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SUSTAINABILITY ASPECTS OF GEOTHERMAL HEAT PUMPS

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ABSTRACT

For geothermal heat pumps (GHPs) the issue of sustainability concerns the long-term production stability of the various heat sources. In the horizontal systems the heat exchanger pipes are buried at shallow depth; for combined heating/cooling by GHPs the heat balance (in/out) is given by the system design itself. In the case of groundwater-coupled GHPs the resupply of fluid is secured by the hydrologic cycle.

The situation with borehole heat exchanger (BHE)-coupled GHP systems is different.

BHE based geothermal heat pump(HP) systems operate, if properly designed reliably on the long term. This has been proven by experimental and theoretical investigations (numerical modeling). The results of modeling for a single BHE show that the long-term performance of the BHE/HP system stabilizes, relatively to initial conditions, at a somewhat lower but practically constant level after the first few years. Thus sustainable operation can be achieved.

The BHE operation creates a local heat sink and thus strong temperature gradients in the BHE vicinity which in turn leads to heat inflow, directed radially towards the BHE, to replenish the deficit created by the heat extraction. This heat flow density attains, compared to the terrestrial heat flow (80 – 100 mW/m^2), rather high values (up to several W/m^2).

After shut-down of BHE operation thermal recovery begins, strong in the beginning and decreasing asymptotically afterwards. Model simulations with different operation/recovery periods show that the recovery duration roughly equals that of operation: e.g. for 30 years of BHE operation the thermal recovery of the ground needs 30 years.

SUSTAINABILITY OF GHP SYSTEMS

The original definition of sustainability goes back to the Bruntland Commission (1987; reinforced at the Rio 1991 and Kyoto 1997 Summits):

"Meeting the needs of the present generation without compromising the needs of future generations".

In relation to geothermal resources and, especially, to their exploitation for geothermal energy utilization, sustainability means the ability of the production system applied to sustain the production level over long times. Often the resources are taken into production (of the reservoir fluid as the heat carrier), mainly to meet economic goals like a quick pay-back of investments for exploration and equipment, in such a way that reservoir depletion is the result. There are numerous examples for this worldwide, the most prominent is the vapor-dominated field of The Geysers/USA. Sustainable production of geothermal energy therefore secures the longevity of the resource, at a lower production level.

A definition of sustainable production from an individual geothermal system has bees suggested recently (ORKUSTOFNUN WORKING GROUP, 2001):

"For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, below which it will be possible to maintain constant energy production from the system for a very long time (100 – 300 years)".

The definition applies to the total extractable energy (=the heat in the fluid as well as in the rock) and depends on the nature of the system but not on load factors or utilization efficiency. The definition does also not consider economic aspects, environmental issues nor technological advances, all of which may be expected to change with time.

In the case of GHPs the issue of sustainability concerns the various heat sources. In the horizontal systems the heat exchanger pipes are buried at shallow depth; the longevity of their smooth operation is guaranteed by the constant heat supply from the atmosphere by solar radiation. In the case of combined heating/cooling by GHPs the heat balance (in/out) is given by the system design itself. In the case of groundwater-coupled GHPs the resupply of fluid is secured by the hydrologic cycle (infiltration of precipitation) and the heat comes either “from above” (atmosphere) and/or “from below” (geothermal heat flow); the relative proportions depend on aquifer depth. This leads to a ± constant aquifer temperature all over the year without any significant seasonal variation. Any deficit created by heat/fluid extraction is replenished by the (lateral) groundwater flow.

The situation with BHE-coupled GHP systems is different. During heat extraction operation the BHE evolves more and more to a heat sink. False design, especially with forced extraction rates (several tens of W per meter BHE length, in low thermal conductivity materials like dry gravel) can lead to freezing of the surrounding ground and thus to system collapse. Therefore the conditions by which a reliable operation can be secured also on the long term (i.e. sustainable operation) need to be established. Several such attempts have been published in the literature; one of the first –and rather complete, supported by theory and experiments– such studies will be summarized below.

GHP SUSTAINABILITY WITH BHE

The question of sustainability of GHPs in general and of BHE coupled HPs boils down to the question: for how long can such systems operate without a significant draw-down in production, i.e. reaching a level which is beyond economic viability. Therefore the long-term production behavior of BHE based GHPs needs to be addressed.

The oldest BHE installations are not older than about 15 - 20 years, thus experience and especially detailed studies on long-term performance (decades) are lacking. Therefore the question arises about the reliability of such systems on the long run. Along the same line come the questions: can such systems operate in a sustainable manner? Is the shallow geothermal resource renewable? I.e. does the ground recover thermally after shut-down of the BHE heat extraction operation which is customarily designed to run over a few decades?

