RECENT DEVELOPMENTS IN SITE INVESTIGATION, DESIGN AND APPLICATION FOR GROUND SOURCE HEAT PUMPS

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Abstract – Ground Source Heat Pumps (GSHP) are a proven technology to harness shallow geothermal energy. Nevertheless, the market introduction of GSHP is rather different among the European countries, as is the industry infrastructure, knowledge and installation skills. Standardisation and clear strategies and rules for exploration, design and installation are crucial to deploy GSHP in countries with an embryonic market. The paper presents recent developments in GSHP technology in several fields, in particular:

- **Site investigation technology TRT**
- **Design software and its validation**
- **Application examples with new approaches**

The constraints controlling GSHP design for a certain building and site are discussed and the role of the developments presented is explained.

Keywords: geothermal, heat pumps, site investigation, design software

1. INTRODUCTION

First Ground Source Heat Pumps (GSHP) are reported from USA in 1945, in Europe the technology dates back to the 1960s. An overview over the historical development is given in [1]. GSHP thus could achieve meanwhile a high degree of evolution and refinement, with proven concepts and reliable components. In 2010, the number of heat pumps operating within the EU exceeded 1 mio. units (figure 1). As this does not include Switzerland and Norway, two countries with a substantial number of installations, the total for all Europe might today be close to 1.5 mio. units.

The main technologies used today for coupling the heat pump to the ground are:

- Borehole heat exchangers ("vertical loops")
- Horizontal heat exchangers ("ground loops")
- Compact heat exchangers (slinky, spiral, cages…)
- Energy piles, foundation walls, etc.
- Groundwater wells

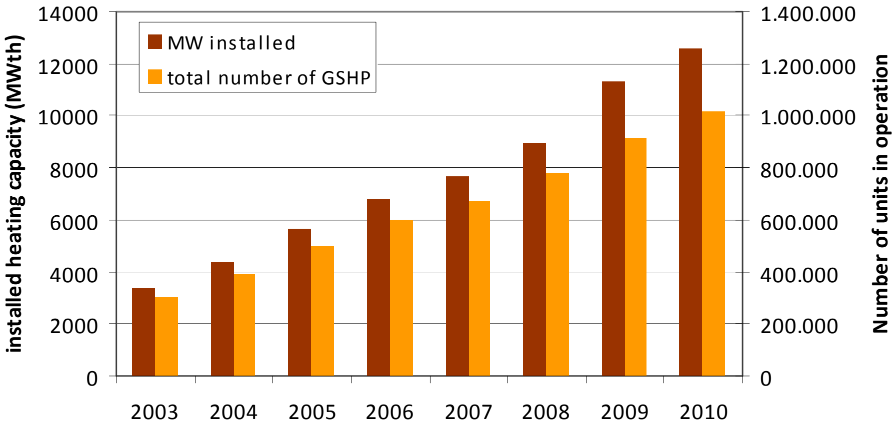

Fig. 1: Number of GSHP units and their installed heating capacity inside EU (after data from [2])

The market in some of the countries is reaching a mature or even saturated phase, as in Sweden and Switzerland. On the other hand, there is a huge market potential in several other countries. A big obstacle in these countries is the lack of awareness in the public (and with the authorities), and the lack of knowledge and specific skills with the installers. Training and education schemes must help in overcoming this obstacle, like the promising approach given in the Geotrainet program [3]. Material and curricula elaborated in the Geotrainet project are available at www.geotrainet.eu.

2. SITE INVESTIGATION / TRT

The Thermal Response Test (TRT) is a tool to investigate ground thermal parameters required for design of borehole heat exchangers (BHE), as used in GSHP. While the theory and the use of the basic principles date back to the 1970s, the first mobile application of TRT is reported in 1995 [4], and the first TRT in Germany was done in 1999 [5]. Since then, a wealth of practical experience could be sampled both in the practical setup of the test (accuracy, reliability, site accessibility, insulation, etc.) as in the understanding of the different evaluation methods. A global review was done in 2005 [6].

The measurement signal of a TRT is a temperature change due to heat injection or extraction. Concerning the basic physics, it does not matter if heat is injected or extracted. The parameter to be determined, thermal conductivity is not dependent from the direction of heat flow. The most important impact is given by the uniformity of the thermal load. This must be as constant as possible, in order to achieve an undisturbed signal.

Practical experiences on test operation has been gained during more than a dozen years of TRT tests throughout many European countries. One result is the importance of having a verification of the final results by using methods of sequential (step-wise) evaluation. Through this method a sufficient length of test time and the prevalence of conductive heat transport can be checked. Beside this verification, an awareness of the overall accuracy of the results as depending on accuracy of data collection is required. For the validity of temperature logs, the bottom heat dissipation can be used as an indicator.

A lot of additional information can be obtained from the test data, in particular if a temperature log inside the borehole is combined with the test. Examples of such information comprise layers with groundwater flow, distinction of layers of different thermal conductivity, quality of grouting, geothermal gradient, etc. It is also possible to use the TRT for investigating the actual depth of the borehole heat exchanger by use of the Thermo-Impulse Method [7].

a) Test procedures and reliability check

Based upon experience, some mandatory routine procedures are suggested to be performed before the start of the response test, in order to avoid unpleasant incidents:

- Power supply check. The test can of course not be performed without electric power, be it from the grid or from a generator. Considering the required power levels, typically 3-phase AC is the source. Wrong phasing of this power supply can result in shunt fault, controller failure, overheating of the device and even smouldering of the test rig. Power breakdown or instable power supply may lead to inconsistent development of the temperatures, and thus makes it difficult or impossible to evaluate the test.
- Sufficient de-aeration. Without proper de-aeration, the flow inside the borehole can collapse after an unknown amount of time, and the test will come to an unexpected early end.
- Insulation of the test rig and connections. The ambient influence (heat or cold) should be kept as low as possible, as it cannot be controlled and heavily affects the test in a similar way as fluctuating power supply.

