Ground Source Heat Pumps – history, development, current status, and future prospects

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Abstract

Already in prehistoric times humans took advantage of the steady temperature inside the earth, by using caves or holes in the ground to store food or to live inside, both in cold and warm climates. However, making active use of this thermal energy reservoir in the underground required a tool for changing temperature, the heat pump. Practical application of the heat pump process was already done in the 19th century, with the example of the steam generation in Ebensee salt works in Austria by Peter von Rittinger, and the first claims on a heat pump extracting heat from the earth were made by H. Zoelly in a Swiss patent as early as 1912. However, the first documented Ground Source Heat Pump (GSHP) application in practice dates from 1945, in Indianapolis, USA, and in Europe the first reports on ground-source heat pumps are from the 1960s.
R&D on geothermal heat pumps had a first boom in the 1950s in USA and Canada, and after the first oil price crisis in 1973, it started in Europe and Japan, and resumed in North America. The paper gives some details on the R&D-activities from the 1980s on and on the related work in IEA-cooperation. Some findings from that time are highlighted, as well as steps towards guidelines and standards, and examples of milestones in practical application are given. An assessment of the current status, both in technical development and market, and some cautious expectations for future development will complete the presentation.

Keywords: Ground Source Heat Pumps;

1. Introduction

1.1. Early thermal use of the underground

Temperature changes on the surface decrease inside the ground, and beneath a depth of about 10-20 m the earth has steady temperature throughout the year. This fact is used by animals since there is life on land, and since prehistoric times also by human beings, hiding in holes or caves to keep cool in hot climate, or warm in cold winters. In areas with suitable geology whole cities were dug into the rock. Areas with similar, well-suited volcanoclastic rocks in New Mexico in the USA, and in Cappadocia in Turkey, have resulted in astonishingly similar 'cave cities', where people and their food supply stay comfortable despite harsh outdoor climate. Old, rural houses and storage sheds in Iceland and Northern Scandinavia used to be partly underground, and even into the modern era deep cellars are used for food, wine, etc. Harvesting ice in winter and storing it (preferably) underground for cooling in summer was commonplace within the 19th and early 20th century. To give an impression of the size of ice movements to storage facilities, a number from just one single operation at the US-Canadian border can be reported, where in 1919 a total of 3000 railroad cars was loaded with ice from Otter

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Lake at Tulameen, B.C., and sent to Spokane [1]. The Bavarian beer-gardens are a lasting testimony to this era: the area on top of the ice cellars existing with most breweries, shaded by chestnut trees to keep the surface cool, served as a place for meeting and enjoying the products of the brewery outlet. Mechanical refrigeration has ended the natural ice business, but new, modern approaches to use of underground space have emerged.

1.2. Scientific understanding of the thermal regime in the underground

Scientific description of the decrease of temperature changes with depth has started in the late 17th century, when temperature readings were taken in the cellar of the Observatoire de Paris, and Antoine Lavoisier later installed a thermometer there. Buffon described in 1778 the steady temperature reading throughout the seasons [2]. Two decades later the German Alexander von Humboldt visits the place during his studies in Paris and states in 1799 [3]: ‘The average temperature which the observations done since 1680 revealed is 9.6 R’. This value is equal to 12 °C, and the seasonal temperature variations are recorded as maximum 0.03 R (0.04 °C).

In Scotland, ground temperature measurements were done since 1838 over many years on the grounds of the Royal Observatory in Edinburgh (fig. 1, left). These data were used by both Thomson [4] and Everett [5] to empirically validate their formulas for the decrease of surface temperature variations towards depth and the retardation of phase. Thomson calculates that temperature variation is only 1/20 of the variation on the surface in 8.1 m depth, and 1/400 in 16.2 m depth.

The temperature in the shallow geothermal realm is also influenced by the geothermal heat flux and the resulting geothermal gradient. With mines exploiting deeper and deeper resources, miners in the middle ages started to feel the geothermal heat. The first to attribute this to a hot interior of the earth and to give a cause (an internal fire) for it was Kircher in 1665 [6]. Based on reports from miners in the region of Chemnitz, Germany, he also suggested a geothermal gradient. It took more than hundred years before another scientist started to put numbers to the geothermal gradient: Buffon in 1778 [2] first also cites accounts from miners, in this case from Eller, Germany: “*à mesure que les mineurs descendent, ils recontrent une température d'air toujours plus chaude”* (the deeper the miners descended, the higher the air temperature they encountered). He then lists numbers for the temperature increase towards depth like the readings from Giromagny near Belfort (taken by de Gensanne) shown in fig. 1 (right).

Cordier published in 1827 a collection of data on underground temperatures from various places [7], and concludes: ‘If some observations that seem to have to big uncertainty are discarded, the others prove in more or less obvious way that there is a temperature increase from the surface towards the interior of the earth; … The differences between results that have been obtained in the same way are not only a result of lacking experience, but can also be attributed to a certain irregularity of the distribution of the underground heat from one country to the other.’ Cordier thus not only described the geothermal gradient, but also the basis for heat flow maps. For the site of the Observatoire de Paris he calculated an increase by 3.6 °C per 100 m. In 1837 Bischof provides a wealth of data [8], showing geothermal gradients of 2 - 4 K per 100 m. He seems to be the first to understand that also the thermal conductivity of the rocks influences the value for temperature increase towards depth. Towards the end of the 19th century, Lebour (1882) can present 57 series of underground temperature data, mostly from France and England [9], and obtains geothermal gradients of 1.1 - 6.4 K per 100 m from these data. The highest gradients were reported from mines in Cornwall with more than 5 K per 100 m.

