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Geothermal Monitoring of eight non-residential buildings with heat and cold production – experiences, results and optimisation

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1. Introduction

This paper covers a study on eight office buildings using underground thermal energy storage (UTES) for space heating and cooling via heat pumps, chillers or passive cooling (table 1). The types of UTES and the respective ground coupling include both borehole heat exchangers (BTES) and groundwater wells (aquifer systems, ATES) (Bohne et al, 2008). Most of the buildings are located in the West of Germany (Nordrhein-Westfalen and Hessen), with relatively mild climate; the mildest area covered is the Rhine Valley near Bonn/Cologne, where three ATES plants are located. Only one (ATES) plant is outside the regions stated above, in Bavaria. 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 high differences. The only project sites with slightly colder climate, obvious from the lower temperatures in table 2, are projects no 3 and 7.

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

No.	Type	Ground coupling	H (kW)	C (kW)	DC (kW)	Building use
1	BTES	154 BHE, 70 m each	425	---	400	O, R
2	ATES	2 extraction / 2 injection wells, 16-20 m	567	721	450	O, L
3	ATES	2 extraction / 2 injection wells, 47-76 m	1014	880	1500	O, L, W
4	BTES	85 BHE, 99 m each	542	500	440	O, R
5	ATES	2 extraction / 3 injection wells, 20 m	300	540	730	O, W, R
6	ATES	2 extraction / 3 injection wells, 140 m	872	794	---	O, R
7	BTES	32 BHE 110 m each	160	160	280	O, L, R
8	ATES	1 extraction / 2 injection wells, 26 m	156	---	550	O, R

H: heating with heat pump C: cooling with heat pump DC: direct cooling
O: offices L: laboratories W: workshops R: restaurant/cafeteria
In the beginning, 2 more buildings were considered, but dropped out during the project.

For UTES plants for heating and cooling with heat pumps, the storage efficiency as such cannot be given. It could in fact be indefinitely high, as retrieving heat or cold is not limited by a strict temperature level. Retrieving heat cools down the ground and thus at the same time means storing cold, and vice versa. So the main efficiency criteria for this kind of plants are given by the performance factors for heating (heat retrieval) and cooling (cold retrieval). A main goal of the project was to investigate these seasonal performance factors (SPF) for all eight plants. Alas, due to data acquisition and consistency problems, reliable SPF values could by now only be established for the three BTES projects.

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

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 BTES plants monitored 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. From 2009-2011, the BTES system 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 4) and the low-temperature distribution inside the building.

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

ATES systems 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 UTES 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 SPF 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 UTES 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 BTES plant, in comparison to project 7, where the BTES 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).

