INTERNATIONAL SUMMER SCHOOL on Direct Application of Geothermal Energy

Chapter 2.1

STATUS AND PROSPECTS OF GEOTHERMAL HEAT PUMPS (GHP) IN EUROPE AND WORLDWIDE; SUSTAINABILITY ASPECTS OF GHPs

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Abstract

The ubiquitous shallow geothermal resources can feasibly be utilized by geothermal heat pumps. They represent the fastest growing segment on the geothermal market. The present status worldwide and in Europe is summarized, with special emphasis on Switzerland, the lead country in the dissemination of GHP technology. Further, the sustainability of GHP systems is addressed, mainly the basic questions of long-term operation. The sustainability of production is demonstrated for a single borehole heat exchanger (BHE) by a combined experimental and theoretical (=numerical modelling) approach. It turns out that BHE/HP systems operate, if properly designed, fully reliable on the long term, i.e. sustainable production can be guaranteed.

Introduction

Geothermal heat pumps (GHP) represent nowadays the fastest growing segment of geothermal energy utilization (Lund 2001). Central to this technology is the heat pump (HP) which can raise (or lower) the temperature of a working fluid. Therefore, GHPs can be used for heating and/or cooling. In moderate climate they can be operated as monovalent systems. In the great majority of cases the HP is driven by electric power.

The base for GHPs is provided by the ubiquitous shallow geothermal resource, the ground right below our feet, in the uppermost few hundred meters of the earth's crust. Traditionally geothermal direct use aims to utilize the heat content of formation fluids (if present). The heat content of the rock matrix is generally higher; this heat is the target of shallow resources utilization.

Heat can be extracted from as well as stored in this shallow reservoir. There are several types of access to the ground to extract heat:

- Groundwater wells
- Horizontal coils
- Borehole heat exchangers
- Geostructures (energy piles, concrete walls).

The latter two can also serve to store heat (or cold) in the ground. The heat source is coupled to the evaporator side of the heat pump whereas the compressor side supplies the heating/cooling circuit. In Europe the latter is generally a hydronic system whereas e.g. in the USA it mainly comprises forced air systems. Sometimes systems which use open surface waters (ponds, creeks) as heat source are also considered as GHPs, e.g. in the USA. Groundwater wells and surface waters belong to the category of open systems.

There is a whole spectrum of GHP applications for various buildings (single- or multi-family dwellings, administrative buildings, schoolhouses, factories etc.) like space heating only, heating plus domestic hot water, combined heating and cooling/air conditioning, in addition to other applications such as road/runway de-icing or lawn heating in stadions.

In most cases the HP is driven by electric power. In the case of heating, the smaller the temperature lift needed (outlet temperature at the compressor to the heating circuit – heat source/inlet temperature at the evaporator) the smaller is the power uptake of the HP and thus its efficiency. For this reason, underfloor heating tubes which require relatively low delivery temperatures (35 – 40 ^{o}C) are used in many countries.

There is a real boom in the dissemination of GHP technology, with spectacular growth rates in several countries. In the following, the current status of GHPs around the world is summarized and special features in various European countries are presented. In addition, the question of reliable long term operation of GHPs is addressed, i.e sustainable production from shallow geothermal resources.

GHPs in the world and in Europe

The following compilation is mainly based on three publications: SANNER et al. 1998, RYBACH and SANNER 2000, and LUND 2001.

The situation worldwide is summarized in Table 1. By far the largest GHP user is the USA. Per capita, Switzerland has clearly the lead. In fact, there is one GHP installation every 2 km^2 in Switzerland (details see below).

There are significant differences from country to country. Whereas there is a large number already in operation and rapid development in several countries there is practically no GHP boom in countries like Japan (although a major HP producer) or numerous European countries in the Mediterranean. And still enormous markets are practically undeveloped (e.g. China). It can be expected that this situation will change rapidly and significantly in the coming years.

