ECONOMIC ASPECTS OF THERMAL RESPONSE TEST – ADVANTAGES, TECHNICAL IMPROVEMENTS, COMMERCIAL APPLICATION

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ABSTRACT

Since the first application of mobile Thermal Response Test in 1995, and the introduction to Germany 10 years ago, this tool has proven its capability in assisting correct sizing of larger borehole heat exchanger systems. The optimization of the methodology, targeting simple, routine application and software-based evaluation, has broadened the range of applications substantially.

This paper present the current status of modern, commercial TRT technology and application. UBeG has not only collected ample experience with ten years of own testing and development, but has exported equipment and expertise to several European countries and to the Far East. Feedback from this use of TRT equipment and evaluation tools now complements the experiences from the own work. General limitations to the test method have been experienced just like ways to overcome some of them, and will be discussed. Statistical evaluation of all the TRT results collected, in combination with parameter studies, allowed to assess the economic advantage of having reliable ground data for the design of borehole heat exchangers.

1. INTRODUCTION

The knowledge of underground thermal properties is a prerequisite for correct design of borehole heat exchangers (BHE). The most important parameter is the thermal conductivity of the ground. Since the mid 1990s a method has been developed (cf. Eklöf & Gehlin, 1996, and Austin, 1998) and refined to determine the underground thermal properties on site, and mobile equipment for these measurements has been built in several countries. In Germany, the first tests have been conducted in summer 1999 (Sanner et al., 1999). Few years later, Sanner et al. (2005) could already report TRT equipment operational in at least 12 countries world-wide. Advertisements from various companies in technical publications (like *bbr* or *Geothermische Energie*), at least in Germany, show the fully commercial character the TRT has achieved in the meantime.

The general layout of a TRT and an example of modern equipment (3rd generation UBeG GeRT) is shown in fig. 1. For good results, it is crucial to set up the system correctly and to minimize external influences. Those can result either from the power source (e.g. fluctuations of voltage in the grid), or from climatic influences, affecting mainly the connecting pipes between test rig and BHE, the interior temperatures of the test rig, and sometimes the upper part of the BHE in the ground. Longer test duration allows for statistical correction of power fluctuations and climatic influence, and results in more trustworthy evaluation. The small size of the current rigs allows for easy transportation directly to the top of the BHE, and thus short pipe connections for reduced external influence.