To answer these questions a combined theoretical/experimental approach has been followed to establish a solid, verified base for the confirmation of reliable long-term performance on one hand, and to clarify the terms of renewability on the other.

Study of long-term performance

The verified base to confirm the reliability of BHE/HP systems on the long term has been elaborated by combining field measurements with numerical model simulations. For this basic study, a single BHE was treated. The approach used is described in detail in EUGSTER and RYBACH (2000).

An extensive measurement campaign has been performed at a commercially installed BHE system in Elgg near Zurich, Switzerland. Object of the study is a single, coaxial, 105 m long BHE, in use since its installation (1986) in a single family house. The BHE stands isolated and supplies a peak thermal power of about 70 W per m length. By this, the BHE is rather heavily loaded. Thus the installation is by no means a particularly favorable example.

The aim of the measurement campaign is the acquisition of ground temperature data in the surroundings of the BHE as well as of operational parameters of the entire system. For this purpose, 105 m long measuring probes were installed in boreholes at 0.5 and 1.0 m distance from the BHE, backfilled with a bentonite/cement mixture like the BHE itself. Both boreholes have been equipped in 1986 with buried temperature sensors at 1, 2, 5, 10, 20, 35, 50, 65, 85, and 105 m depth. The use of pre-aged Pt100 sensors, in combination with a high-resolution multimeter (DATRON 1061 A), provides maximum long-term stability (± 0.1 K accuracy, ± 0.001 K precision) over the entire measurement period. In addition to the ground temperatures, the atmospheric temperature variations and all parameters relevant to the operation for the entire system (hydraulic system flow rates, circuit temperatures, power consumption of the HP etc.) have also been recorded in 30 minute intervals.

The first campaign extended over the years 1986-1991 and supplied a unique data base (details in EUGSTER, 1991). The ground temperature results are displayed in Figure 1. Atmospheric influences are clearly visible in the depth range 0 - 15 m; below 15 m the geothermal heat flux dominates. It is obvious that in the near field around the BHE the ground cools down in the first 2 - 3 years of operation. However, the temperature deficit decreases from year to year until practically a new stable thermal equilibrium is established between BHE and ground, at temperatures which are some 1 - 2 K lower than originally. (This temperature deficit is characteristic of the measurement site with typical Tertiary "Molasse" formations).

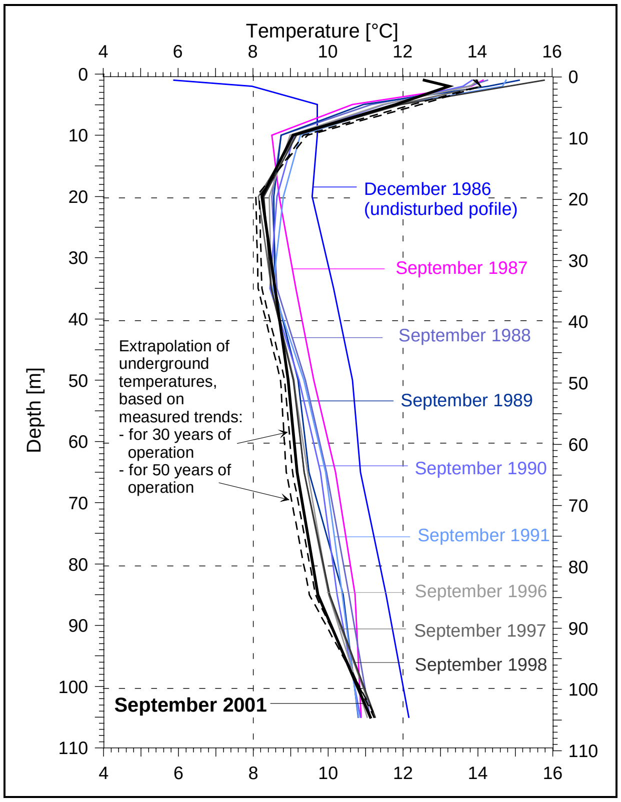

Figure 1. Measured ground temperature profiles at a distance of 1m from the BHE in Elgg. Curve "December 1986" marks the undisturbed profile at the start of the first heating season. The subsequent curves show the conditions after winter heat extraction and summer recovery, just before the start of the next heating season. For extrapolations into the future see text.