Over the past ten years there was a large increase in the installation and use of GHPs worldwide, with almost a 10 % annual increase. Most of the growth is concentrated in the USA and in some European countries. The present worldwide capacity is near 7 GWt and the production is around 25'000 TJ/yr. The data about the actual number of GHP systems are incomplete; it is certainly above 500'000. The size of individual units can be quite different, ranging from a few to over hundred kW.

For systems with electric HPs the seasonal performance coefficients (which take into account the power uptake for the HP as well as for the circulation pumps) are now generally > 3.0. Load factors (full load hours per year) can vary according to location and climate. In Switzerland, for example, the actual number of full load hours is about 1600 h/yr. Low load factors are not necessarily a disadvantage: short running times mean less electricity consumption and thus lower running costs.

The worldwide abundance and distribution of GHP systems is highly inhomogenous and the data base about existing and newly installed systems (number, type, size) is incomplete. Some information is given below; it should be kept in mind that due to the uneven but rapid developments the situation is changing rapidly. Compilations for Europe are given in Tables 2 and 3.

Table 1. Geothermal Heat Pumps Worldwide (status in 2000), from LUND (2001)

Country	Installed capacity (MWt)	Energy produced (TJ/yr)
Australia	24.0	57.6
Austria	228.0	1'094.0
Bulgaria	13.3	162.0
Canada	360.0	891.0
Czech Rep.	8.0	38.2
Denmark	3.0	20.8
Finland	80.5	484.0
France	48.0	255.0
Germany	344.0	1'149.0
Greece	0.4	3.1
Hungary	3.8	20.2
Iceland	4.0	20.0
Italy	1.2	6.4
Japan	3.9	64.0
Lithuania	21.0	598.8
Netherlands	10.8	57.4
Norway	6.0	31.9
Russia	1.2	11.5
Poland	26.2	108.3
Serbia	6.0	40.0
Slovak Rep.	1.4	12.1
Slovenia	2.6	46.8
Sweden	377.0	4'128.0
Switzerland*	300.0	1'962.0
Turkey	0.5	4.0
UK	0.6	2.7
USA	4'800.0	12'000.0
Total	**6'675.4**	**23'268.9**

*) from RYBACH et al. (2000)

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USA

Most of the GHP growth is in the midwestern and eastern states, from North Dakota and Florida. In 2000, there were about 500'000 units, with 50'000 new ones installed annually. Of these are 46 % vertical closed loop, 38 % closed loop, 38 % horizontal closed loop and 15 % open loop

Table 2. General heat pump ("total") and ground source heat pump systems (GSHP) installed 1993–1996 in various European countries (residential sector, in 1000 units, from RYBACH and SANNER 1999)

Country	**All heat pumps**	**Ground source fraction (%)**	**GSHP systems**
Austria	22.2	11	2.42
Denmark	3.3	18	0.59
France	25.0	11	2.75
Germany	5.7	4	0.23
Netherlands	0.12	7	0.01
Norway	4.0	8	0.32
Sweden	42.3	28	11.8
Switzerland	15.0	40	6.0
Total			**24.12**

Table 3. Share of ground coupled heat pumps in total residential heating demand (RYBACH and SANNER 1999)

Country	**%**
Austria	0.38
Denmark	0.27
Germany	0.01
Norway	0.25
Sweden	1.09
Switzerland	0.96

systems. Even President Bush has a bore-hole GHP system in his home in Texas.

Austria

In 1996 the percentage of closed loop systems was 83 % and that of the open-loop systems 12 %. There are some spectacular systems with geostructures like foundation piles or supporting walls equipped with heat exchanger tubes like the architecturally famous Museum of Fine Arts and the Festival Hall in Bregenz, or the Convention Hall in Dornbirn.

Belgium

Here the combined use for heating/cooling by means of underground storage in gaining increasing attention, mainly for larger complexes. Various building types are supplied like banks, factories, hospitals etc.