The so-called “Stepwise Evaluation” (sequential data analysis) allows for cross-checking if any of the effects mentioned above have had an influence on the test operation (fig. 2).

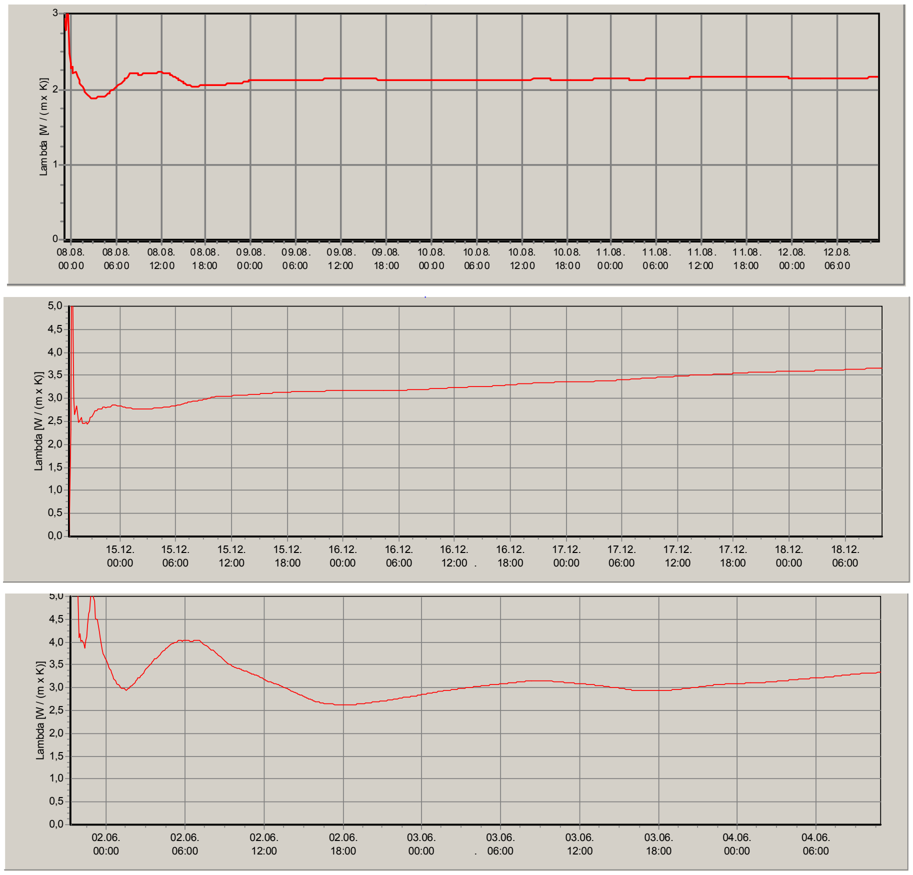

Fig. 2. Examples of stepwise evaluation of TRT: Dominated by conductivity, good reliability (top), dominated by advection and not usable (middle), and high fluctuations and low reliability (bottom)

An evaluation of the recorded data is performed in a stepwise evaluation with a fixed start time and increasing length of the data set, until the full duration to the end time. The resulting thermal conductivity for each time-span can be calculated and plotted over time. Usually in the first part of such a curve the thermal conductivity swings up and down, converging to a steady value and a horizontal curve in the case of a perfect test (figure 2, top). This procedure is a useful tool to check the quality of the data collected and the validity of the results.

With substantial influence of flowing groundwater, the curve rises upwards steadily after some time (figure 2, middle). Thus the test result value (λ) is determined by the duration of the test, and the longer the testing time is, the higher the λ will be. There is no reliable result for such a test. In case of influence of fluctuating power supply or environmental influences (e.g. solar radiation), the test result is not stable, and testing time must be extended (figure 2, bottom).

Beside the thermal conductivity of the underground, the undisturbed ground temperature (as average over the BHE length) is of crucial importance when calculating a BHE-field design. This parameter can be drawn from the temperatures recorded with the TRT device before the heating phase started with just the circulation pump running (fig. 3). Another method is the temperature log (fig. 4).