In the autumn of 1996 (i.e. after 10 years of BHE operation) the measurement system was restarted and the ground temperatures before the start of a new heating season ("September") have been measured in subsequent years. Due to the forced aging of the Pt100 sensors the high quality of temperature measurement has been maintained and the repeatability of the measurements is still better than ± 0.01 K. The new temperature profiles ("September 1996", "September 1997", "September 1998", and "September 2001", Figure 1) show only small shifts towards lower temperatures, thus demonstrating that a quasi-steady equilibrium has been reached after the first few years. From 1996 to 2001 the ground temperatures fluctuate within a limited interval of about 0.5 K, depending on the specific annual heating demand. For a correctly designed BHE system in the absence of groundwater and with borehole depths of this order this behavior corresponds to our theoretical expectations. Extrapolations for 30 and 50 years of operation, based on the measured temperature trends, are also shown on Fig. 1.

These measurements represent a unique data base which in turn was used to validate a numerical model. For this, the results of the first measurement campaign (1986-1991) were used to calibrate a 2D numerical code (COSOND, in cylindrical coordinates). The code treats diffusive heat transfer in the ground, advection in the BHE, heat transfer between the BHE fluid and the wall materials, as well as heat transfer between atmosphere and ground. The program flow is controlled by a load profile which contains the atmospheric temperatures and the operational data of the heat pump. Details are given in GILBY and HOPKIRK (1985) and EUGSTER (1991). First, the temperature curve "September 1996" was predicted by simulation and in turn compared with the measured curve. The agreement was excellent; the deviations were within measurement error (± 0.1 K), see RYBACH and EUGSTER (1998). The excellent agreement between measured an calculated time histories at a number of specific points in the underground gives confidence to extrapolate future trends and situations by modeling.

These computer simulations have now been recalculated using an adapted load profile based on the atmospheric temperatures of the years 1991-1997 actually measured in the meantime at a nearby meteorological station (Tänikon/TG) as well as on the home-owner's records about heat pump operation times. The model grid had 11'700 grid cells in a model volume of $2x10^6$ m^3 (for details see EUGSTER and RYBACH, 2000).

The operation of the Elgg BHE plant has been extrapolated for additional 19 years to a final period of 30 years (1986 - 2015), see Figure 5. The load profiles for these simulation runs are based on the new Swiss Standard Climatic Database (METEONORM, 1997).

Thermal conditions around a BHE

The transient thermal conditions around a BHE in operation are very complex. Several processes are superimposed:

- a heavy cooling-down and a subsequent rewarming of the immediate vicinity of the BHE up to some 10 cm during a operational cycle (hourly cycle);
- the dissemination of this cooling and rewarming period up to several meter as a funnel-like temperature effect during a seasonal operation (yearly cycle);
- a large-scale, but only minimal cooling-down of the surrounding underground up to a distance of several 10's of meters during the full life cycle of the BHE (30-years-cycle);
- both the horizontal and vertical heat fluxes increase around the BHE. The massive cooling

down of the BHE vicinity enlarges the heat flows from the atmosphere and from the underground.

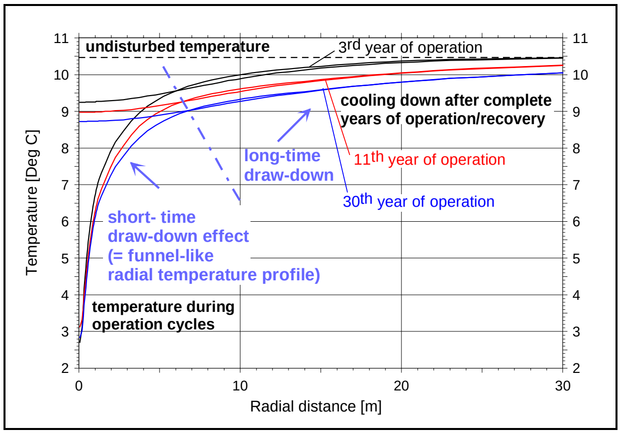

Figure 2. Funnel-like temperature distribution and long term cooling-down around a BHE. The short term and the long term influences are well documented.