France

The dominating electricity company Electricité de France (EdF) has started with the promotion of GHP systems. A number of different test facilities are in operation and the results shall serve for a country-wide initiative. The prestigeous Palais d'Europe in Strasbourg uses groundwater-based GHP.

Germany

The potential of GHPs using shallow geothermal resources is estimated to be around 960 PJ/yr (KALTSCHMITT et al., 1997). This means about 10 % of the end energy use. The installed GHP capacity in 1995 was estimated to be around 250-450 MWt, with an annual increase of some 2'000 new systems. In some regions, promoted by local utilities, there is remarkable progress like in the Rheinland-Westfalen area supplied by the RWE utility (some 200 new installations in 1997 versus only 9 in 1993).

The Netherlands

The development of GHPs –which aims to replace traditional gas-fired heating systems by this envoronmentally friendly technology – is coordinated by the Dutch Agency for Environment and Energy NOVEM. The GHP sytsems are mainly of the ground-coupled type. Although in 1997 only about 1'000 GHP systems were in operation their number increased since 1994 by more thank 300 %. The Netherlands are also known as one of the pioneers of heat storage in aquifers, with some 50 units already in operation for important objects like the Rijksmuseum in Amsterdam, the KLM Operations Center at Schiphol Airport, the IBM Netherlands Headquarters in Zoetemeer, the Europe Center of Nike in Hilversum, the IKEA Center in Deuven or the EU Patent Office in Den Haag.

Poland

One of the first GHP in Poland was built in 1993 for the hotel "Ornak" in Zakopane, with horizontal ground loops. On of the most recent horizontal loop installations is for heating of a block of flats in Lomza. There are also groundwater heat pumps, as for heating apartment- and administration buildings in the Slowinski National Park in Smlodzin with 150 kW. Some further, recent examples of GHP in Poland include objects like churches, banks and hospitals. Polish manufacturers of heat pumps exist meanwhile, offering a range of thermal capacity from 4-200 kW.

Sweden

Sweden is one of the classic countries of heat pump use. Around 55,000 BHE-systems are operational, with a total installed capacity of ca. 330 MW_{th}. GSHP are a generally accepted form of heating, and due to the high share of hydropower in the electric power supply, heat pumps always offer an opportunity for reduction of emissions.

Besides in GSHP use, Sweden is also leading in underground thermal energy storage technology. Here often BHE are used, and in areas with glacio-fluviatile sediments or, in the Southern part of the country, with fractured limestone, groundwater is used directly.

Cooling of telecommunication stations is done using BHE, like those in Ängby, Devikstrand, and Stockholm. Besides, 54 television relay stations are supplied by BHE-coupled HPs (for cooling).

A particular success story can be told of Strömstad, a town of 6000 about 200 km to the North of Gothenburg. The rocky subsoil is not suited for district heating, and thus 140 GSHP with a total of 400 BHE have been installed for heating of houses and apartments for 3000 people (SANNER and HELLSTRÖM 1998).

Switzerland

With a total of 60,000 presently installed heat pumps for space heating/warm water supply Switzerland is, per capita, world leader in this environmentally friendly technology. The general popularity of heat pumps in Switzerland lead also to a real boom of heat pump coupled BHE systems. Today, every third newly built single family house is equipped with a heat pump system. Although air-source heat pumps are significantly lower in installation cost (there are no drilling costs as for a BHE system) nearly 40 % of the heat pumps installed today have a geothermal (BHE) source. The generally lower seasonal performance coefficient of air-source heat pumps (due to the low source temperature in winter) is the main reason of this high percentage. The majority of GHPs have a BHE source, with an energy share of 71% (Fig. 1)

The share of heat delivered by GHP systems in the Swiss geothermal mix is overwhelming (75 % of a total of 439 GWh in 1997, RYBACH and WILHELM 1999).