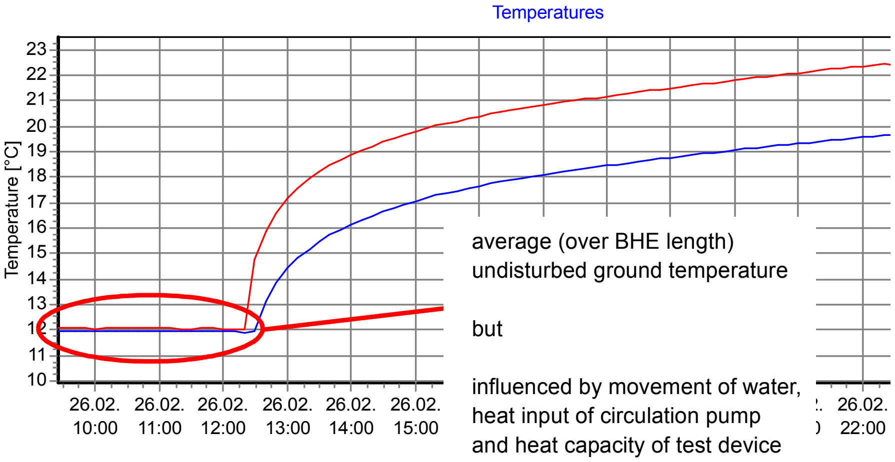

Fig. 3. : Undisturbed ground temperature from TRT

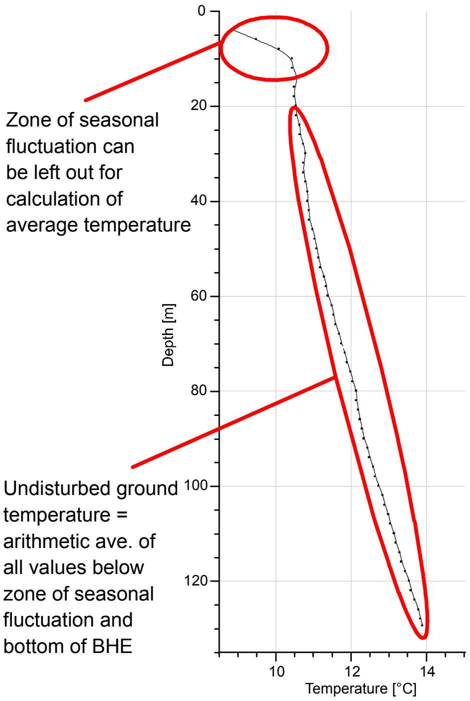

Fig. 4: Temperature profile before performing TRT

When running the circulation without heating, however, due to the (very small) heat input from the circulation pump, a small increase of the value might occur over time. An observation of temperature development without heating over some hours (as in fig. 3) also can help in detecting any residual heat from drilling or solidifying of the grout, given away by a temperature decreasing over time.

The temperature log (fig. 4) in addition allows for exclusion of the zone of annual variation and gives much more details that could be used for further information, There are several tools available for taking a log, even inside a 32-mm-pipe as used for most BHE. Logging requires some patience to allow for full thermal equilibrium at each depth level to be measured, and some handling skills not to get a tool stuck in a well or pipe.

b) Extended range of applications

The temperature log before the test as shown in fig. 4 should be complemented with temperature logs after the end of the TRT (a recommendation could be a log directly after, one about 1 hour later, and another one 2-3 hours after the end of the test). These logs will show the gradual cooling of the fluid inside the pipes and allows for various conclusions as shown in figures 5 and 6. It should be taken into account that the exact time of the temperature measurement is not the same over the depth of the BHE, as the logging takes some time (up to 30 minutes for 100 m). So the signals might by slightly different with depth.

Among the features visible (figures 5 and 6) are groundwater flow, missing grout (to cool down so quickly as in figure 6, the BHE must have a direct contact to flowing groundwater, i.e. not being encased by the grouting), or layers with different conductivity. Sometimes it is not clear if the temperature sensor went all the way to the bottom of the BHE, or if the BHE is just blocked (e.g. by a pinch). The "Bottom Heat Dissipation" (figure 5 right) gives a confirmation for having reached the bottom, as at this point the heat is also transported in vertical direction downwards, and a faster cooling can be seen.

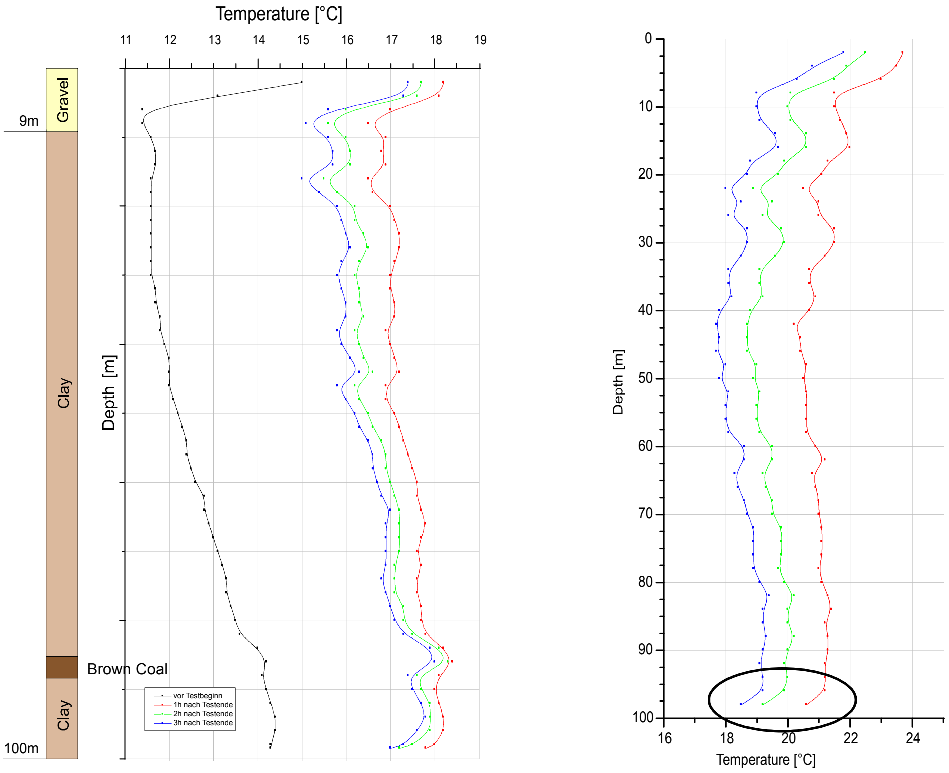

Fig. 5: Features as elucidated by temperature log before and after TRT: presence of a low-conductivity layer (left), prove of final depth (right)

