Geothermics 39 (2010) 365–369

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Sustainability aspects of geothermal heat pump operation, with experience from Switzerland

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ARTICLE INFO

Article history:
Received 15 October 2009
Accepted 18 August 2010

Keywords:
Geothermal
Borehole heat exchanger
GHP data base
Ground thermal recovery
Switzerland

ABSTRACT

Geothermal heat pumps are the key to the utilization of the ubiquitous shallow geothermal resources. Theoretical and experimental studies, performed in Switzerland over several years, have established a solid scientific base of reliable long-term operation of borehole heat exchanger-coupled heat pump systems. Proper design, taking into account local conditions like ground properties and building needs, ensures the sustainability of production from systems with single and multiple borehole heat exchangers. Long-term experience acquired at operational objects confirms the predictions.

1. Introduction

Geothermal energy is often labelled as renewable and sustainable. It is, therefore, listed together with solar, wind and biomass alternative energy options in governmental R&D programs. The sustainability attribute applies only with certain restrictions, which must be addressed in a fully objective manner.

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".

It is generally accepted that the principle of sustainability relies on three basic pillars: economy, ecology, society. Nowadays environmental, traditional and cultural aspects are often addressed and considered in sustainability discussions. Here we restrict the considerations to geothermal energy.

In relation to geothermal resources and, especially, to their exploitation, sustainability means the ability to sustain the production level over long periods of time. Sustainable production of geothermal energy therefore secures the longevity of the resource, at a lower than maximum possible production level. A definition of sustainable production from an individual geothermal system has been 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 not consider economic aspects, environmental issues or technological advances, all of which may be expected to change with time. The terms renewable and sustainable are often confused; the former concerns the nature of a resource and the latter applies to how a resource is utilized (for details see Axelsson et al., 2002).

In the following, sustainable production from geothermal heat pumps (GHP) will be addressed, first by theoretical and experimental investigations, then by experience with operating systems, and finally by considerations of future developments.

2. Geothermal heat pumps

Geothermal heat pumps (GHP) are ground-coupled heat pumps: they operate with subsurface heat exchanger pipes (horizontal or vertical), or with groundwater boreholes (Lund et al., 2003). Here 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 provided by the system design itself: replacement of heat

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doi:10.1016/j.geothermics.2010.08.002

extracted in winter by heat storage in summer. For 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" (terrestrial heat flow); the relative proportions depend on aquifer depth. This heat supply leads to a more or less constant aquifer temperature throughout the year without any significant seasonal variation. Any deficit created by heat/fluid extraction is replenished by the (lateral) groundwater flow.

Nowadays the GHP systems with borehole heat exchangers (BHE) are the most commonly used types. The question of sustainability of GHPs in general, and of BHE-coupled heat pumps boils down to the question: for how long can such systems operate without a significant drawdown in production, i.e. reaching a level which is economically not viable. Therefore the long-term production behavior of BHE-based GHPs needs to be addressed. In the following, experimental and numerical modeling studies are presented to answer the posed questions.

3. Field measurement campaign at Elgg, Canton Zurich (Switzerland)

For a significant market penetration of BHE/HP systems in Switzerland a proof of long-term reliable operation was needed. Therefore, a program of field measurements in conjunction with numerical simulations was carried out to confirm the long-term reliability of BHE/HP systems.

An extensive measurement campaign has been performed at a commercially operated BHE installation (heating alone) in Elgg near Zurich, staring with the heating season of 1986–1987. Object of the investigation is a single, coaxial, 105 m long BHE, in use since its installation (in 1986) in a single family house. The BHE stands alone and supplies a peak thermal power of about 70 W/m length. The BHE is rather heavily loaded, in a setting without groundwater flow. The installation is by no means a particularly favourable example, but the acquired data are unique, since many relevant parameters have been digitally recorded over several years.