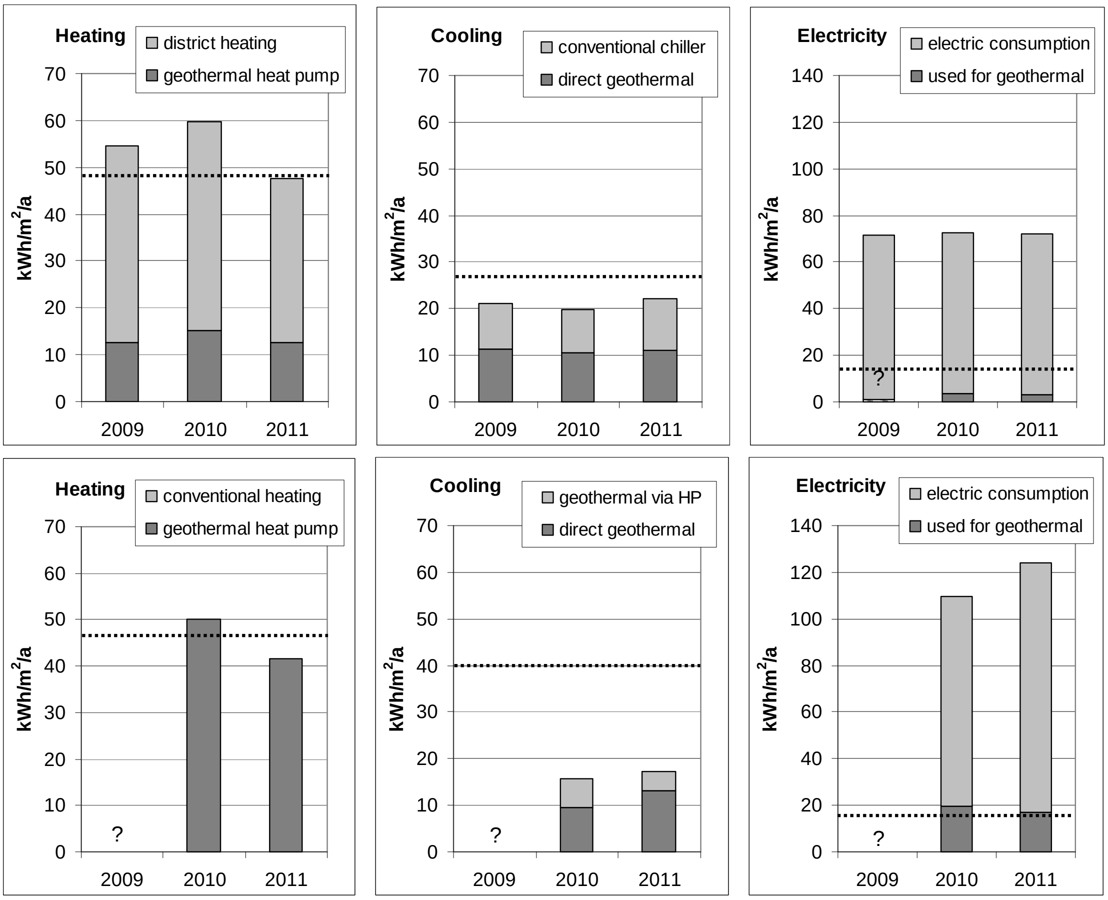

Figure 1: Annual specific energy use (kWh/m^2/a, for NFA), and geothermal contribution or share in the case of electricity consumption, respectively, for project no 1 (above) and no 7 (below); dotted lines: design values

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/m^2/a for heating and 15-20 kWh/m^2/a for cooling.

In project 1 (BTES system with 154 BHE), some constraints are given from a number of drinking-water wells about 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 (cf. chapter 4). Table 4 shows that this goal (given with a ratio 1 : 0.87 in the design) was achieved in all years covered.

3. Validation of geothermal design tools

The monitoring project provided an opportunity for validation of geothermal design tools with actual measured data. 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.

Table 5: Measured ground-side heat loads in the BTES system of 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)