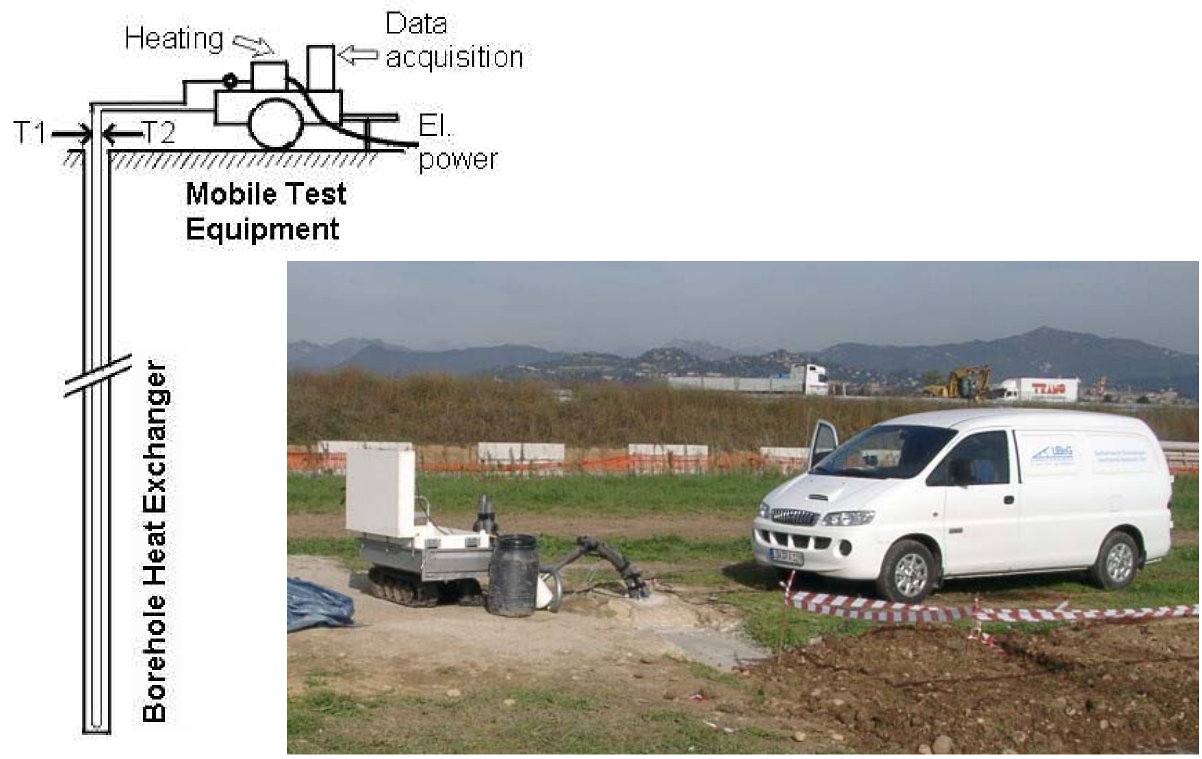

Figure 1: Schematic of TRT and photo of compact test rig (3rd generation UBeG GeRT), to be moved on a small crawler and transported in a van (example of rig from Germany transported to a test site in Northern Italy)

Not in all hydrogeological situations a TRT can be performed successfully. A limitation is the amount of groundwater flow. Because the thermal conductivity obtained includes convection/advection effects, with high groundwater flow[1] the thermal conductivity *sensu strictu* becomes masked, and the values can typically not be used for design of BHE plants (Chiasson et al. 2000, and Gehlin, 2002, discuss these limitations). A useful method to check for excessive groundwater flow in the standard line-source evaluation is the step-wise evaluation with a common starting point and increasing length of data-series. This method also shows if other external factors (weather, unstable power for heating, etc.) are disturbing the measurement. However, it allows only for rejecting a test on a site not suitable for it (after it was performed). In some cases, advanced evaluation methods can help to achieve a result nevertheless. In order to determine the thermal conductivity also under groundwater flow conditions, Witte & van Gelder (2006) have proposed and demonstrated a method using several heat injection/extraction pulses at different power levels, and evaluation with numerical parameter estimation.

An even more problematic kind of groundwater influence is groundwater flowing upwards or downwards in the borehole annulus. This may occur in open boreholes (standard in Scandinavia), but also in poorly grouted BHE or in those backfilled with sand. In combination with confined aquifers or other vertical pressure differences this leads to tests which cannot be evaluated at all, as all heat injected is quickly carried away. The thermo-syphon effect discussed by Gehlin (1998) is similar, but less pronounced, as it mainly comprises of convection in non-grouted boreholes induced by the temperature differences during operation.

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[1] The groundwater flow considered here is not the simple velocity (the time a water particle travels from one point to another, e.g. in m/s), but the Darcy-velocity, which is a measure for the amount of water flowing through a given cross-section in a certain time ($m^3/m^2/s$, resulting also in m/s). The Darcy-velocity thus depends both on the porosity and the velocity.

2. TRT EQUIPMENT (GeRT) AND APPLICATION

Over the period of almost a decade, the test equipment used by UBeG has been continually improved, both for accuracy and for ease of handling (fig. 2). From a trailer filled with heating device and a larger electrical cabinet for power and control (1^{st} generation) the way led to a smaller test comprising of two boxes, one for control and one for the heating/hydraulic part. These two boxes could be installed in a smaller trailer or a van. Two 2^{nd} generation GeRT rigs have been exported to the Far East, to China and to South Korea. Since 2006 the 3^{rd} generation GeRT contains all parts in one water-tight box. This box can be lifted onto a motor crawler platform and thus moved in and out of a van and to any location even in rough terrain by one person only. As this type meanwhile has been built in series, improvements in particular to the electrical part have been included when becoming available.