The measurement campaign was designed to acquire 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 distances of 0.5 and 1.0 m from the BHE, backfilled with a bentonite/cement mixture like the BHE itself. Both probes are equipped with 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 1061A), provides reliable long-term data stability (±0.1 K accuracy, ±0.001 K precision). 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 been recorded at 30 min intervals.

The first measurement campaign extended over the years 1986–1991 (Eugster, 1991). The ground temperature results are displayed in Fig. 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 cooling (=temperature deficit) decreases from year to year until a new quasi-stable thermal equilibrium is established between BHE and ground, at temperatures, which are 1–2 K lower than the undisturbed temperatures. (This temperature deficit is characteristic of the measurement site with typical Tertiary "Molasse" formations.)

In the autumn of 1996 (i.e. after 10 years of BHE operation) the measurement system was restarted. Due to the forced ageing 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", Fig. 1) do not show any further significant shift towards lower temperatures, thus demonstrating that a quasi-steady equilibrium was reached after the first few years. The small differences between the profiles of subsequent years after, at least 3 years of operation, are a result of the different yearly heating demands which, given the unchanged living habits of the owners, are a function of the atmospheric temperature. In the following years 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 corresponds to the theoretical expectations.

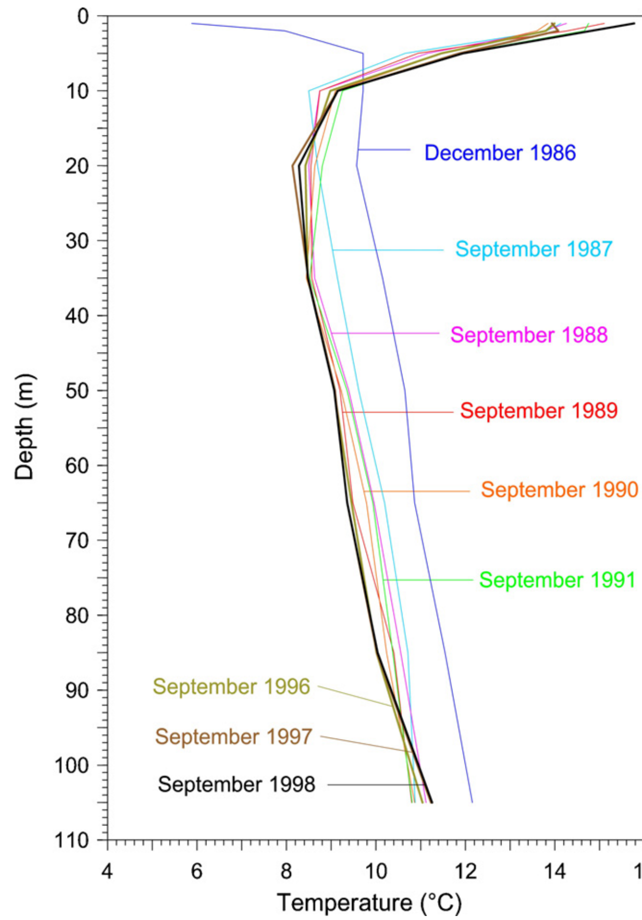

Fig. 1. Measured ground temperature profiles at a distance of 1 m from the BHE in Elgg. The December 1986 curve marks the undisturbed profile at the start of the first heating season. The subsequent curves show the conditions after winter heat extraction and summer recovery, just before the start of the next heating season (Eugster and Rybach, 2000).

These measurements represent an extensive data base, which in turn was used to validate a numerical model. 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). Details of the numerical model are given elsewhere (Rybach and Eugster, 1998).

The measured temperature histories at a number of specific points in the underground are used to calibrate the numerical model. The calibrated model can in turn be used to forecast the future behavior of the BHE/HP system.