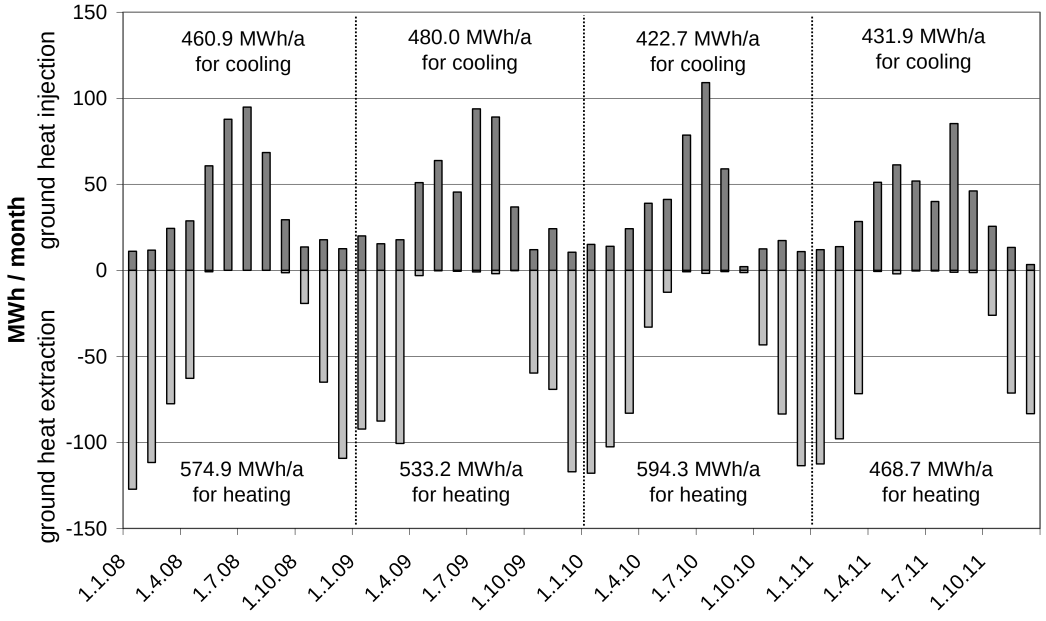

Figure 2: Monthly heat extraction from the ground (for heating) and injection into the ground (for cooling), for project no 1

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 3 and 4 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).

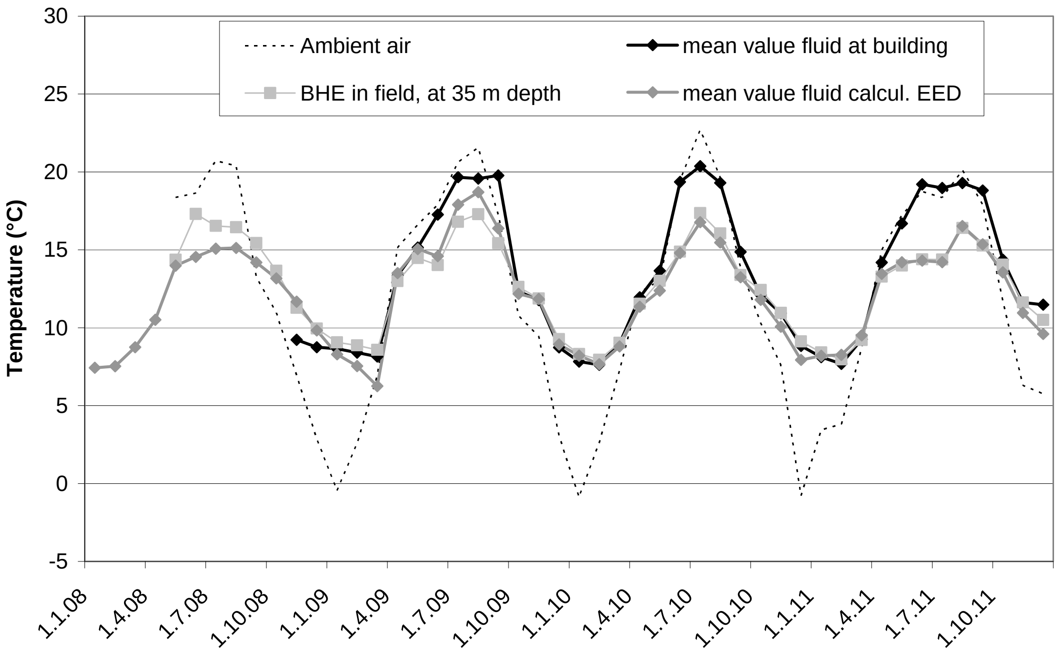

Figure 3: Measured temperatures in ambient air and in the BHE (monthly averages), compared with EED-calculation of BHE, for project no 1

Beside the monthly averages shown in figure 3, 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 4 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.