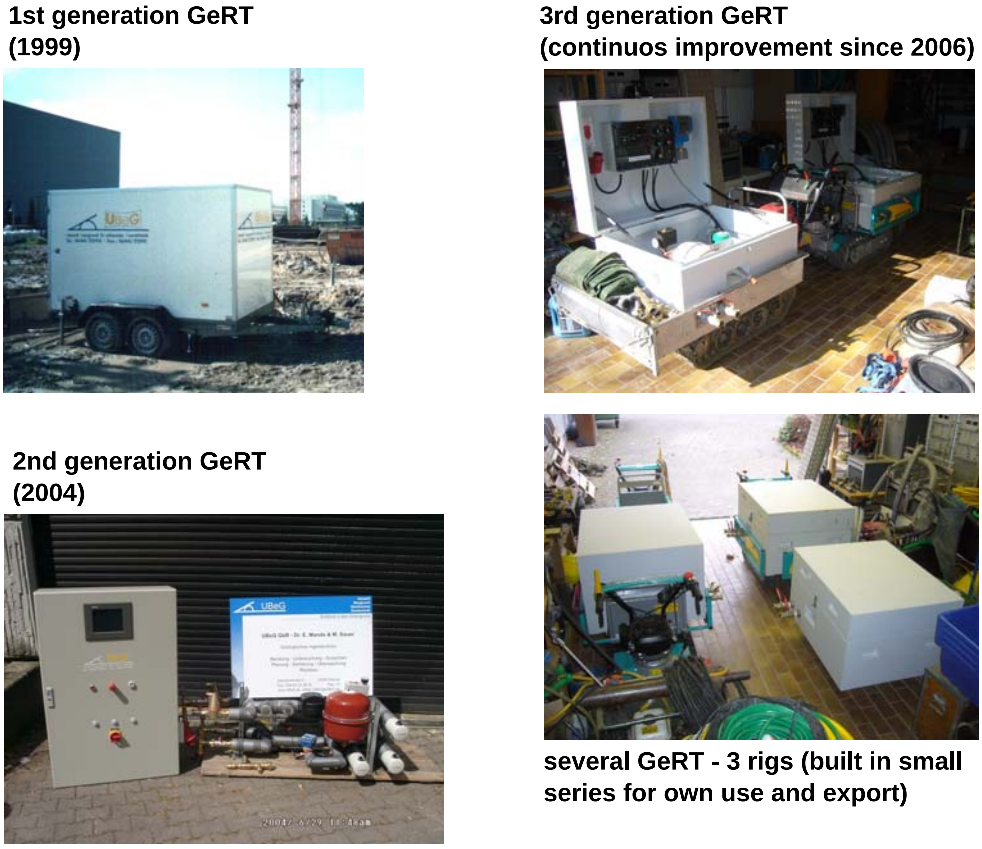

Figure 2: The currently existing 3 generations of GeRT (UBeG-TRT-rig)

GeRT-3 units have been exported to several European countries (fig. 3); this goes always with the necessary training, evaluation software, etc. UBeG has developed own software (GeRT-Cal), based on the line-source approximation and also allowing for some validity check and parameter estimation (in the most recent version). Experience from the own application by UBeG as well as feedback from the users abroad has resulted in an easy-to-use, reliable and reasonably accurate device for TRT. The target of development was the routine commercial use, with the aims to reduce cost and time (while keeping the net test time >48 h) and to secure reproducible results.

