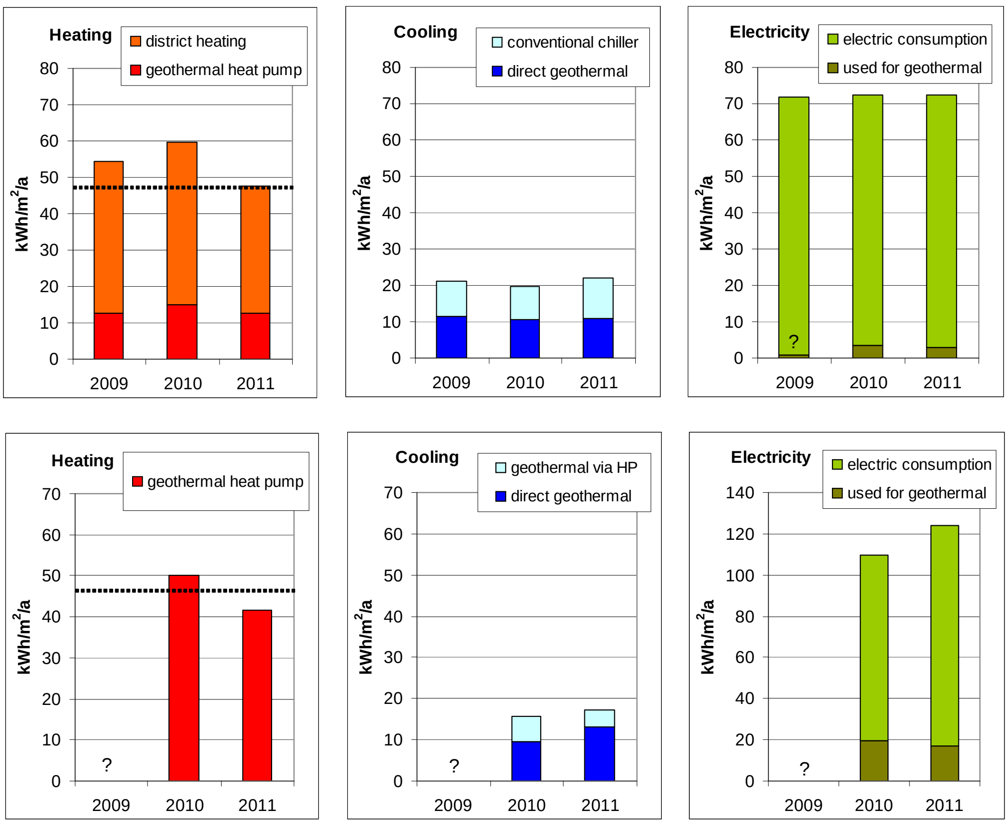

Figure 1: Annual specific energy use (kWh/m²/a, for NFA), and geothermal contribution or share in the case of electricity consumption, respectively, for project no 1 (above) and no 7 (below); dotted lines: design values

Table 5: Measured ground-side heat loads in project no 1

	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)

The comparison of load data from the design phase and the actual measurement was good for some surprise. In project 1, the design started with rather high values both for heating and cooling in the order of 1.4 GWh/a on the geothermal side (left in figure 2). Subsequent building simulation and optimisation (insulation, shading, reduced internal loads; Seidinger et al., 2000) resulted in substantial lowering of the calculated geothermal loads, as to the design value in table 5. These were the last load data that could be taken into account for the design, while drilling for the first BHE was ongoing already.

The measured data for the years 2009-2011 are all below even the latest design data for the ground side (table 5), while the total heating for the building was even somewhat higher than expected (figure 1, top left). The main reason is that more district heat was used and less ground heat, a typical phenomenon in larger projects with several heat/cold sources. Only optimised automatic control and training of the operational staff can mitigate that, with thorough monitoring being a prerequisite therefore!

In project 7, the system design was done for the ground source heat pump to provide all heating and most of the cooling (some technical rooms have their own, independent cooling). Hence no additional heat source can take over, and the monitored values reflect the actual building demand. In figure 3, the design values from two different building designers are compared to the measured amounts of 2010 and 2011. The ground-side thermal loads calculated with a building simulation model (Plan G) are much closer to the actual values, but still higher. These values had been used for the system design of 32 BHE 110 m deep each.