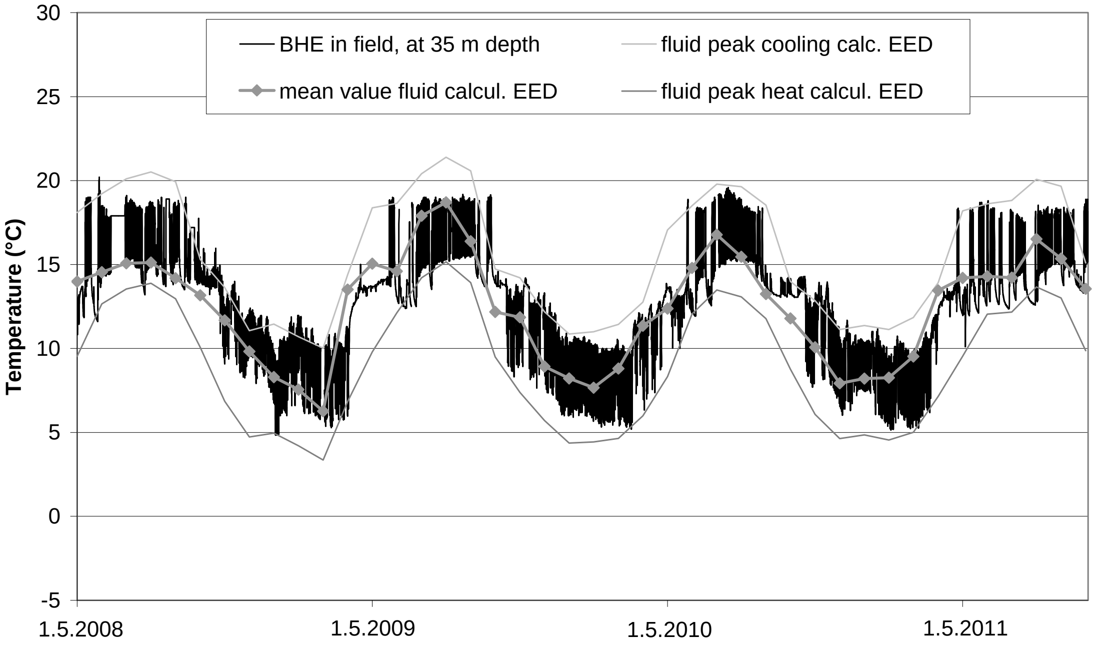

Figure 4: EED-calculation showing the development of monthly averages of mean fluid temperature on the ground side and minimum and maximum values for temperature during peak-load conditions, compared with the annual averages of temperature at a BHE in the field, for project no 1

4. Groundwater influence

Storage losses in UTES concern heat transport out of or into the storage volume. They can be due to conductive heat transfer, convection or advection (transport in moving groundwater). With heat pump assisted systems and balanced heating and cooling loads, the heat/cold usually can be recovered and thus no explicit storage losses are encountered. However, the heat/cold transported to the surroundings might have an impact on groundwater, in particular in ground with advective heat transport. This is obvious for ATES systems, where the groundwater is the main agent and the underground therefore shows some permeability, but it can also be an issue with BTES plants on sites with groundwater flow in the underground.

An example for groundwater issues in a BTES plant is given in project 1. The ground consists of Quaternary and Tertiary sands and clays and is regionally used for drinking water production. A number of wells are located in the direction of assumed groundwater flow from the BHE fields. Three monitoring wells were drilled to a depth of 26 m into the active groundwater layer (figure 5) in order to monitor the groundwater temperatures. In the direction of assumed groundwater flow, one well is located before the BHE field, one just outside the field, and one some 100 m behind the BTES.

The temperature in well BR1 (directly at the BHE field, figure 5) is clearly following the temperature development in the BHE, with a delay of about 2-3 months (figure 6). Temperatures in all three wells were measured by UBeG since 2000 in varying intervals (3, 6 or 12 months) according to requests by the water authorities. In well BR1, a temperature logger was used for some time to get continuous readings (“LUH” in figure 6). The long-time graph in figure 7 reveals that while BR1 at the edge of the BHE field is reacting to heat extraction and injection, wells BR2 and BR3 do not. The temperatures in the downstream well BR3 are in fact slightly lower than in the upstream one, so no heating up of the groundwater can be seen.