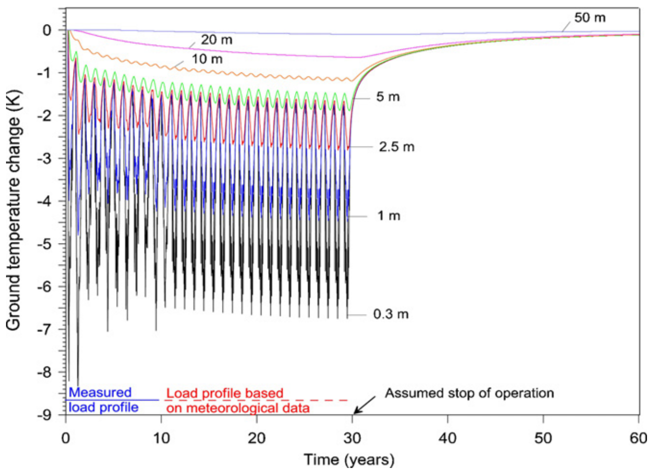

Fig. 2. Simulated ground temperature changes of the BHE at Elgg relative to the undisturbed situation in December 1986 over 30 years of operation and 30 years of recovery (Rybach and Eugster, 2002).

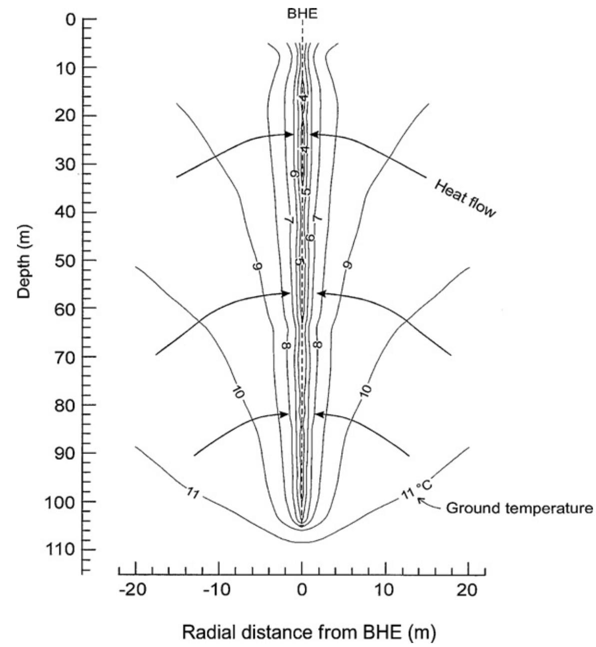

Fig. 3. Calculated isotherms around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg/ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m^2 (Rybach and Eugster, 2002).

4. Performance predictions by numerical simulations

The data collected during the first measurement campaign (1986–1991) were used to calibrate a two-dimensional 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 borehole wall materials, as well as heat transfer between atmosphere and ground. The program flow in COSOND is controlled by a load profile, which includes the atmospheric temperatures and the operational data of the heat pump. Details are given in Eugster (1991). Ground temperatures over the first 5 years of measurement were fitted to within one or two tenths of a degree Celsius. Additionally the formation temperature was predicted for several years beyond 1991 using assumed load profiles.

These computer simulations were repeated in 1997 using an adapted load profile based on the atmospheric temperatures for the years 1991–1997, recorded at a nearby meteorological station (Tänikon/TG), and the homeowner's records on heat pump operation times. In addition, the model grid was refined to take advantage of the available computers: 11,700 grid cells in a model volume of 2×10^6 m^3 instead of 1300 cells in 165,000 m^3 used for the earlier modelling (details in Eugster, 1998).

The operation of the Elgg BHE installation was extrapolated for an additional 19 years to a final period of 30 years (1986–2015), as shown in Fig. 2. The load profiles for these extrapolation runs are based on the new Swiss Standard Climatic Database (Meteonorm, 1997). The simulation runs show on one hand the expected decrease of the yearly temperature deficit and on the other hand an increasing area around the BHE, which is affected by the cooling. The cumulated temperature deficits after different years of operation are listed in Table 1, for a depth of 50 m below the ground level. At a depth of 50 m, the cooling is only caused by the BHE operation, and any atmospheric influences can be excluded. The results show increasing cooling with time. Therefore the question about ground thermal recovery after the termination of heat extraction must be addressed.