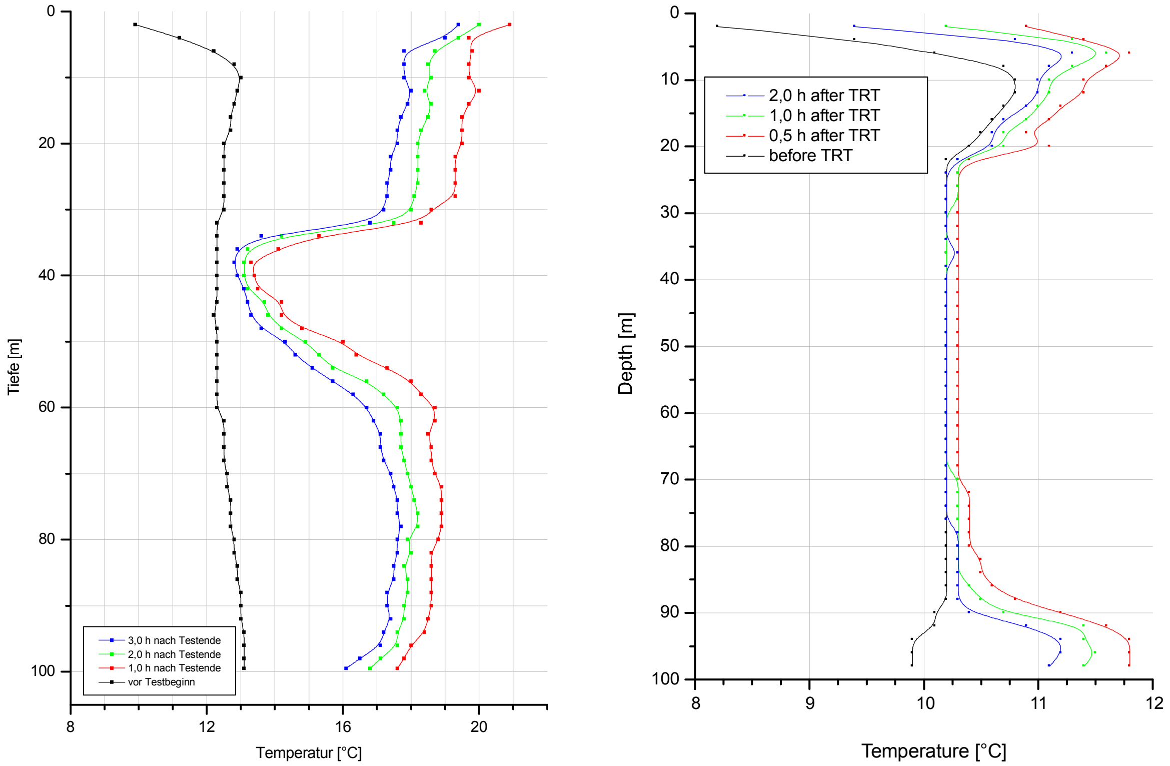

Fig. 6: Features as elucidated by temperature log before and after TRT: Influence of groundwater-flow (left), poor or non-existent grouting (right)

c) Thermo-Impulse Method

Using the Thermo-Impulse Method, a practical issue can be solved in shallow geothermal installations. Sometimes disputes arise over the question if the BHE actually has the full length as contracted. The TRT rig can offer a convenient method of determining the actual BHE-depth within a narrow margin of error. The method was first published in Sauer et al. (2010). It comprises the following steps (fig. 7):

- A strong thermal signal (impulse) is injected into the BHE circuit
- The time the impulse needs to return is measured.
- With the (measured) flow rate and pulse-time-delay the volume of the BHE can be calculated.
- With the known diameter of the BHE tube and the volume the length can be calculated.

Tests with recurring Thermo-Impulse measurement at the same borehole heat exchanger confirmed the reproducibility of the depth measurement (table 1).