The boom resulted in the installation of over 25,000 BHE systems to date, with a total of about 4,000 km of BHE length. At present, 1 m of BHE costs (drilling and installation included) about 40 US-$. Figure 2 shows the spatial distribution of BHE installations, delivered by just one comercial company (GRUNDAG, Gossau/SG: 7,900 BHE's with 695 km total length; status in mid 1997). The pattern of BHE system locations corresponds roughly to the population density. The widespread BHE installations secure Switzerland a leading position: Areal BHE density in Switzerland is highest worldwide (1 BHE installation every 2 km^2). The number of installations increases yearly by >10 %, as well as the heat production. The annual growth is also impressive (Fig. 3).

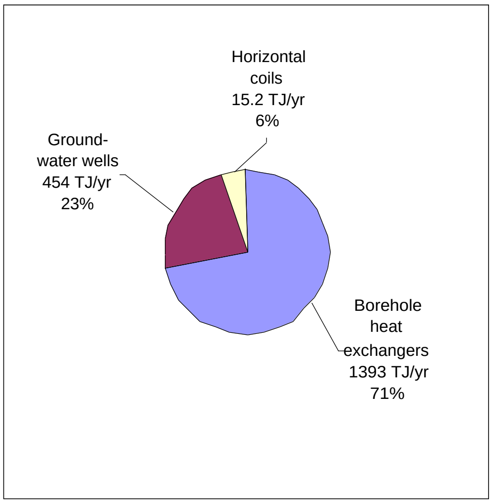


Figure 1: *Geothermal heat pump systems in Switzerland in 1999.*

New technologies like geostructures ("energy piles"), combined heating/cooling are rapidly progressing on the market. A prominent example is Dock Midfield, the new terminal at Zurich International Airport, This terminal building is a 30 meters wide new construction. It is funded on 440 fundation piles 0.9 – 1.5 m in diameter, of which 315 are equipped with heat exchanger tubes (="energy piles"). The piles stand at 30 m depth on a tight ground moraine formation. Through this special BHE system 1.1 GWh heat are extracted annually from the ground for heating in the winter. In the summer, the building heat is deposited in the ground which thus acts as a storage medium. For air conditioning, some 500 kWh cooling energy is supplied by the energy piles.

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".

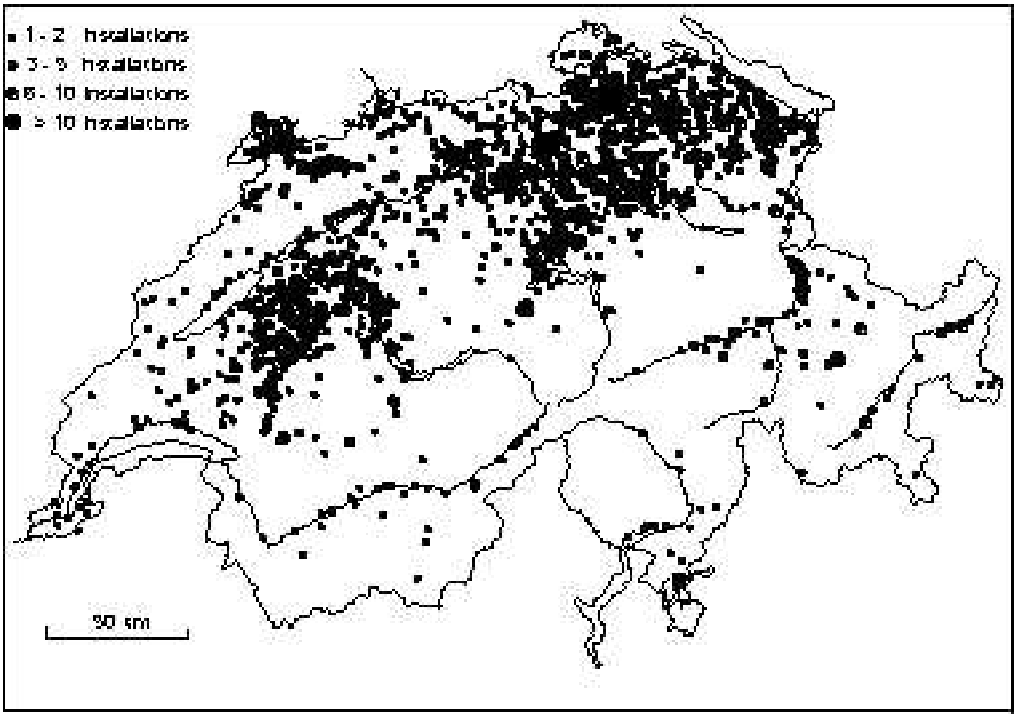
In relation to geothermal resources and, especially, to their exploitation for geothermal energy utilization, sustainability means the ability of the production system applied to sustain the production level over long times. Often the resources are taken into production (of the reservoir fluid as the 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 issu-es nor technological advances, all of which may be expected to change with time.