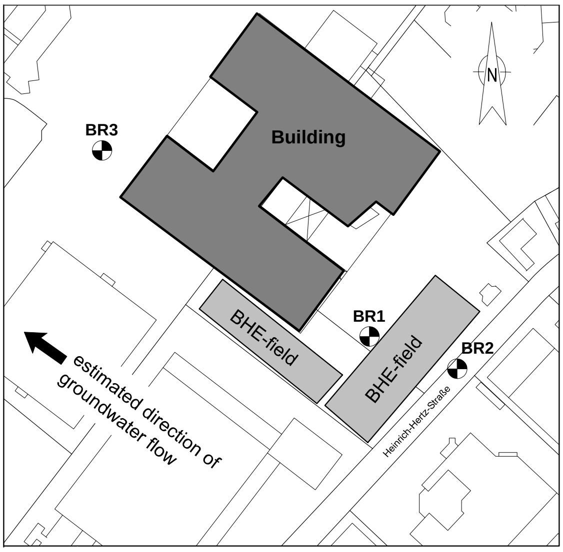

Figure 5: Monitoring wells (temperature and chemistry) and groundwater flow for project no 1

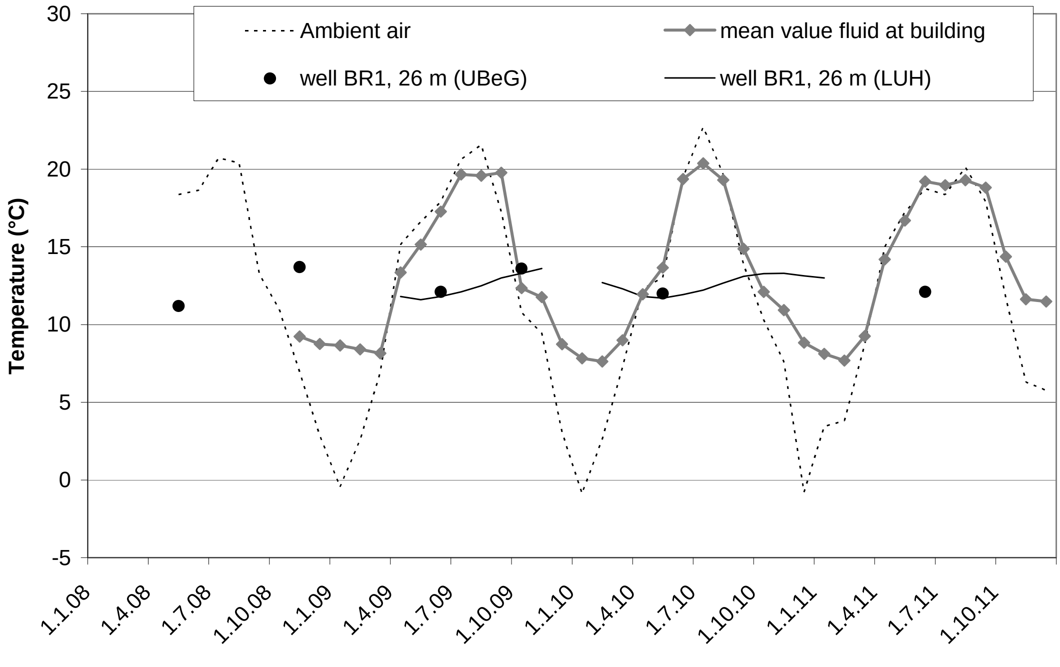

Figure 6: Temperatures in well BR1 at 26 m depth in relation to temperature at BHE and temperature in ambient air (monthly average), for project no 1

For ATES system, two basic principles exist: continuous flow production-injection all time, or seasonal reversing of the flow. A well system for continuous flow is much easier to build and to control, and in applications for heating and cooling with heat pumps they are quite appropriate. Projects no 2, 3, 6 and 8 follow this path since construction, while no 5 was designed for seasonal reversing. Project no 2 was changed to seasonal reversing later (see below).