5. Short- and long-term ground recovery

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. For details see Eugster and Rybach (2000).

The pronounced heat sink forms a cigar-shaped isotherm pattern, with the BHE as its center (see Fig. 3). The heat sink creates steep 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. Compared to the terrestrial heat flow (80–100 mW/m^2), the heat flow towards the BHE has high values (up to several W/m^2 – see Fig. 3).

After cessation of heat extraction, recovery of the ground temperature begins. During the production period of a BHE, the drawdown of the temperature around the BHE is high during the first few years of operation (see Fig. 4). Later, the yearly temperature deficit asymptotes to very small values.

During the recovery period after stopping BHE operation (assumed to happen after 30 years of operation), the ground tem-

Table 1
Calculated cooling of the ground at different radial distances from the BHE and at a depth of 50 m below the ground level.

Distance (m)	Calculated cooling of the ground (K) at 50 m depth after specified years of operation			
	2 years	5 years	11 years	30 years
0.5	−1.13	−1.23	−1.50	−1.75
1.0	−1.12	−1.22	−1.49	−1.73
5.0	−0.82	−0.98	−1.22	−1.56
10.0	−0.44	−0.65	−0.87	−1.18
20.0	−0.06	−0.22	−0.40	−0.64
40.0	0.00	−0.02	−0.11	−0.25
50.0	0.00	0.00	−0.03	−0.10

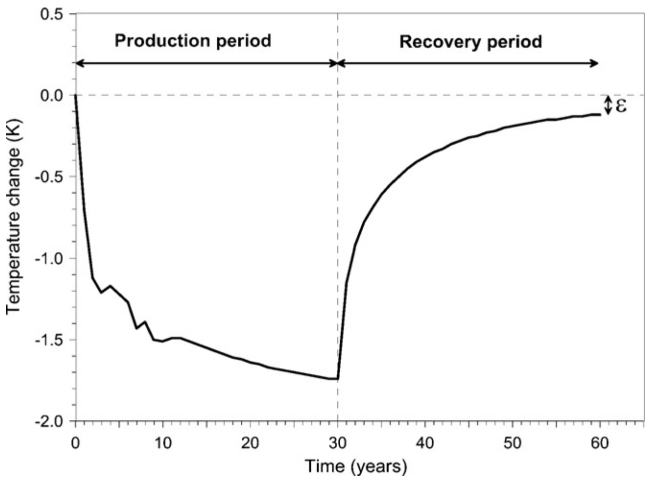

Fig. 4. Calculated ground temperature change at a depth of 50 m and at a distance of 1 m from a 105 m long BHE during a production period and a recovery period of 30 years each (Eugster and Rybach, 2000). After 30 years of recovery the deficit (ε) is marginal.

perature shows a similar behavior: during the first years, the temperature recovery is rapid, 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 in operation. Principally, the recovery period equals the operation period.

Sustainability aspects of GHP systems have been addressed above, with emphasis on Borehole Heat Exchanger (BHE)/heat pump (HP) systems. BHE/HP are a feasible way to tap shallow geothermal resources which, located directly below our feet, represent a unique, ubiquitous and therefore enormous geothermal potential. These systems operate reliably also over the long-term. The results of numerical modelling for a single BHE show that the long-term performance of the BHE/HP system stabilizes, relative to initial conditions, at a somewhat lower but quasi-steady level after the first few years. Thus sustainable operation can be achieved.

Above discussed investigations of long-term performance presented here are for a single BHE, for heating alone. Similar studies have also been performed for multiple BHEs (Signorelli, 2004; Signorelli et al., 2005); they fully confirm the findings for single BHEs.

The theoretical and experimental results reported above can best be substantiated by evaluating operational experience, acquired over years. Below, the experience at two installations (the one already described system at Elgg/ZH and another one in Untersiggental/AG) is presented.