As the GeRT-3 is mounted onto a motor crawler, this allows one single person to unload the equipment from a smaller van, to bring it to the BHE, to connect it, to start the test, and later to retrieve test equipment and data. The test duration is >48 h, so ideally the unit arrives on site before noon, is set up and started, and is retrieved in the afternoon of the second day after.

When choosing a weekend, even 3 days test duration can be achieved easily, by starting the test on Friday and retrieving the unit on Monday. For tests on already operating construction sites, another advantage of weekends is given by the fact that typically there is a break in work on sites with drilling or construction, minimising external disturbances.

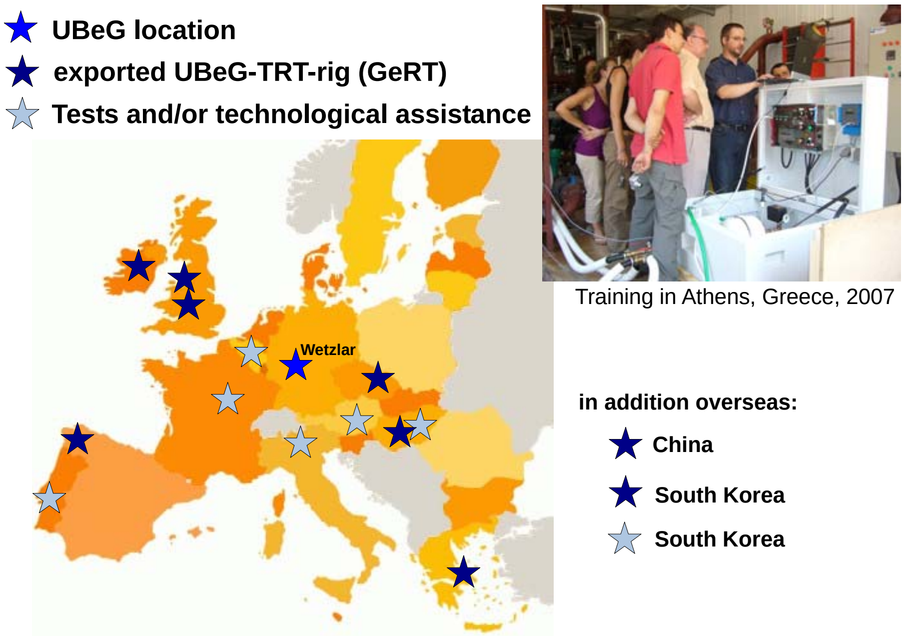

Figure 3: Map of EU member states showing countries where UBeG-TRT-rigs have been exported to, and where technological assistance was provided or tests were performed by UBeG directly (outside Germany)

In order to achieve usable results even in cases where the limitations mentioned in the introduction may apply (e.g. groundwater influence), some additional data collection is performed. With small sensors, temperature logs can be recorded inside the BHE. UBeG routinely runs the following logs

- one log before starting the test, in order to see the undisturbed ground conditions,
- two logs after the test has been stopped (one log <1 hour after stop, the other about 1 hour later).

Measuring during operation of the test is not possible with these sensors.

The temperature logs help to identify zones of higher or lower heat transport along the borehole axis. As the TRT results give an average value for thermal conductivity over the whole BHE length, the temperature logs allow some vertical differentiation. In fig. 4 a test is shown where a strong groundwater influence can be seen in a very narrow zone (sand on top of silt). After 1 hour almost all temperature increase has vanished in the high permeable zone. Nevertheless, in this case the value for thermal conductivity is not much affected, because the permeable layer is not thick and thus the actual amount of water relatively low.

3. ECONOMIC EVALUATION OF TRT APPLICATION

The consequences of under- or overestimating ground thermal conductivity are summarized in fig. 5. However, concerning the TRT, in discussions with costumers typical questions are:

- How much is the chance that I can save money with TRT results?
- Is a TRT also economic for smaller projects?

The reason that a TRT allows for a design based on actual knowledge of the ground parameters instead of estimations is not so often considered.