In aquifer storage the groundwater flow is of vital importance for the whole operation. So from the start of the design this aspect will be addressed, firstly using simple techniques, and in advanced design stages using numerical modelling. The simplest method is a plain energy and groundwater balance, based on aquifer thickness and porosity. This technique works well if no significant groundwater flow is expected. A simple-to-use software for pre-design of ATES systems is CONLOW, a program calculating the thermal front from heat injection or extraction in moving groundwater. This program has been developed at Lund University (Claesson et al, 1994; Probert, 1995) and was used for several ATES projects in Sweden, Turkey and Germany. Alas, further development of this program was not done.

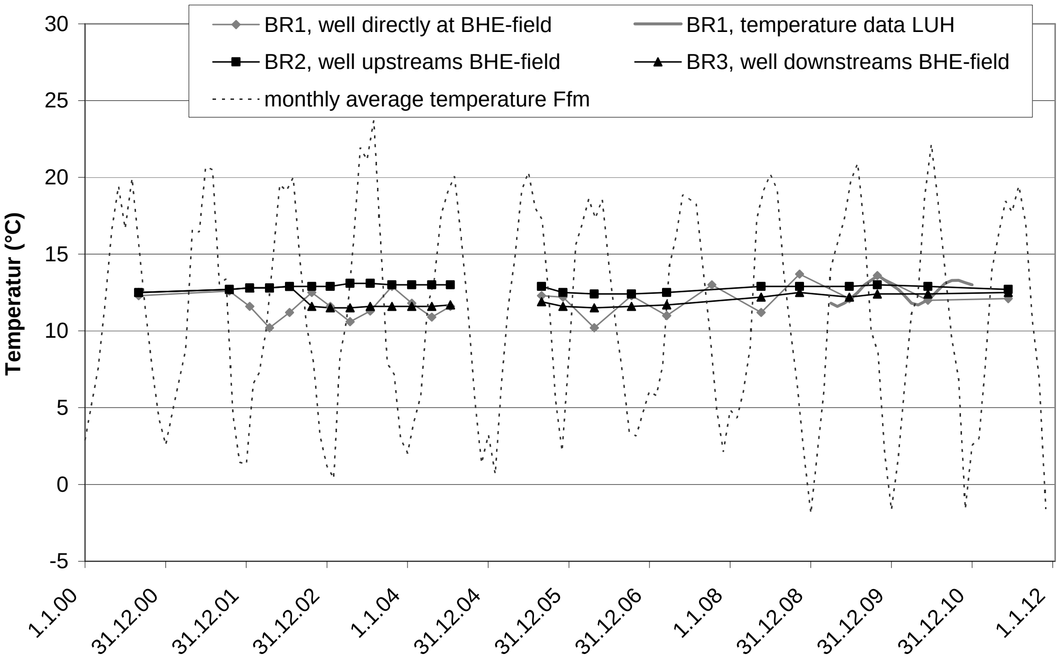

Figure 7: Temperature development in wells BR1-BR3 since start of operation, for project no 1; the development of monthly average air temperature is taken from published data of DWD weather station Frankfurt