A comparison of temperature curves for the monthly averages, obtained from EED-calculations based upon the two design scenarios and the measured values, reflects this nicely (fig. 4, left). The calculation of the fluid temperature development under peak heating and cooling conditions, which should result in an envelope for the actual temperature development (cf. chapter 4), shows the minimum design temperatures of ca -3 °C, in line with guideline VDI 4640 and also SIA 384/6 (SN 546 384/6). The actual, measured temperature does not decrease beneath +5 °C. In the next chapter it is shown that the EED calculation allows for a rather good prediction of the temperature development.

The system is, based on the design load parameters, oversized for the actual loads. The relatively low SPF values below 4 (table 3) therefore need to have a different reason, not related to the rather favourite temperatures on the ground side of the system.

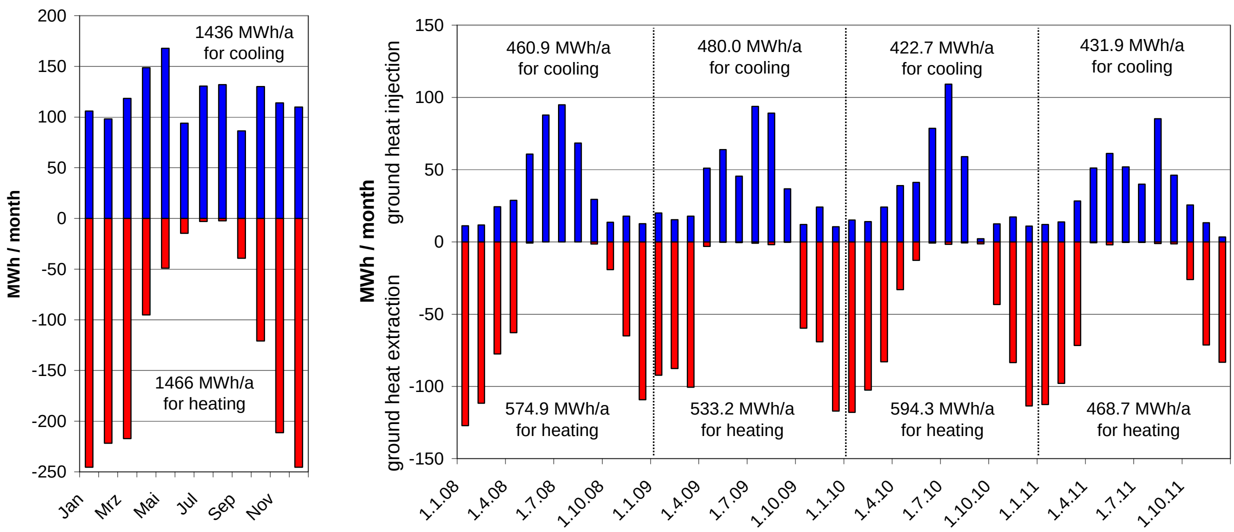

Figure 2: Monthly heat extraction from the ground (for heating) and injection into the ground (for cooling), for project no 1; early design values of 1999 (left) and measured values 2008-2011 (right)