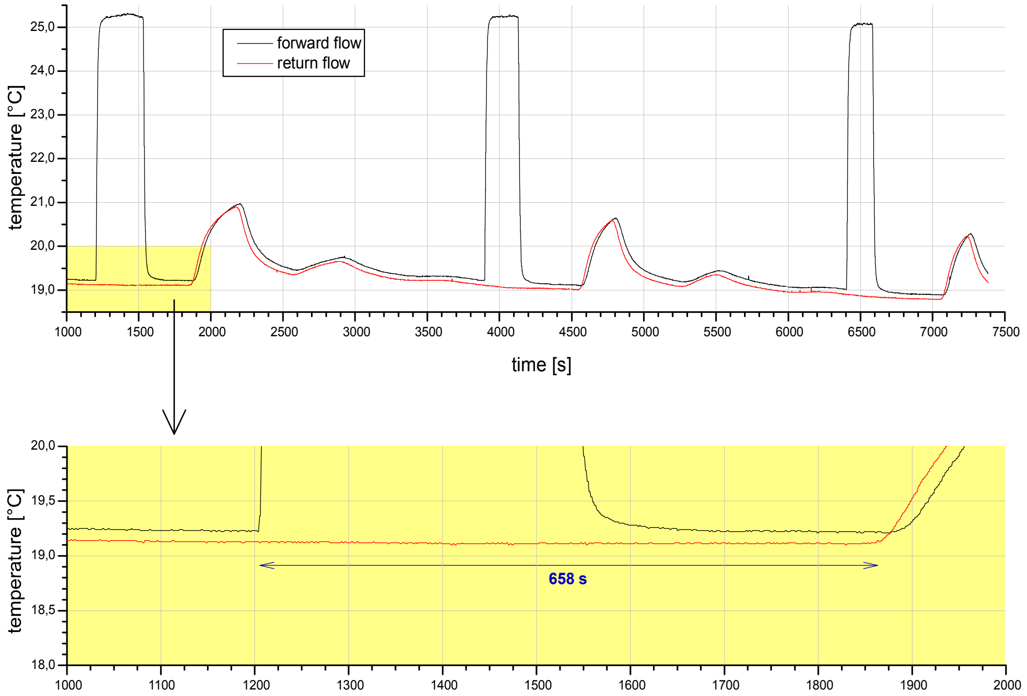

Fig. 7: Principle of Thermo-Impulse method (recurrence of impulse)

Table 1: Reproducibility of Thermo-Impulse measurement

Measurement	Time delay to recurrence	Depth (m)
1st:	658 s	129.0
2nd:	662 s	130.2
3rd:	659 s	129.7
Average		129.6
Maximum deviation		±0.6 m (±0.5 %)

d) Possible use of TRT for investigation of deep geothermal potential

As a side note, some thoughts are presented here on measurements in TRT that could be of interest for deep geothermal projects. From temperature logs before TRT, the geothermal gradient (temperature increase with depth) and, with knowledge of the thermal conductivity as a result of the TRT, the geothermal heat flux can be determined as:

$$Q_g = k_g * \lambda$$

with: Q_g = Geothermal heat flux (W/m^2)
k_g = geothermal gradient, in K/m
λ = thermal conductivity (W/m/K)

Estimates on the expected lithology under the site allow for extrapolation of these values down to the depth required for deep geothermal projects (heat and/or power). Naturally, such extrapolation will not sufficiently reflect deep groundwater movements and other factors contributing to geothermal anomalies, but it can be a first hint to the geothermal character of an area where no deep boreholes yet exist.

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 [8], 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 [9] 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 [10], was used for reference. For the use of EED, the measured heat loads had to be summarised into monthly values (figure 8). The values in table 2 and figure 8 are those actually extracted from or injected into the underground, not the loads on the building side.

Table 2: 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)

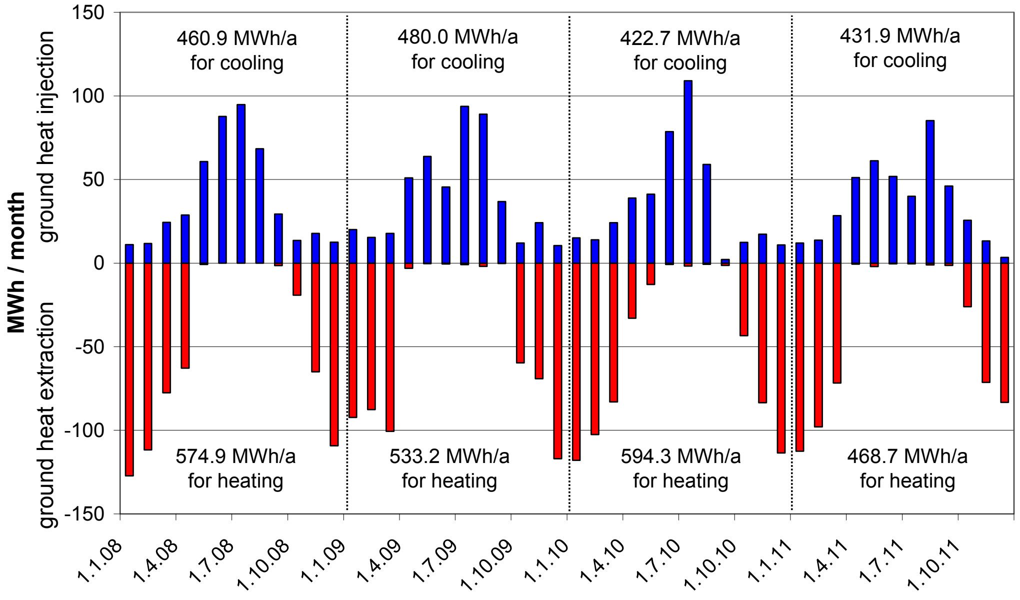

Figure 8: Monthly heat extraction from the ground (for heating) and injection into the ground (for cooling) in Langen GSHP

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 [5]. 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 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 9, 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 10 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.