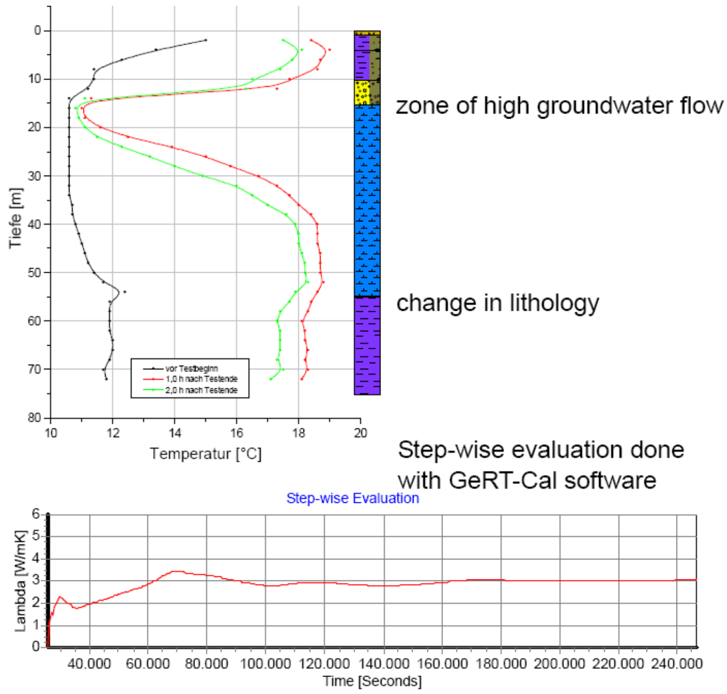

Figure 4: TRT with groundwater flow in a narrow zone at ca. 15 m depth; temperature logs inside BHE and step-wise evaluation of thermal conductivity using GeRT-Cal

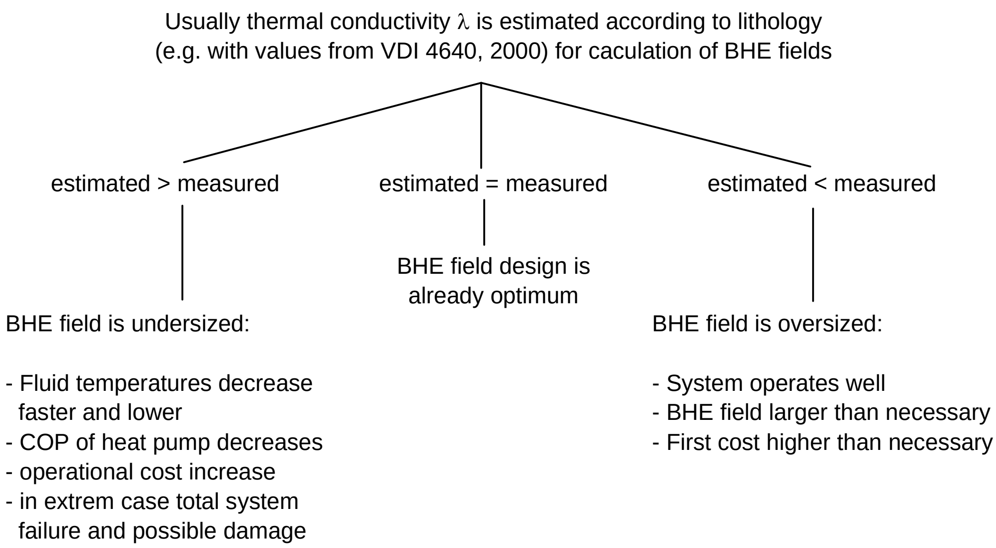

Figure 5: Possible consequences of error in estimated thermal conductivity values

To answer the economic question, a statistical evaluation of tests and a parameter study has been performed. From among the hundreds of test results meanwhile available to UBeG, those were selected where values had been estimated from expected lithology in pre-feasibility studies, and later been measured with TRT (86 samples at the time the study was done, see fig. 6). The evaluation revealed the following:

- In 25% of the cases the estimated values have been higher, which means that the TRT was required to adjust the design to a sound level.
- In 65% of the cases the TRT allowed for cost savings, where the underground conditions were better than expected.
- Only in 10% the measurement did yield the estimated value with some accuracy.