Figure 2: *Location of BHE systems in Switzerland, delivered by a single company (GRUNDAG AG, Gossau/SG; from RYBACH and EUGSTER 1998).*



Geothermal heat production from BHE systems in Switzerland

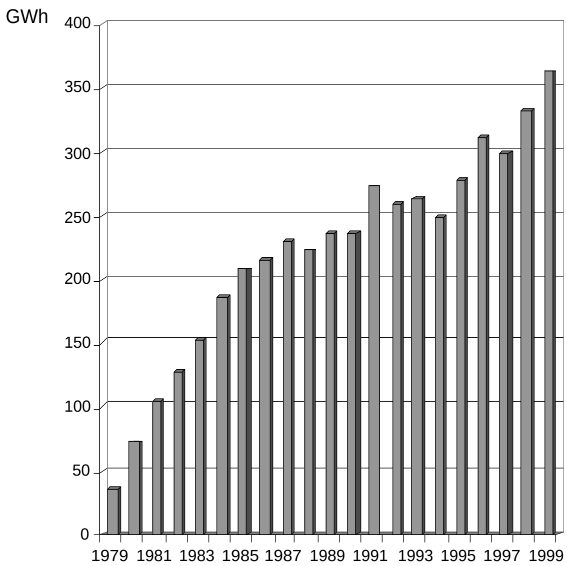


Figure 3: *Geothermal heat production from borehole heat exchangers. The fluctuations around the development trend are caused by annual changes in heating demand (strong/mild winters). From RYBACH et al. (2000).*

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.

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 collaps. 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 drawdown 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 installlled 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 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 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 sys-

tem (hydronic system flowrates, circuit temperatures, power consumption of the HP etc.) have also been recorded in 30 minute intervals.