When new wells for a neighbouring systems (Mands et al, 2010) were built in 2008/09, these 6 wells had to be placed within the expected influence area of project no 2 in its original form (figure 8). Redesign calculations had to be done for project no 2; one option was seasonal reversal, in order to minimize the thermal footprint of the existing ATES. For this kind of calculations, simple programs like CONFLOW are not suitable at all. So for the complex arrangement of ATES system no 2, neighbouring ATES system no 5, and the new ATES from 2009, numerical simulation was required, in this case based upon the FEFLOW software. A further complication to take into account in the model is the influence of groundwater infiltrating from the nearby river, at varying temperature over the year. As to the knowledge of the authors, a final decision has not been taken yet, and re-arrangement of wells in project no 2 was not done so far. This demonstrates that beside technical constraints within a system and within the immediate underground, outside constraints like other wells, protected areas, etc. can influence the available design options

In project no 3 the temperature measurements allowed for reconstruction of travelling time of the thermal front. Of the 5 wells drilled only 3 are actually used; VB5 is the injection well, while production is done in wells VB2 and VB3. Injection well VB1 had serious clogging problems and thus was isolated. Because of the good performance of VB5, no second injection well is required. VB4 is a monitoring well. The travel times of thermal signals from injection well VB5 to the production wells are shown in figure 11. As the aquifer consists of fractured limestone, the groundwater flow is following a preferred direction, resulting in a narrow thermal front. The use of the wells originally was planned in the opposite direction and with VB4 as active well (later replaced by VB5), thus the CONFLOW results from the design phase as shown to the right in figure 11 are reversed. However, the thermal front is in the same order of magnitude, considering the lower pumping rates in the actual project than in the design parameters.

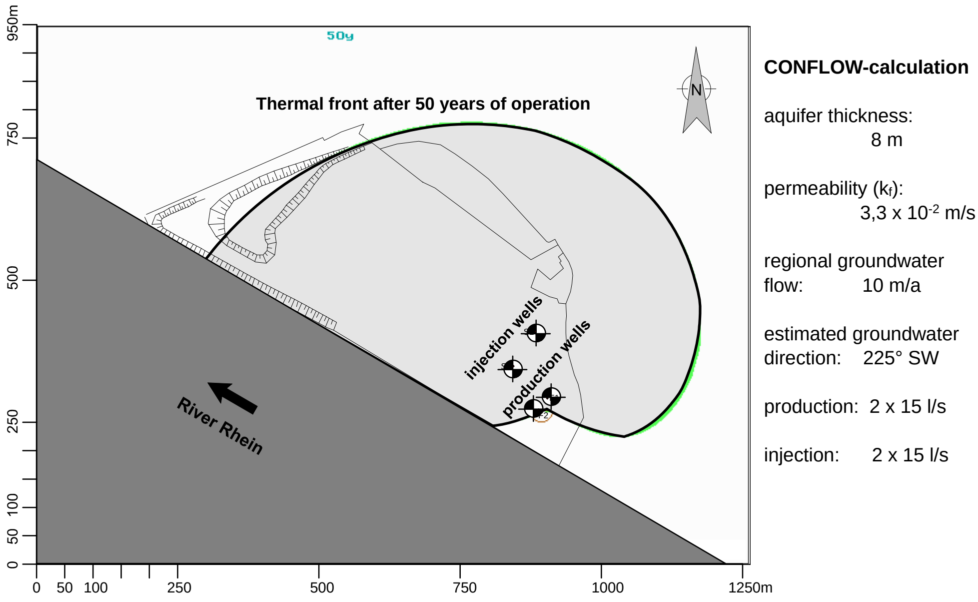

Figure 8: First estimates from 2003 for the influenced area of the one-directional UTES systems for project no 2 using CONFLOW