In total, a deviation higher than ±0.5 W/m/K was found in 45% of the cases.

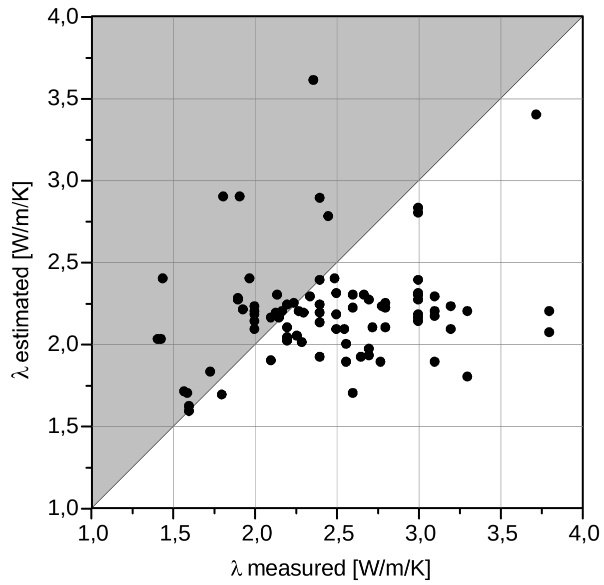

Figure 6: Comparison of estimated and measured values for ground thermal conductivity (86 values, see text)

The parameter study was done for evaluating the impact on operational cost (in case of over-estimation/undersizing) and first cost (in case of underestimation/oversizing); details for the first study are given in Sauer et al. (2007). The base case considered was a small commercial application with 50 kW heating demand, no cooling, and a ground dominated by shale, with a thermal conductivity of λ = 2.2 W/m/K (a rather frequent situation in Germany). The BHE should reach a length of about 100 m, otherwise the number of BHE should be changed. In order to study also smaller installations, some additional calculations for heating loads down to 30 kW have been performed. EED was used for the design calculations.

For the base case, a layout of 12 BHE slightly longer than 100 m was found sufficient. The efficiency of the GSHP system with that design was set to SPF = 4.0, a good value achieved in systems with a well-designed heat distribution at low supply temperature. Then the resulting fluid temperatures with lower thermal conductivity values were calculated, and the change of SPF due to lower evaporating temperatures was determined using COP-curves from heat pump manufacturers. The results are shown in fig. 7; according to the different input data, the results vary by ±15 %

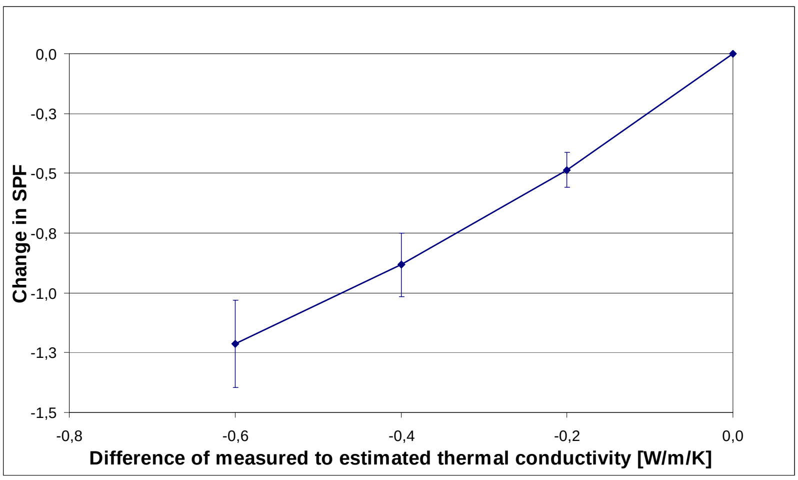

Figure 7: Effect of overestimation of thermal conductivity on the SPF for a sample 50 kW GSHP, average result and span of variation (see text)