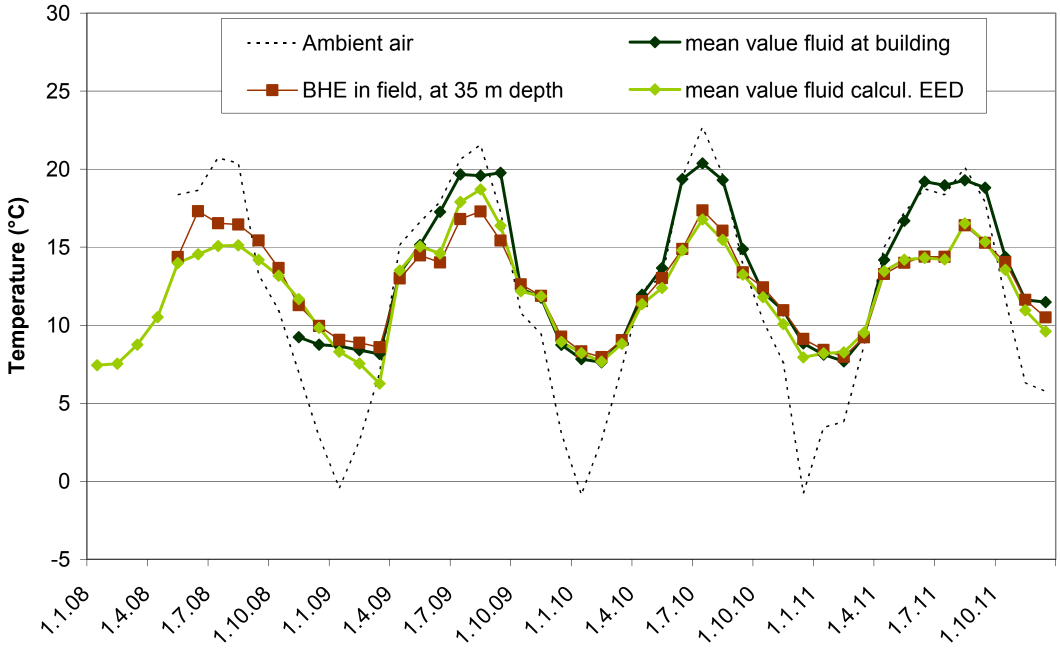

Figure 9: Measured temperatures in ambient air and in the Langen BHE (monthly averages), compared with EED-calculation of BHE

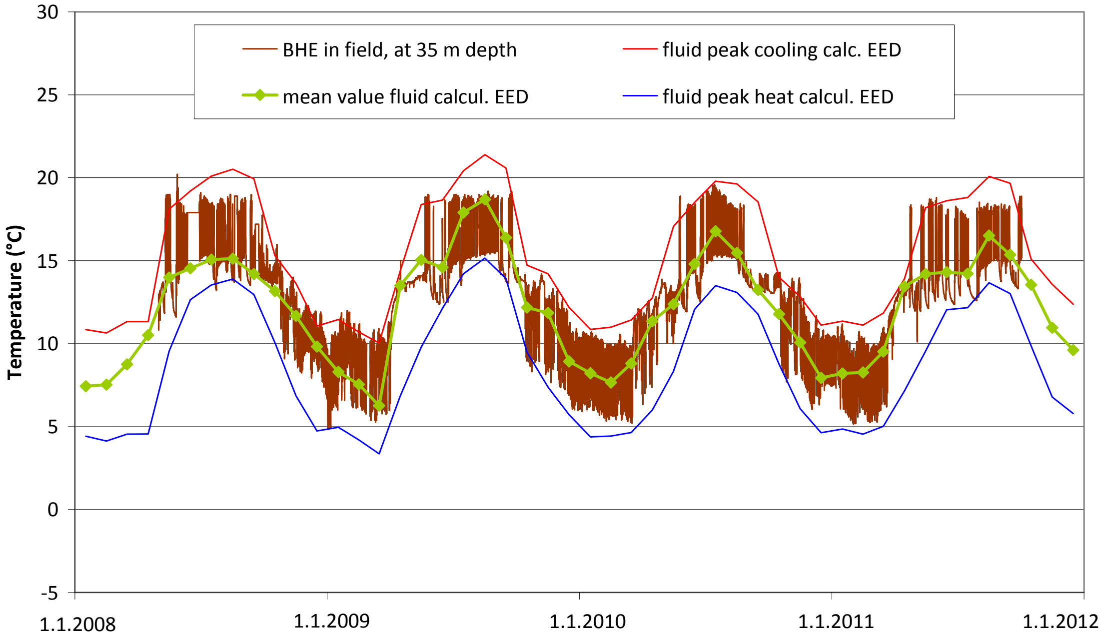

Figure 10: EED-calculation showing the development of monthly averages of mean fluid temperature on the ground side in Langen and minimum and maximum values for temperature during peak-load conditions, compared with the annual averages of temperature at a BHE in the field

4. Application and operation strategies

Monitoring allows for understanding the functioning of a GSHP plant. Since the earliest experiments, detailed monitoring campaigns have been executed in many countries. The earliest monitoring report found in literature was published exactly 60 years ago [11]. 20 years ago, a listing of monitoring results and literature for the first phase of GSHP application in Europe and North America was given in [12].

a) Monitoring energy flows

Data from monitoring were already used in the previous chapter, for validation of design software. The main reason for monitoring is, however, the check of function and efficiency of a certain project. For the Langen GSHP project from the previous chapter, some energy figures are given here (Table 3, cf. [9]). As the GSHP in this relatively large project (154 BHE) is 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 11 shows the total specific heating and cooling loads and the part covered by the ground.

In figure 11 also the electricity consumption of the building and the share of electric power used by the GSHP system (ground-side pumps and heat pumps) can be seen. The specific energy loads are calculated using the net floor area (NFA) of the building. 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. Table 2 shows that this goal (given with a ratio 1 : 0.87 in the design) was achieved in all years covered.