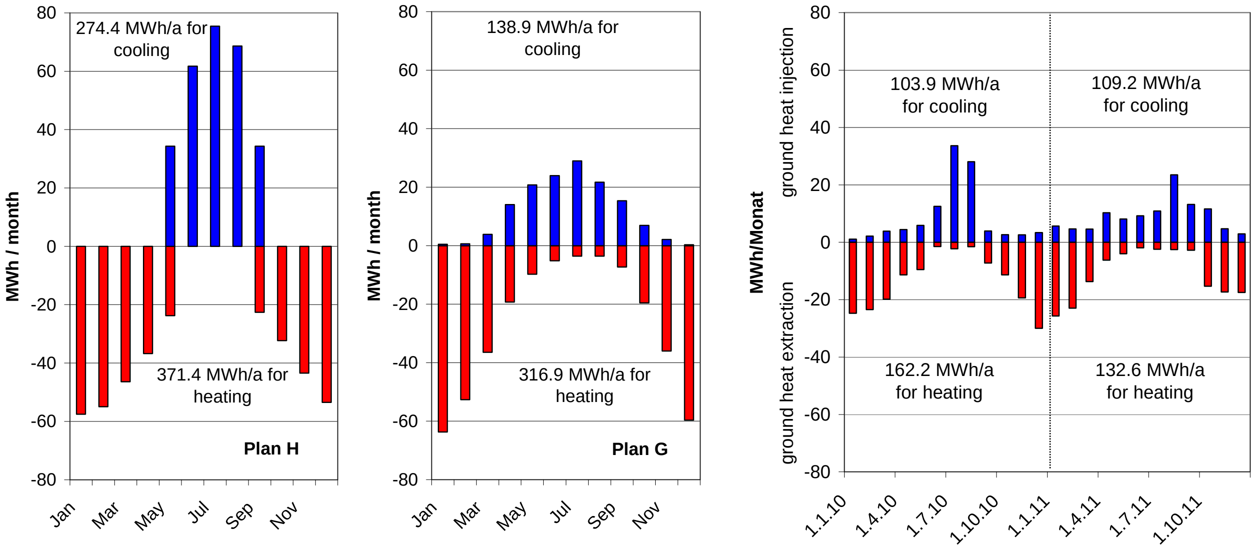

Figure 3: Monthly heat extraction from the ground (for heating) and injection into the ground (for cooling), for project no 7; design values for two calculation methods (left and centre) and measured values 2010-2011 (right)

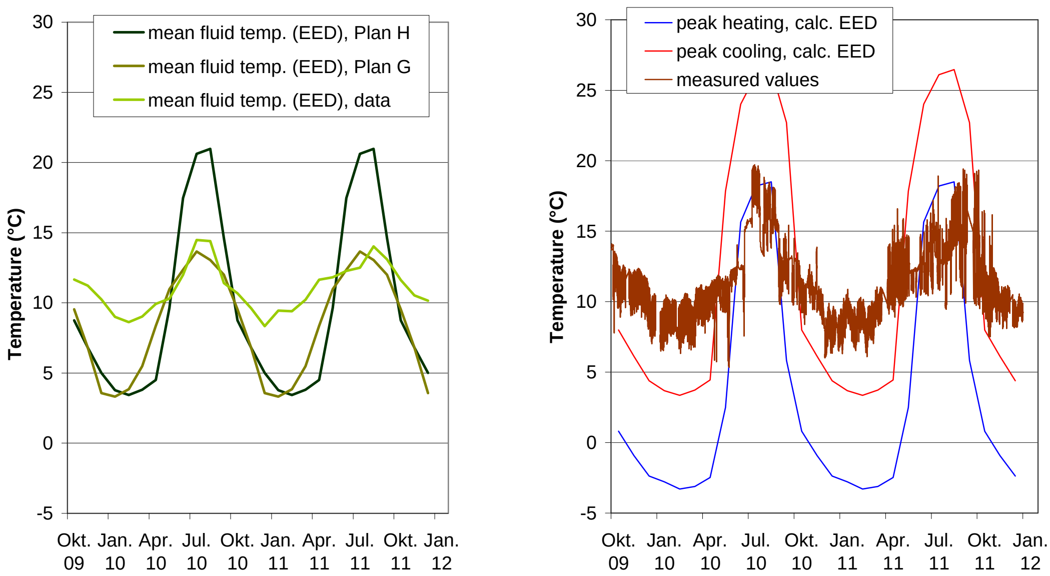

Figure 4: Comparison of fluid temperature development for project 7, calculated with EED according to two design scenarios and to measured data for 2010-2011 (monthly averages, left) and EED-calculation for temperature development und peak load conditions for scenario plan H compared to measured data (right)

4. VALIDATION OF DESIGN TOOLS

The monitoring project provided an opportunity for validation of geothermal design tools with actual measured data (Bohne et al., 2012). For the BTES systems, this was done with the software EED. Being around for quite some years (Hellström & Sanner, 1994), EED now is in version 3.16 from 2010, and can be considered one of the standard tools for design of borehole heat exchangers (BHE). For the use of EED, the measured heat loads had to be summarised into monthly values (figure 2). The values in table 5 and figure 2 are those actually extracted from or injected into the underground, not the loads on the building side.