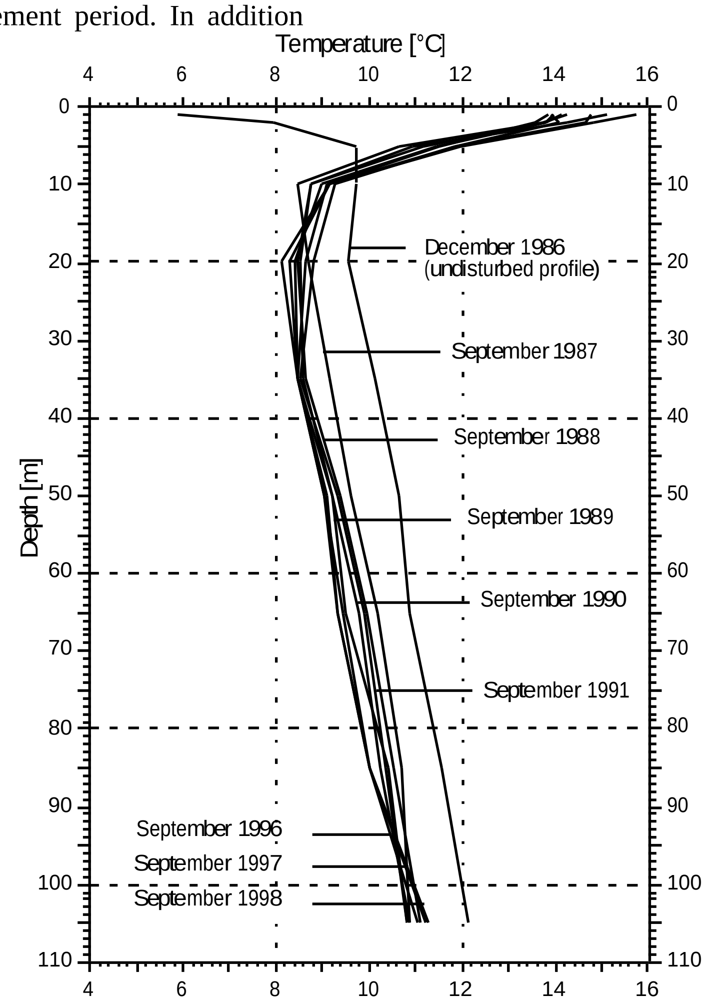


Figure 4: *Measured ground temperature profiles at a distance of 1m from the BHE in Elgg. Curve "December 1986" marks the undisturbed profile at the start of the first heating season. The subsequent curves show the conditions after winter heat extraction and summer recovery, just before the start of the next heating season*

. 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 4. 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 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).

In the autumn of 1996 (i.e. after 10 years of BHE operation) the measurement system was restarted. 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", Figure 3) do not show any further significant shift towards lower temperatures, thus demonstrating that a quasi-steady equilibrium has been reached after the first few years. The small differences between the profiles of subsequent years after at least three years of operation are a result of the different yearly heating demands which, given unchanged living habits of the owners, are uniquely a product of the outside 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 our theoretical expectations.

These measurements represent a unique 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), 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 modelling.

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). Ground temperatures over the first five years of measurement were fitted to within one or two tenths of a degree Celsius. Additionally the formation temperature was predicted for several further years using assumed load profiles (EUGSTER, 1991).

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 homeowner’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). The load profiles for these extrapolation 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.

These pure conductive processes are rather complicated and visualized in Figure 5. But in free nature, flowing groundwater and - in saturated formations - water vapor diffusion processes add their effects to this complex system.

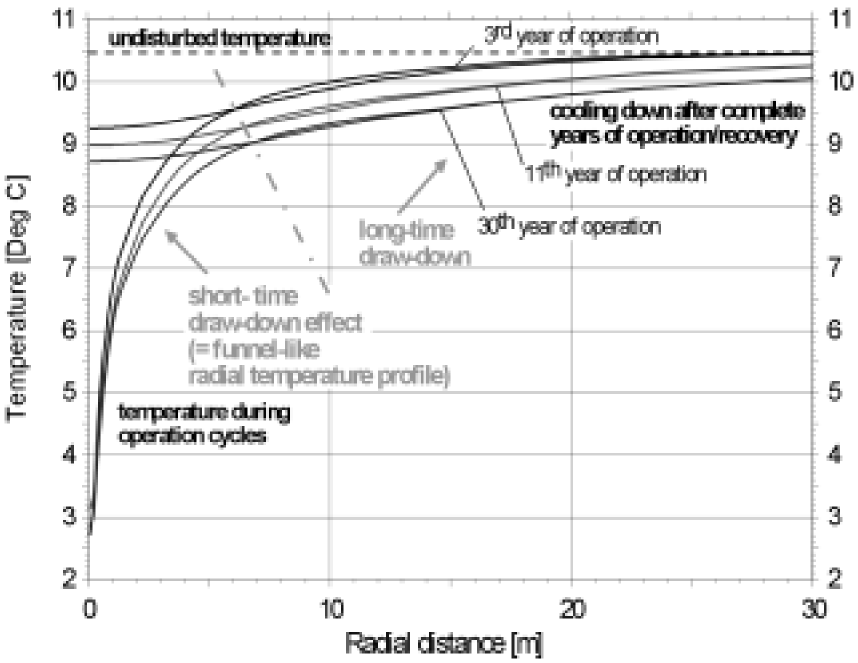


Figure 5: *Funnel-like temperature distribution and long term cooling-down around a BHE. The short term and the long term influences are well documented.*

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. Fig. 6 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. Tem-peratures 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 Fig. 6. The influence from the surface is visible in the uppermost ca. 10 m (see also Fig. 4), 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 Fig. 7 from a site in Elgg/ZH, Switzerland.