6. Long-term operational experience

Numerous GHP installations have operated fully satisfactorily in Switzerland, for decades. A systematic evaluation of operating experience was first performed in 1985 (Rohner, 1994), addressing GHP systems with BHEs, running for 9–14 years at that time. The study reported consistently positive experience. A new project, financed by the Swiss Federal Office of energy, systematically evaluated the operational experience of 33 GHP systems in Switzerland, functioning over 25–31 years. The investigation (Signorelli et al., 2010) confirmed the findings of the first study. Here two systems are described; the first the Elgg/ZH installation reevaluated in 2001 and another installation in Untersiggental/AG, operating since 1987.

The data acquisition system at Elgg was switched on again in fall of 2001. Data gathering started on 27 August and ended on 25

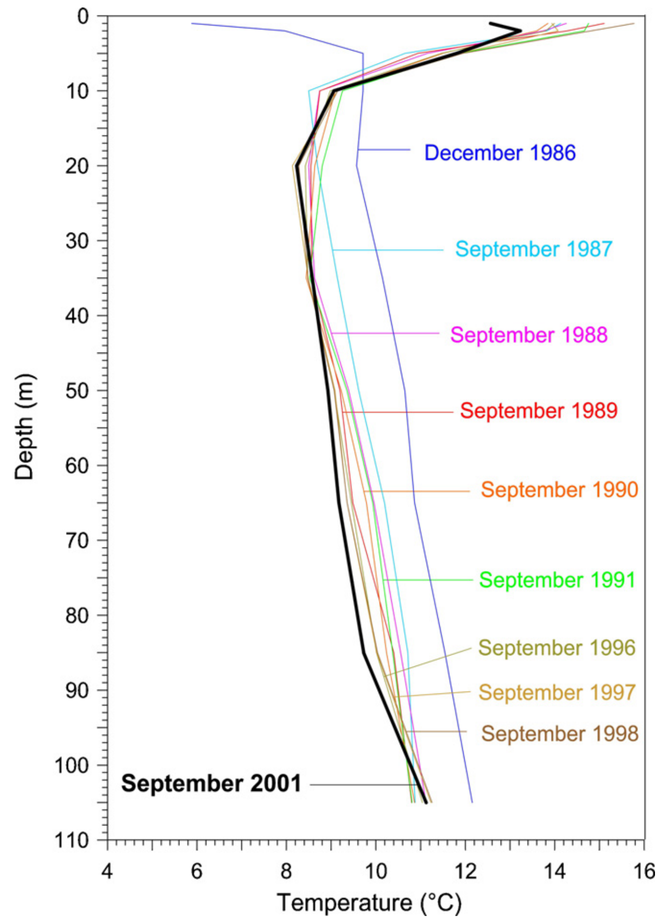

Fig. 5. Measured ground temperature profiles at 0.5 m distance from a 105 m deep operating BHE at Elgg/ZH, repeatedly measured over 15 years. The last measurement is from fall 2001 (curve "September 2001"). The ground temperatures stabilized over the last few years of system operation (Eugster, 2001).

September. One temperature sensor did not function; the missing data have been estimated by extrapolation (for more details see Eugster (2001)). The measurements are shown in Fig. 5; it is evident that the ground temperatures stabilized in the last couple of years of system operation. Thus, sustainable production has been achieved over the 15 years of system operation. The observational borehole with temperature sensors at 1 m distance from the BHE shows practically identical results (Eugster, 2001).

At Untersiggenthal, Canton Aargau a GHP system operates with two 70 m deep BHEs. The total heating capacity for the single family house is 11 kWth. Since the summer of 1996 the system is also being used for space cooling. Extensive experience, especially system improvements like replacing an old heat pump with a more efficient one are described in numerous publications by the owner, Dr. Klaus F. Stärk. Fig. 6, taken from Stärk (2008), shows the return temperature of the fluid circulating in the BHEs over the years 1997–2008. Stability and sustainability are evident in Fig. 6, thus sustainable operation characterizes this installation too.