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 project 1, values from first Thermal Response Tests (TRT) in Germany in 1999-2000 could be used (Sanner et al, 2000). 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.

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 figures 5 and 6 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).

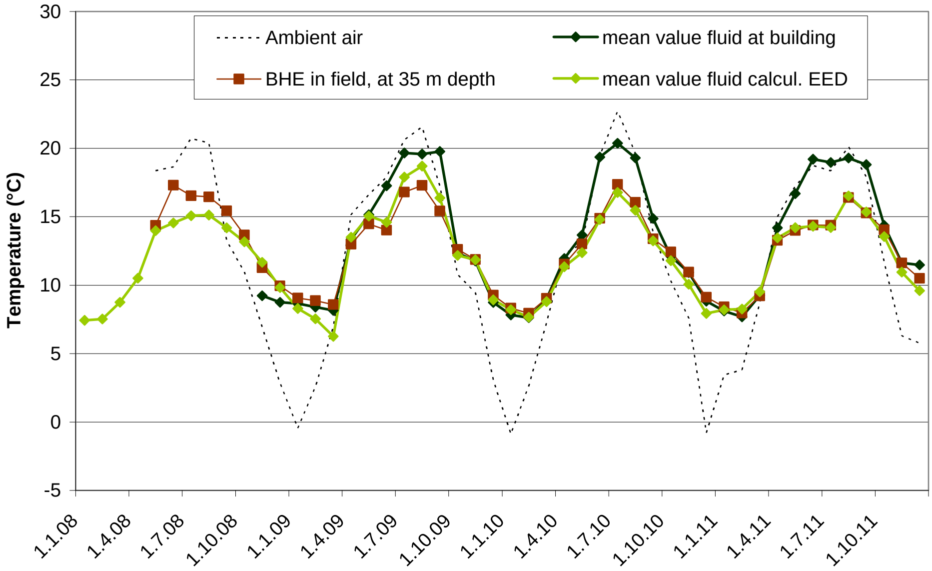

Figure 5: Measured temperatures in ambient air and in the BHE (monthly averages), compared with EED-calculation of BHE, for project no 1

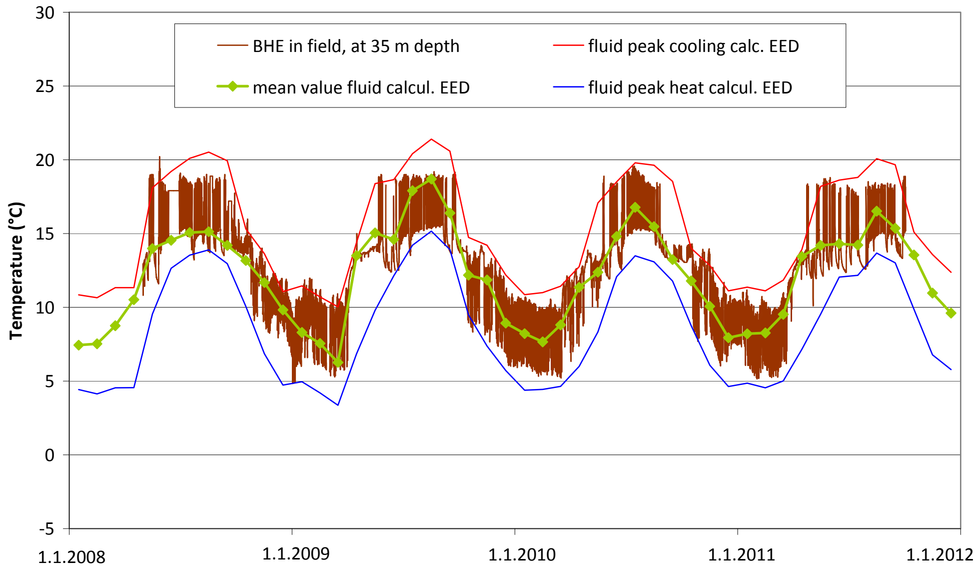

Figure 6: EED-calculation showing the development of monthly averages of mean fluid temperature on the ground side and minimum and maximum values for temperature during peak-load conditions, compared with the annual averages of temperature at a BHE in the field, for project no 1

Beside the monthly averages shown in figure 5, 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 6 this min-max-envelope is shown for the period May 2008 – October 2011, for which consistent values for the hourly temperatures at the BHE in 35 m depth could be used for comparison. The prediction given by EED is rather well matching the actual temperature development.