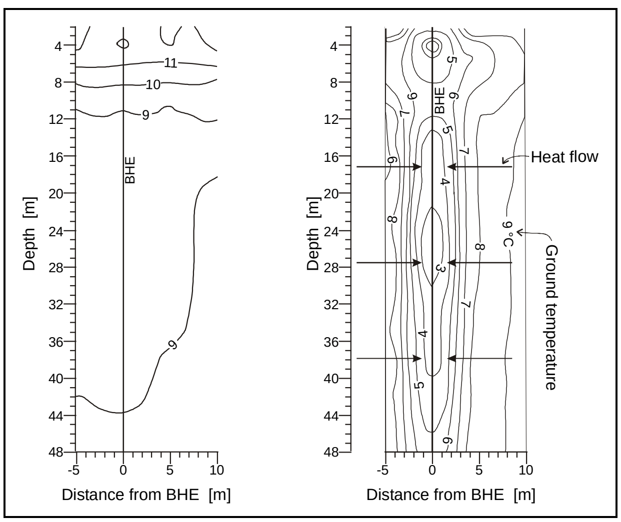

Figure 3. Measured temperature distribution in the ground at the beginning of the monitoring period (left, on 1.10.1986, after a total of ca. 2 hours of test operation) and at the end of the first heating season (right, on 1.5.1987), Schwalbach GSHP test plant, Germany (after RYBACH and SANNER, 1999).

These pure conductive processes are rather complicated and visualized in Figure 2. But in free nature, flowing groundwater and - in saturated formations - water vapor diffusion processes add their effects to this complex system.

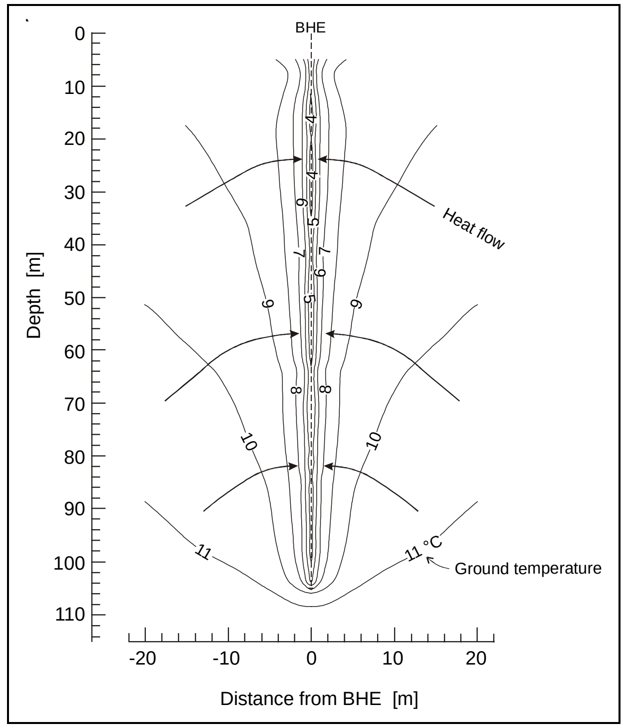

Figure 4: Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg/ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m^2.

The operating BHE creates a heat sink in the ground which has cylindrical shape. The isotherms are, after a certain operational time, concentrated near the BHE. Figure 3 shows the measured temperature distribution around a 50 m long BHE, at the German test plant at Schöffengrund-Schwalbach near Frankfurt/Main.

Here a 50-m-BHE was surrounded by a total of 9 monitoring boreholes at 2.5, 5 and 10 m distance, also 50 m deep. Temperatures in each hole and at the BHE itself were measured with 24 sensors at 2 m vertical distance, resulting in a total of 240 observation locations in the underground. This layout allowed to investigate the temperature distribution in the vicinity of the BHE, as shown in Figure 3. The influence from the surface is visible in the uppermost ca. 10 m (see also Figure 1), as well as the temperature decrease around the BHE at the end of the heating season. The latter creates strong temperature gradients in the BHE vicinity which in turn leads to heat inflow, directed radially towards the BHE, to replenish the deficit created by the heat extraction. This heat flow density attains, compared to the terrestrial heat flow (80 – 100 mW/m^2), rather high values (up to several W/m^2). A similar situation is depicted in Figure 4 from a site in Elgg/ZH, Switzerland.

Thermal recovery

The long-term behavior of the single BHE-HP system was further investigated by numerical modeling. The results of the simulation runs show on one hand the expected decrease of the yearly temperature deficit and on the other hand an increasing volume around the BHE which is affected by the cooling (see Figure 5).

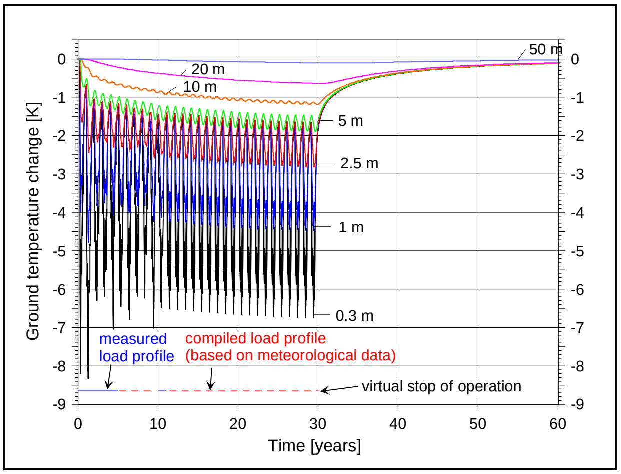

Figure 5. Simulated ground temperature changes of the BHE at Elgg relative to the undisturbed situation in December 1986 over 30 years of operation and 30 years of recovery.