Thermal recovery

The long-term behavior of the single BHE-HP system was further investigated by numerical modelling. 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 8). After shut-down of heat extraction, regeneration of the ground begins. During the production period of a BHE, the draw-down of the temperature

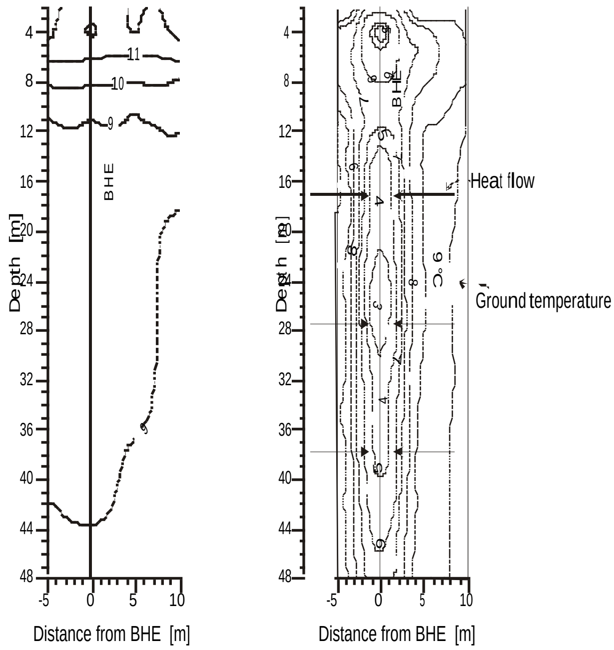


Figure 6: *Measured temperature distribution in the ground at the beginning of the monitoring period (left, on 1.10.1986, after a total of ca. 2 hours of test operation) and at the end of the first heating season (right, on 1.5.1987), Schwalbach GSHP test plant, Germany (after RYBACH and SANNER, 1999).*

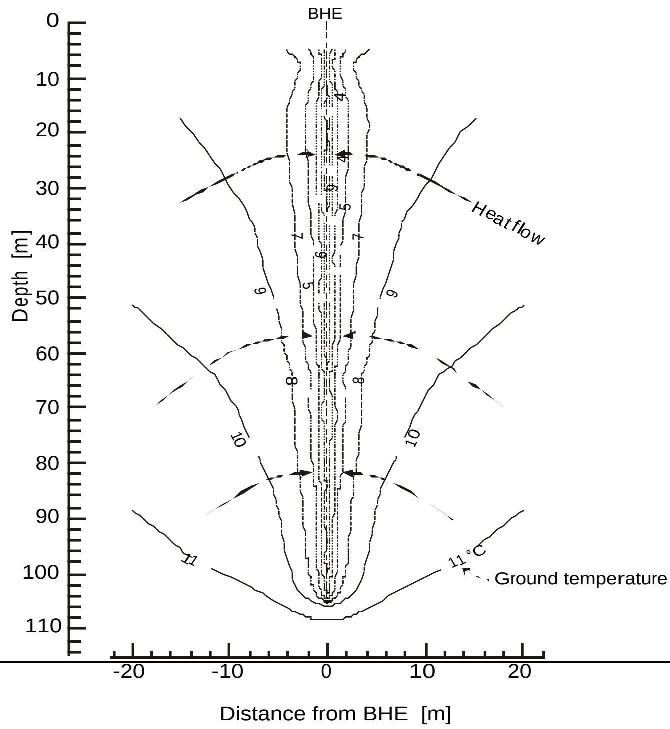


Fig. 7: *Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg/ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m*^{2}.

around the BHE is strong during the first few years of operation. Later, the yearly deficit decreases asymptotically 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 and tends with increasing recovery time asymptotically to zero. The time to reach a complete recovery depends on how long the BHE has been operational. Principally, the recovery period equals nearly the operation period. This is shown in Figure 9 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 optimisation.