A similar exercise could be done for project 7, using measured temperatures and thermal energies from the period October 2009 – December 2011. The calculation of monthly averages results in a rather good match to the mean temperatures measured at the ground-side interface of the system (figure 7). For the peak loads, the measured values are more or less inside the predicted envelope; however, the minimum in winter was predicted several degrees lower than the actually measured temperature (probably lower duration of full load than assumed for calculation).

In general, EED can be considered as a valid tool for design, achieving sufficient accuracy for engineering purposes. Numerical simulation should be able to achieve much better matches to real temperature developments, however, the extremely quick calculation with EED is an advantage in daily practice.

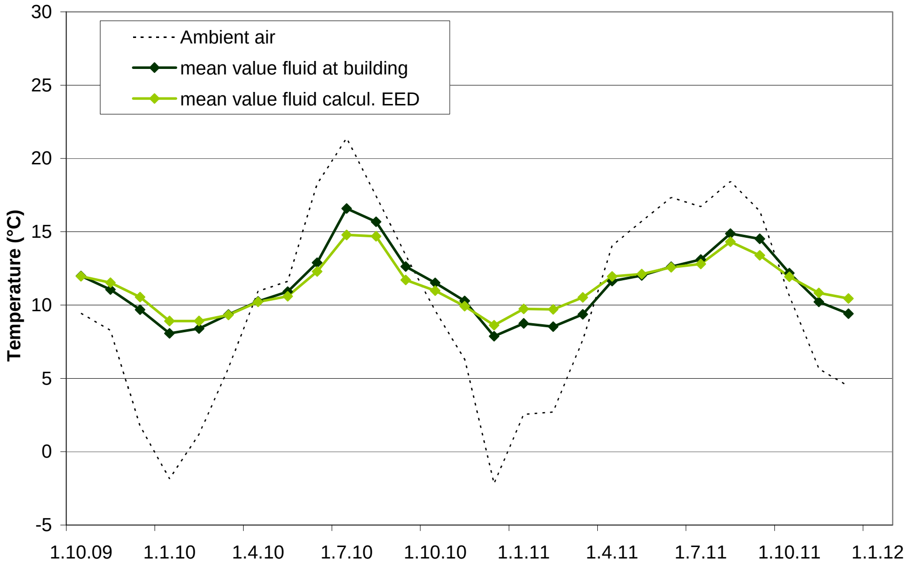

Figure 7: Measured temperatures in ambient air and at the building (monthly averages), compared with EED-calculation of BHE, for project no 7

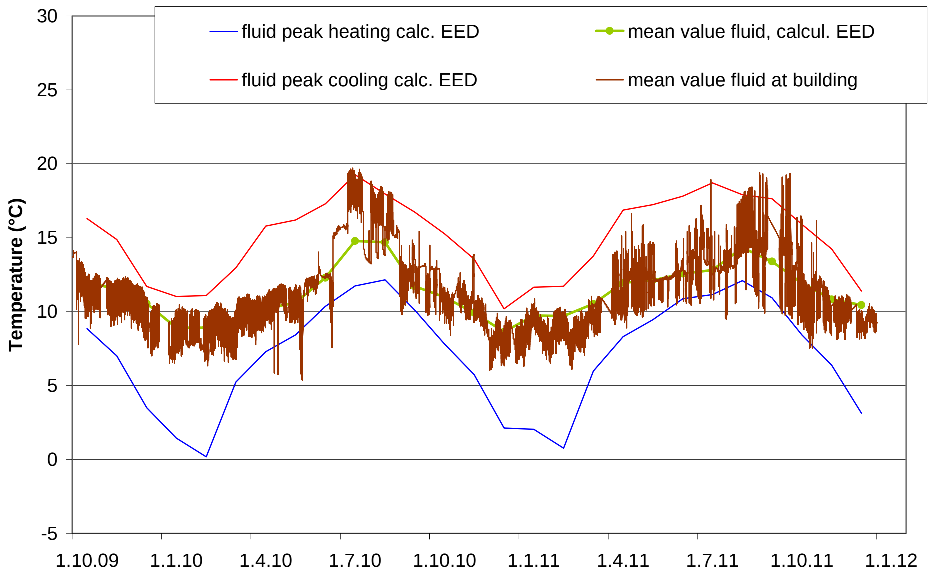

Figure 8: EED-calculation showing the development of monthly averages of mean fluid temperature on the ground side and minimum and maximum values for temperature during peak-load conditions, compared with the annual averages of temperature at the building, for project no 7