7. Proper GHP design

State-of-the-art dimensioning of GHP systems (especially in calculating the number, depth, and spacing/geometrical array of BHEs, considering the entire heating/cooling system) is essential for ensuring the sustainability of operation.

Engineering standards and quality assurance are important instruments to guarantee the accomplishment of these goals. As an

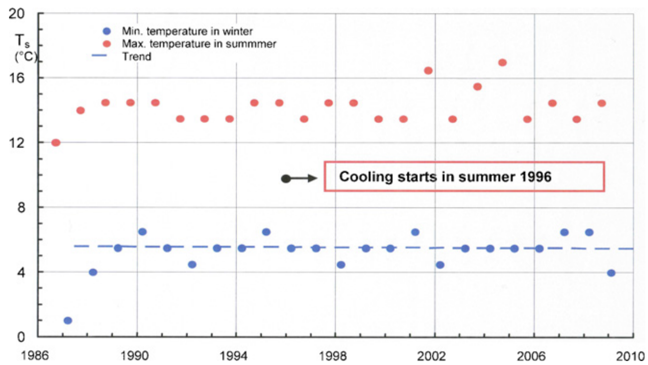

Fig. 6. Stability of fluid temperature from borehole heat exchangers during the time period 1987–2008. T_s: return fluid temperature from BHE (upper dots: in summer, lower dots: in winter). Data for a single family house installation at Untersiggenthal, Switzerland.
Modified from Stärk (2008).

example, the Swiss engineering norm SIA 384/6 "Erdwärmesonden" is mentioned (SIA, 2009). Quality assurance by means of certification has been or is being introduced in various countries.

An important factor in dimensioning BHE-coupled GHP heat pump systems is the ground thermal conductivity, especially for larger installations (>50 kWth). Here not only the average thermal conductivity but also its vertical distribution is relevant. The latter can be determined by the Enhanced Response Test (e-TRT; Wagner and Rohner, 2008). In addition, the design must take into account the local meteorology, ground properties, and technical supply conditions.

8. Conclusions and outlook

Experimental and numerical investigations show that borehole heat exchanger-coupled geothermal heat pumps can operate reliably over the long term, provided that the systems are well designed. In particular, sustainable heat delivery can be secured. In heating mode, the ground temperatures reach a quasi-equilibrium, after some initial cooling.

The installation at Elgg (Canton Zurich, Switzerland) with its data acquisition system has been revisited several times; the measurements confirm the theoretical calculations predicting the long-term behavior. Another system, in Untersiggenthal (Canton Aargau) demonstrates sustainable heating and cooling operation over decades.

The positive long-term operational experience with combined heating and cooling is leading to new applications such as BHEs beneath buildings, energy piles, and large installations with several tens/hundreds of BHEs. Design support by innovative measurement techniques, for example to determine the ground thermal conductivity profile by the e-TRT method, is also evolving. The ground is increasingly used as heat source and heat sink, since the shallow subsurface is a cost-efficient store for compensating the daily and seasonal delay between need and supply of heat and cold. Large objects with complex energy demand need correspondingly sophisticated design, which in turn call for adequately flexible simulation tools (see e.g. Megel et al., 2010).

Rapid growth of GHP installations is now taking place in many countries and development can also be expected in other countries where GHP systems have not been deployed so far. Standardization and quality assurance will help to establish a worldwide boom in GHP technology and deployment.

Acknowledgments

The continuous support of theoretical and experimental investigations into the long-term behavior and production sustainability of GHP systems in Switzerland by the Swiss Federal Office of Energy (SFOE), the Nationaler Energie Forschungs Fonds (NEFF), and the Projekt- und Studienfonds der Elektrizitätswirtschaft (PSEL) is gratefully acknowledged.

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