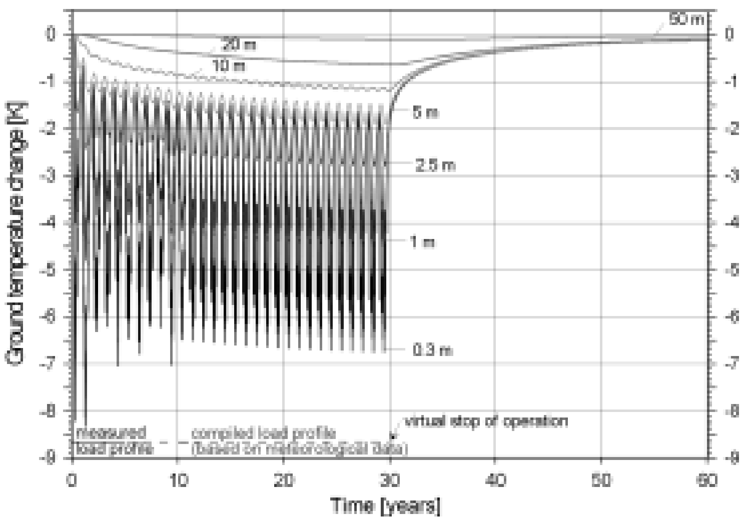


Figure 8: *Measured and modelled ground temperature changes of the BHE at Elgg relative to the undisturbed situation in December 1986 over 30 years of operation and 30 years of recovery.*

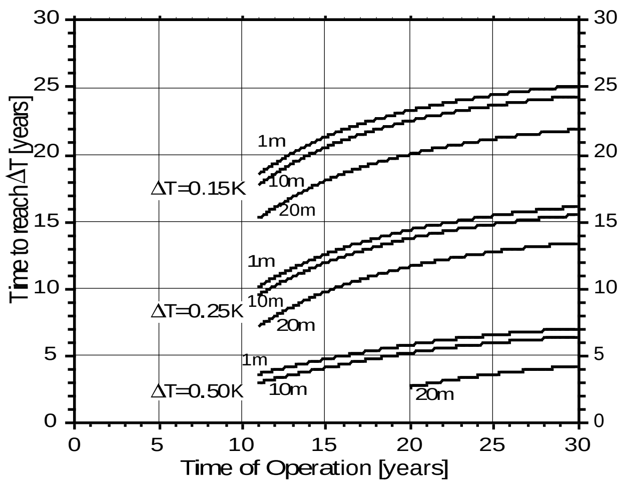


Figure 9: *Duration of recovery period to reach a minimal final temperature deficit (ΔT) of 0.5, 0.25 and 0.15K for different distances from the BHE as a function of the time of operation.*

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

- Geothermal heat pumps (GHP) represent the fastest growing segment of geothermal energy utilization. There is a whole spectrum of GHP applications for various buildings (single- or multi-family dwellings, administrative buildings, schoolhouses, factories etc.) like space heating only, heating plus domestic hot water, combined heating and cooling/air conditioning, in addition to other applications such as road/runway de-icing or lawn heating in stadions.
- There are significant differences in the GHP technology dissemination from country to country. Whereas there are great advances in countries like the USA, Sweden and, especially, Switzerland (one GHP system every 2 km^2) there is little to no development in other countries. Nevertheless the general development trend is clear; in some countries the annual increase is > 10 %.
- Sustainability aspects of GHP systems also 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 modelling code. The results of modelling 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 constant 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 then it tends, in the subsequent years, asymptotically towards zero.
- 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).

ß 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.

ß 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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