5. CONCLUSIONS

Projects using borehole heat exchangers (BHE) and ground water wells are examined. The efficiency of the systems varied widely, with good and also rather poor results. A general problem can be seen in operation and control of the systems in particular where different heat and cold sources are connected into one system. Another typical observation was that the design values differ from the real operation, resulting in ground-side installations no longer sized at optimum. Luckily, the tendency is towards lower loads and thus towards over-sizing of the ground installations, which at the end is good for a safe operation (albeit not as good for the economic side).

The monitored data were also used to validate design software, of which the program EED for BHE design is shown in this paper. The matches were satisfactory, and EED could be confirmed as a suitable tool for larger projects also, as long as advective flow is not predominant. Thermal impact on the ground and groundwater was investigated in some cases, and all projects can be said to have either no impact at all, or at least no negative impact.

A new monitoring project, focusing in particular on the interaction of building system and ground, direct cooling, and control of the system has started with four new buildings (Bockelmann et al., 2012).

REFERENCES

Bockelmann, F., Fisch, M.N., Kühl, L., Petruszek, T., Nüssle, F., Sanner, B. & Mands, E.: Optimization of ground coupled heating and cooling supply systems in office buildings – reversible heat pump and free cooling. *Proc. INNOSTOCK 2012*, paper INNO-U-07, Lleida (2012), 1-9

Bohne, D., Mands, E., Harhausen, G., Wohlfahrt, M., Sauer, M. and Sanner, B.: Thermisches Monitoring an Nichtwohngebäuden mit Einsatz von oberflächennaher Geothermie und Validierung von Wärmeeintrag- und Entzug in den Untergrund – Projektvorstellung und erste Ergebnisse. *Tagungsband Geothermiekongress Karlsruhe 2008*, GtV-BV, Berlin (2008), 417-418.

Bohne, D., Wohlfahrt, M., Harhausen, G., Sanner, B., Mands, E., Sauer, M. & Grundmann, E.: Geothermal Monitoring of eight non-residential buildings with heat and cold production – experiences, results and optimization. - *Proc. INNOSTOCK 2012*, paper INNO-U-26, Lleida (2012), 1-10

Harhausen, G. and Wohlfahrt, M.: Oberflächennahe Geothermie zur energieeffizienten Temperierung von Bürogebäuden. *bbr Sonderheft 2011 Oberflächennahe Geothermie*, Bonn (2010), 28-35.

Harhausen, G., Wohlfahrt, M., Sanner, B, and Bohne, D.: Geothermisches Monitoring an neun Nichtwohngebäuden mit Wärme- und Kälteerzeugung – Projekterfahrungen, Ergebnisse, Optimierungen. *OTTI-Symposium Erdgekoppelte Wärmepumpen*, Regensburg (2011), 1-9.

Hellström, G. and Sanner, B.: Software for dimensioning of deep boreholes for heat extraction. *Proc. CALORSTOCK 94*, Espoo (1994), 195-202

Sanner, B., Reuß, M., Mands, E. and Müller, J.: Thermal Response Test - Experiences in Germany. *Proc. TERRASTOCK 2000*, Stuttgart (2000), 177-182

Seidinger, W., Mornhinweg, H., Mands, E. and Sanner, B.: Deutsche Flugsicherung (DFS) baut Low Energy Office mit größter Erdwärmesondenanlage Deutschlands. *Geothermische Energie 28-29/00*, Geeste (2000), 23-27

Acknowledgements

The research project was running from Sept. 2007 until June 2012 and was funded by the German Federal Ministry of Economics and Technology (BMWi, ID: 0327364B). The authors like to thank for this funding; the responsibility for the content of this paper is, however, with the authors only..