With the SPF-values it is possible to calculate the required annual electricity consumption and energy cost. In fig. 8 the incremental cost compared to the base case are plotted over the thermal conductivity (base case λ = 2.2 W/m/K), for plants with 50 kW and with 35 kW heating capacity. In the same manner it is possible to investigate the effect of underestimated thermal conductivity: The number and length of BHE required to achieve the same fluid temperature development than in the base case with λ = 2.2 W/m/K is calculated for higher thermal conductivity. The amount of BHE that could be saved directly converts (with average drilling and material cost) into immediate savings in the investment. Fig. 9 shows that development for examples with 30, 40 and 40 kW.

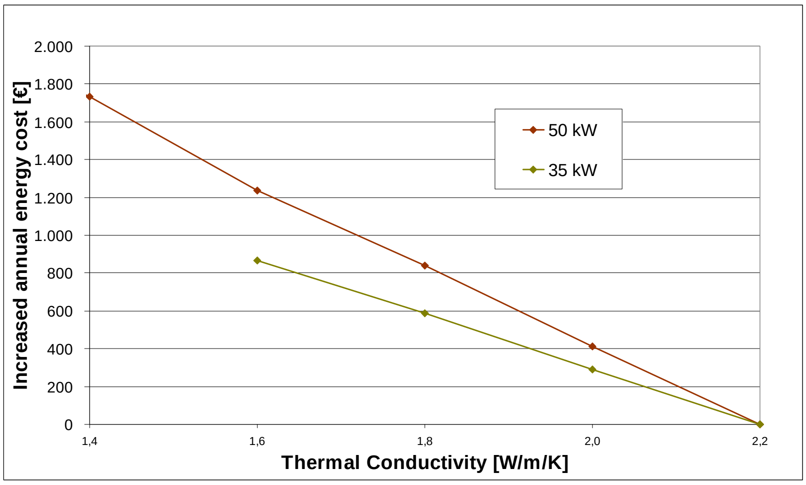

Figure 8: Effect of overestimation of thermal conductivity on the annual energy cost for sample 35 kW and 50 kW GSHP (see text)

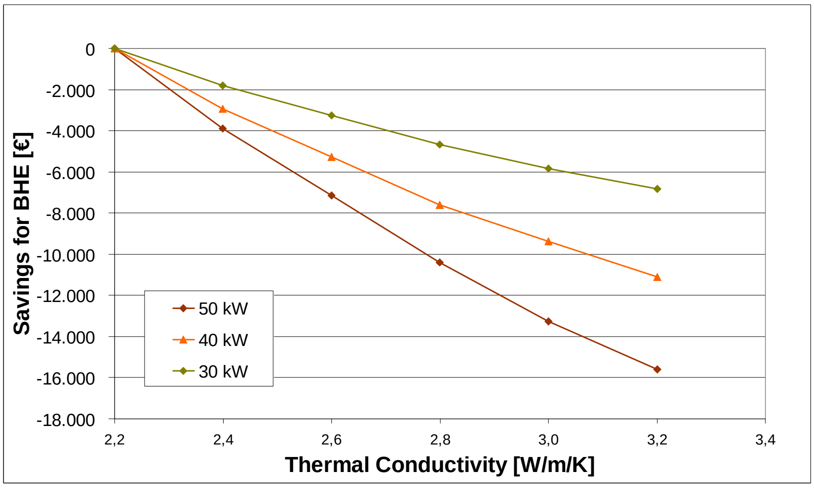

Figure 9: Effect of underestimation of thermal conductivity on cost for necessary BHE-field for sample 30-50 kW GSHP (see text)

It should be considered further that a substantial undersizing of the BHE field does not only result in decreasing fluid temperatures and consequently lower SPF, but also has an effect on the heat pump heating capacity. In the end the heat load can no longer be met by the heat pump in spite of excessive electric power consumption. The heat pump eventually will fail (probably when it is most needed) and the building will be without proper heating.