After shut-down of heat extraction, regeneration of the ground begins. During the production period of a BHE, the draw-down of the temperature around the BHE is strong during the first few years of operation. Later, the yearly deficit decreases asymptotically practically to zero. During the recovery period after a virtual stop-of-operation, the ground temperature shows a similar behavior: during the first years, the temperature increase is strong but tends with increasing recovery time asymptotically towards zero (EUGSTER and RYBACH, 2000). The time to reach nearly complete recovery depends on how long the BHE has been operational. Principally, the recovery period equals the operation period. This is shown in Figure 6 for different distances from the BHE and for different final temperature deficits.

In summary, the measurements and model simulations prove that sustainable heat extraction can be achieved with such systems. The installation in Elgg supplies on the average about 13 MWh per year. In fact, the BHE's show stable and reliable performance which can be considered renewable. Reliable long-term performance provides a solid base for problem-free application; correct dimensioning of BHE gives great scope of widespread use and optimization.

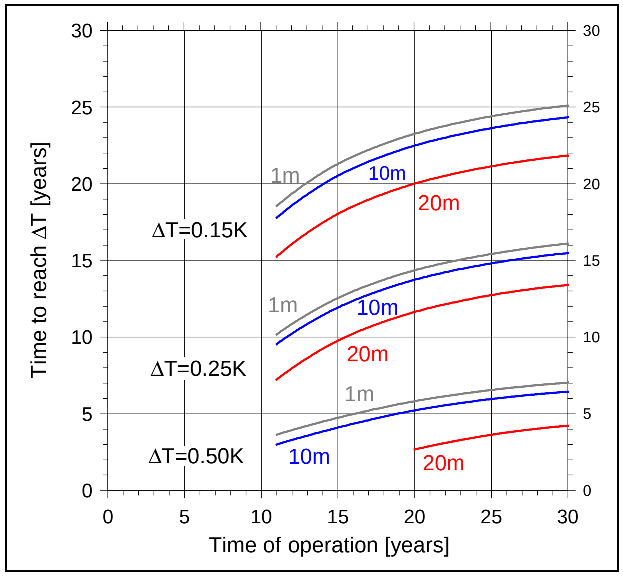

Figure 6. Duration of recovery period to reach a minimal final temperature deficit (ΔT) of 0.5, 0.25 and 0.15K for different distances from the BHE as a function of the time of operation.

The above investigations have been performed for a single BHE. Similar studies have now been initiated for BHE groups in regular as well as irregular patterns.

CONCLUSIONS

Sustainability aspects of GHP systems have been addressed, with emphasis on Borehole Heat Exchanger (BHE)/heat pump (HP) systems. They prove to be a feasible way to tap shallow geothermal resources which, located directly below our feet, represent a unique, ubiquitous and therefore enormous geothermal potential. They operate reliably also on the long term. This has been proven by experimental and theoretical investigations: data of an extensive measurement campaign over several years were used to calibrate a numerical modeling code. The results of modeling with this code for a single BHE show that the long-term performance of the BHE/HP system stabilizes, relatively to initial conditions, at a somewhat lower but quasi-steady level after the first few years.

Thus sustainable operation can be achieved. The ground around the BHE behaves in the following way: the long-term heat extraction causes heat depletion/temperature decrease. The temperature drop (which decreases with radial distance from the BHE) is significant after the first years of operation but the ground temperature decrease slows down very much with increasing time.

The BHE operation creates a local heat sink and thus strong temperature gradients in the BHE vicinity which in turn leads to heat inflow, directed radially towards the BHE, to replenish the deficit created by the heat extraction. This heat flow density attains, compared to the terrestrial heat flow (80 – 100 mW/m^2), rather high values (up to several W/m^2).

After shut-down of BHE operation thermal recovery begins, strong in the beginning and decreasing asymptotically afterwards. Model simulations with different operation recovery periods show that recovery duration roughly equals that of operation: e.g. for 30 years of BHE operation the thermal recovery of the ground needs 30 years.

The basic studies about long-term performance presented here apply to a single BHE. Similar studies are underway for BHE groups/patterns.

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