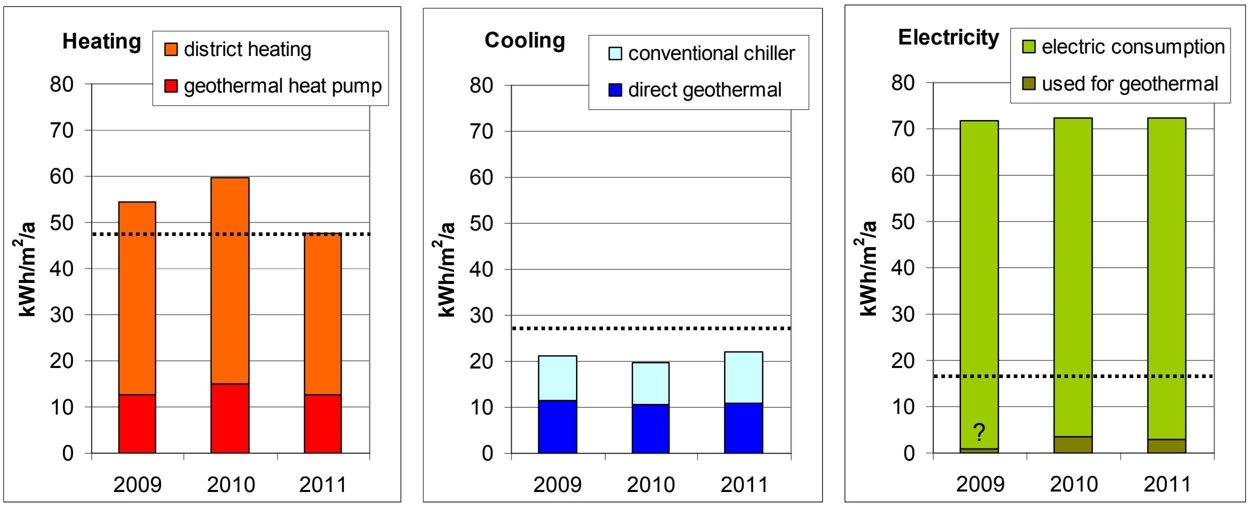

Figure 11: Annual specific energy use (kWh/m^2/a, for NFA) in the Langen building, and geothermal contribution or share in the case of electricity consumption, respectively; dotted lines: design values (after [9])

Table 3: Annual performance (SPF) and geothermal share of the heating and cooling energy supplied to the Langen building (after [9])

	design	2009	2010	2011
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 %

b) Example of design for specific climate conditions

In the southwest of Spain, a new retail outlet was planned in Jerez de la Frontera [13]. A little more than fifteen km from the Atlantic Ocean, Jerez is characterized by mild winters and very hot and dry summers, with 17.7 °C annual average. The extreme temperatures in August in a long-term average rise to 33.1 °C maximum and fall to 18.4 °C minimum, and the actual readings exceed 38 °C each year on several occasions. Thus cooling demand in this region exceeds any heating demand by far, in particular in commercial buildings with lot of internal heat sources. Designing a GSHP for cooling under these conditions requires unconventional solutions; seasonal storage is hardly feasible, with mean temperatures in winter not lower than 10 °C.

The company owning the retail outlet has equipped already a number of its large stores with GSHP, mainly in Northern Europe, but the one in Jerez is quite different for the specific climatic conditions it has to deal with. Given the climate of Jerez and the building design and concept used for the retail building, there is a totally unbalanced thermal energy demand:

Heating demand: 75 MWh/a
Cooling demand: 4’104 MWh/a

Thus heat accounts for only 1.8% of the demand for cooling. The monthly building loads are given in figure 12; even in winter, the monthly cooling demand is higher than heating demand!

The design target under these conditions was to create a geothermal HVAC system that covers the full (small) heating demand and a part of the total cooling demand as large as possible. For this extremely unbalanced situation, a substantial part of the cooling can only be covered if sufficient cold is stored in the underground, or in other terms, surplus heat is extracted from the underground. The final design hence did not only include cold storage in wintertime for a seasonal balancing, but also short-term cold storage during night in summer. With using all time available for heat extraction, considering the periods when ambient air temperature is sufficiently lower than ground temperature, a maximum annual cooling supply of about 700 MWh/a might be achieved.

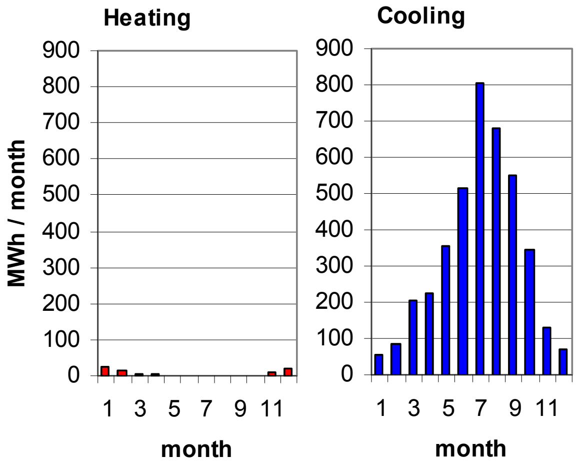

Figure 12: Monthly heating and cooling loads as to building design for Jerez retail outlet (after [13])

For the BHE design, several thermal response tests (TRT) had been done in advance with a resulting thermal conductivity of 1.5 W/m/K. The undisturbed underground temperature was 19.8 °C, a rather high value compared to classical GSHP countries like Sweden or Germany.

From economic considerations, the maximum number of BHE was limited to 50, with a maximum distance of 8 m among each, and a maximum depth of 130 m. So the primary design task was to check what would be the maximum cooling that could be provided by a BHE-field of this size. Calculations using a standard approach resulted in the possible loads as shown in table 4; of the total annual cooling demand of >4 GWh, only about 7 % could be covered from the ground that way.

As the percentage of geothermal coverage of the cooling load is so small, an almost steady operation over the whole year for this very base load can be assumed. The heating in wintertime is only able to reduce the heat injection into the BHE field, but not to turn it into heat extraction. As a result, the operation would be dominated by continuous heat dissipation into the underground, and in consequence the ground temperature would rise constantly.