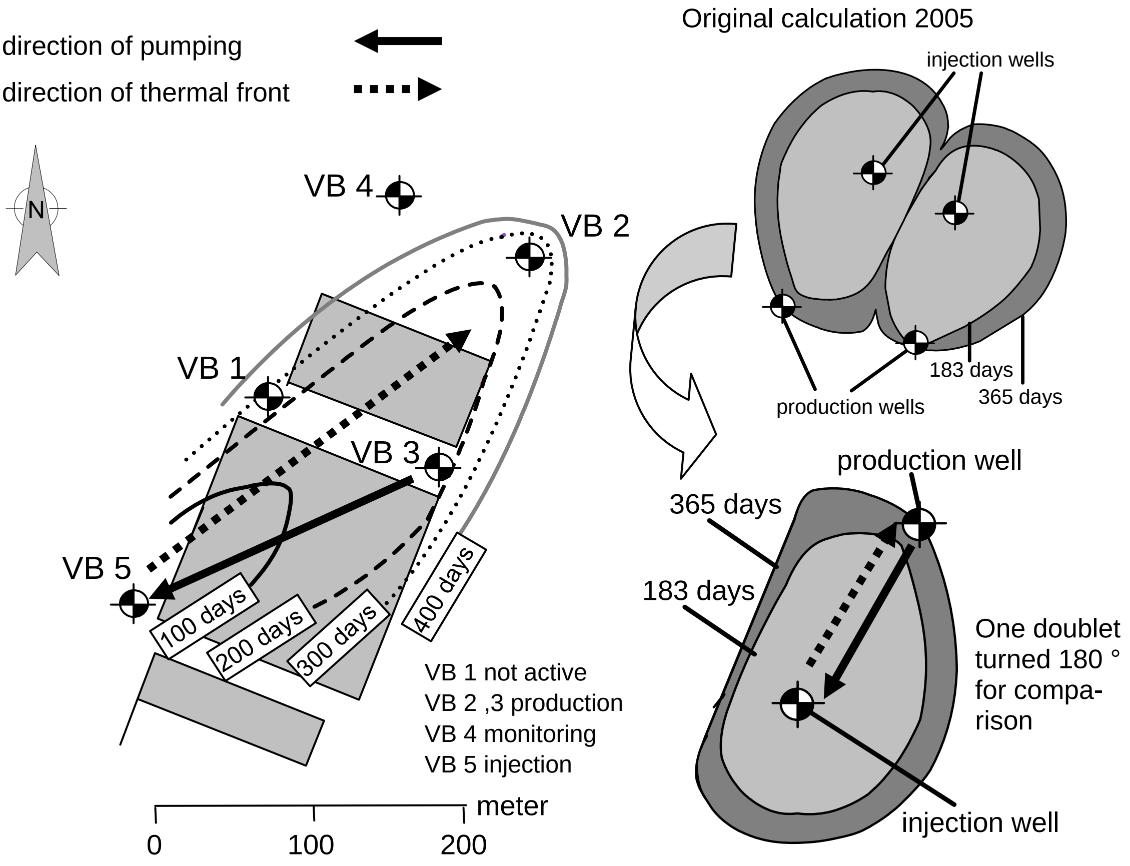

Figure 9: Measured travel times of the temperature front in the one-directional UTES systems for project no 3 (left), compared with thermal fronts calculated with CONFLOW in the design phase (2005, with wells VB 1-4 planned for operation, and assuming opposite flow direction than eventually built; well VB 5 was added later, and VB 4 converted to monitoring); a part of the CONFLOW result (one doublet) is turned 180° to allow for easier comparison with the measured thermal front

5. Conclusions

Projects using borehole heat exchangers (BTES) and aquifer systems (ATES) are examined. In order to achieve meaningful energy data, the monitoring project included the installation of non-invasive sensors for temperatures and volume rates, data analysis on energy consumption and in-depth analysis at the controller data level. Some optimizations of energy efficiency and controller performance have been achieved during the process. Results show the feasibility of the general UTES concept at medium to high energy efficiencies. However, loss of performance and temporary breakdown of some systems as well as inconsistent concept implementation are being observed.

The monitored data were also used to validate design software both for ATES and BTES. The applicability of easy-to-use programs like EED could be confirmed for BTES design; in Sauer et al (2008) design procedures and alternatives for larger projects are discussed in detail. For 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.

6. References

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