In a second study, the annual operating cost and first-cost savings for the example with 50 kW heating capacity have been calculated in more detail (hence the values in figures 8 and 9 and in tables 1 und 2 differ slightly). Table 1 shows that due to a reduced seasonal performance factor (SPF), the annual operation cost can increase by more than 1000 € with only 0.4 W/m/K over-estimation of thermal conductivity. In case of under-estimation of about 0.4 W/m/K, the first cost for BHE is about 10’000 € higher than necessary (table 2). In both cases the cost for TRT (in the order of 3000-3500 €) would be well justified.

Table 1: Incremental annual electricity cost due to undersizing, calculated for sample GSHP 50 kW (see text), for estimated thermal cond. $\lambda = 2.2$ W/m/K

measured therm. conduct. [W/m/K]	SPF [-]	annual power cons. [MWh/a]	annual electricity cost [€/a]	incremental cost [€/a]
2.2	4.0	26.3	3’945	-
2.0	3.5	30.0	4’500	555
1.8	3.1	33.9	5’085	1’140
1.6	2.8	37.5	5'625	1’680

Table 2: Incremental investment cost due to oversizing, calculated for sample GSHP 50 kW (see text), for estimated thermal conductivity $\lambda = 2.2$ W/m/K

measured therm. conduct. [W/m/K]	necessary length for 12 BHE [m]	total BHE length [m]	first cost of BHE [€]	incremental cost [€]
2.2	102.2	1’226.4	91’980	-
2.4	96.7	1’160.4	87’030	4’950
2.6	91.5	1'098.0	82’350	9’630
2.8	86.7	1’040.4	78’030	13’950

4. CONCLUSIONS

TRT has developed into a standard tool for investigating ground thermal parameters for the design of BHE plants. The concept has proven reliable and results are reproducible. A pre-requisite therefore is high accuracy in the temperature sensing, diligent test setup and operation, and sufficiently long test time. The standard line-source-based evaluation method is sufficient in most cases and can be enhanced by step-wise evaluation. Parameter estimation with numerical modelling may be required in case of external influences, it also can yield additional accuracy and information if required.

Further development of TRT points in two directions:

- “Quick and dirty” tests with lower cost, but reduced accuracy for routine checking in quality control during the construction of BHE-fields, or for design of small systems in residential houses. The ideas for doing TRT while drilling (Tuomas et al., 2003; Gustafsson & Nordell, 2006) also point in that direction.
- More sophisticated tests with additional information, e.g. vertical thermal conductivity distribution along the BHE, and increased accuracy of the sensors, in particular for use in R&D.

The current approach with the UBeG TRT (GeRT) is to find a compromise; reasonably quick and accurate tests at affordable cost, with some additional information if required,

A parameter study has yielded some cost for under- and overestimation of thermal conductivity. With this cost data and the statistical evaluation of estimated and measured data in 86 projects, the chance to save money by performing a TRT can be assessed.

When accepting all cases with a deviation of less than ±0.1 W/m/K as accurate, the average value of overestimation of thermal conductivity from the cases plotted in fig. 6 can be determined to $\Delta\lambda$ = -0.45 W/m/K, and the average value for overestimation to $\Delta\lambda$ = 0.61 W/m/K. Hence for the sample case of 50 kW, there is a probability of about 25 % to have an increase in annual operational cost in the order of 1200 €/a (or 12'000 € in 10 years), and a probability of ca. 65 % to have invested about 14'000 € more than necessary.

With the current prices for TRT, the lower capacity limit for allowing a TRT to become economic will be in the order of 30 kW heating.

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