Table 4: Load data on building and ground side for two different scenarios for Jerez retail outlet (cf. [13])

	supply to building	geothermal coverage *	expected SPF	BHE extraction for heating	BHE extraction from re-cooling	total BHE extract. / inject.
Standard case						
Heating	75 MWh/a	100 %	5	60 MWh/a	-	60 MWh/a
Cooling	300 MWh/a	7 %	3			450 MWh/a
Maximum cooling case						
Heating	75 MWh/a	100 %	5	60 MWh/a	420 MWh/a	480 MWh/a
Cooling	530 MWh/a	13 %	3	-	-	795 MWh/a

* percentage of total building loads

Even in summertime, ambient air at night can be colder than the temperature in the BHE field. As temperature in the underground will rise steadily over the years also when active re-cooling is done (the increase just being slower than in the standard case), the opportunities for re-cooling with nighttime ambient air will improve over time.

Weather data from nearby Cadiz were used to assess the amount of re-cooling that could be done during spring, summer and autumn (example for July given in figure 13). In order to use the cold from the ground efficiently, no geothermal cooling was assumed from November to March, as the lower ambient air temperatures in wintertime will allow for efficient use of air coolers. Using the ground for cooling is more desirable in summer, when ground temperatures are much lower than cooling water from air coolers. The software EED was also used here to calculate the temperature development, and eventually the load data as given in table 4 were deemed feasible.

The complete geothermal system consists of borehole heat exchangers (BHE), heat pump and dry cooler(s). The 50 BHE were finished in 2010, and the underground thermal storage volume around the BHE now extends to about 553’000 m^3. Alas, by the time of writing, no monitoring data could be evaluated yet.

With this innovative design concept, adapted to Mediterranean climate and combining both diurnal and seasonal cold storage, the cooling output from BHE can be increased in a sustainable way. In summer, the underground works as a store of cold during the night and as a sink of heat during the day (diurnal storage). In wintertime, the regular operation of the heat pump for heating extracts some heat from the ground, and additional heat extraction (or re-cooling) is done by dry cooler (seasonal cold storage).

5. Conclusions

Ground Source Heat Pumps (GSHP) are used throughout Europe, in small applications (residential houses) as well as in large projects for commercial or institutional buildings, and in various climatic zones from Northern Scandinavia to the Mediterranean Sea. In particular for large installations, good knowledge of the thermal parameters of the underground and thorough forecasting of building loads are crucial in achieving highly efficient and long-term sustainable heating and cooling systems. Recent developments in investigation of ground thermal parameters and design software have been presented above.

With suitable investigation and design tools, the behaviour of a certain shallow geothermal system can be predicted quite accurately. However, depending on building type and climate, further considerations need to be made in order to match building, geology and climate. The example of a retail building in Jerez in southernmost Spain given in this paper shows how GSHP can be adapted even to rather extreme conditions.

In order to understand better the real behaviour of large GSHP systems, and to check if the expected efficiency and planned operation strategy could be met in reality, more monitoring of this kind of installations is required. Alas, the benefits of monitoring typically are not apparent to the building owners, and thus they avoid the related cost. The authors hope that research funds from governments and foundations will be granted more to support monitoring campaigns. The need for this kind of funding was expressed recently within the document on Research Priorities for Geothermal Heating and Cooling [14].

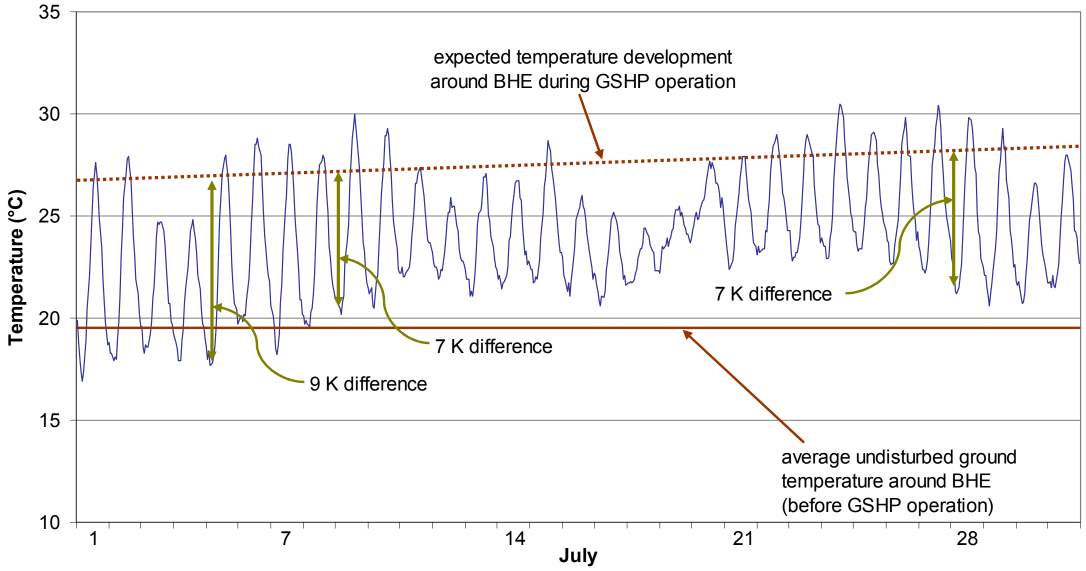

Figure 13: Hourly dry air temperature in July (data for Cadiz, from Spanish Meteorological Service) and ground temperatures in undisturbed situation and during GSHP operation (cf. [13])

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