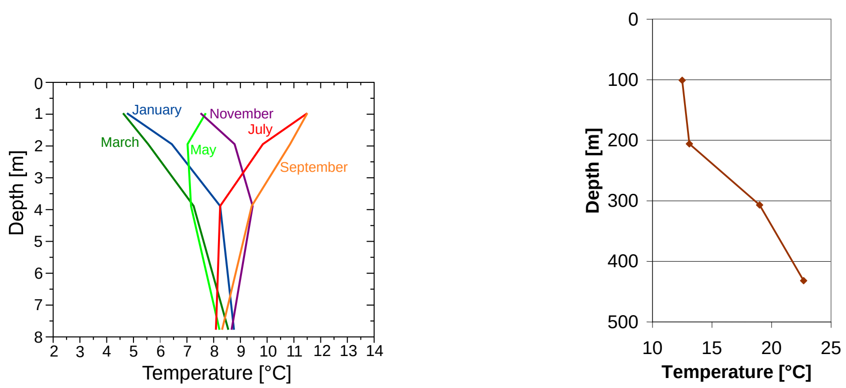

Fig. 1. Measurement of ground temperature at the Royal Edinburgh Observatory, average values 1838-1854, after data from [5] (left) and temperature increase with depth as given by [2] for Giromagny (right); original values converted to modern units by the author

The effects of seasonal variations of surface temperature, decrease of such variations into the ground, and the geothermal heat flow from below control the shallow geothermal systems. A typical temperature distribution resulting from the interplay of these factors is shown in fig. 2. At the end of the 19th century, these facts were fairly well understood.

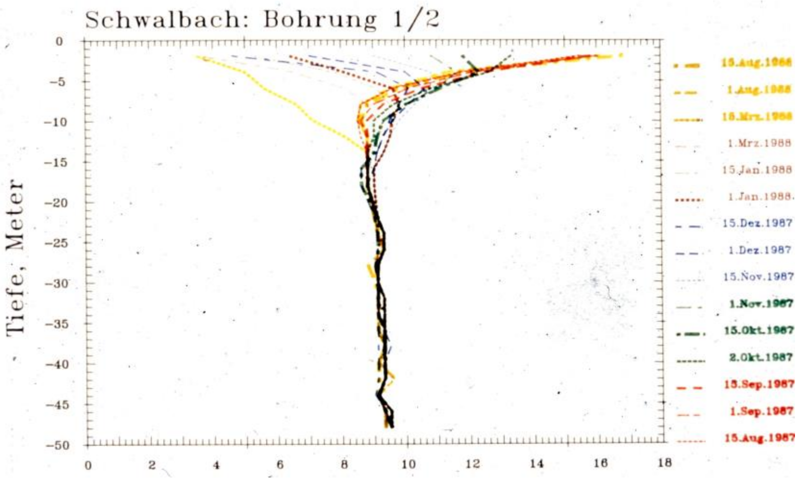

Fig. 2. Original plotter graph from 1987 showing the undisturbed temperature development along a borehole 50 m deep over one year, from August 1986 to August 1987, in the Schwalbach GSHP research station

1.3. Development of machines to change temperature

In order to actively use the shallow underground for energy production or storage, a tool is required for changing temperature: the heat pump to increase it, and the chiller (or a heat pump in reversed mode) for decreasing temperature. An early vision of such a machine with two cylinders in series was given already in 1853 by Thomson [10], the processes being intended both for heating and cooling. In a note added to the article in 1881, Thomson writes that in the meantime, machines based in his principle were used for cooling, e.g. for transporting meat on ships, and continues: "*The method of heating air described in the article remains unrealized to this day*". Practical application of thermodynamic processes is reported in the second half of the 19th century, primarily for refrigeration (e.g. producing ice), with working fluids like water vapour, methyl ether, carbon dioxide, and ammonia.

Today it is generally accepted that the first practical application of the heat pump principle was made by Peter von Rittinger in 1857, using vapour compression in a closed batch circuit to evaporate water and thus produce salt from concentrated brine in the Ebensee salt factory in Austria. He explained his idea in the words 'Steam can generate mechanical work, but hardly any physicist will doubt the sentence expressed in the reversed sense, mechanical work can generate steam' [11]. The Ebensee compressor was driven by water, a readily available resource in the area, and thus valuable firewood could be saved with the process. The heat pump reputedly had a thermal capacity of 14 kW [12].

2. Development in the 20th century

2.1. Development until the first oil price crisis 1973

It is well known that on 13th February 1912 a patent in which a ground-source heat pump is described was applied for by Heinrich Zoelly, of some fame in water and steam turbine design and with the development of steam turbine locomotives. The main claim in this Swiss patent No. 59350, granted in 1919, was as follows (cited after [13]; translated by the author):

> '*Heating process, in which an electric motor drives a compressor which forwards a heat carrier medium in a process cycle, the principle of which is equivalent to the process cycle a*

refrigerant experiences in the operation of a compression cooling machine, and where facilities are foreseen to allow the heat carrier medium to take in heat from the ground.'

For house heating, heat pumps were first applied in the 1930s, for instance 1938 in Zurich, Switzerland, where the town hall was heated by a heat pump using river water as heat source, with entering water temperatures as low as 1.2 °C in winter [14] (in Europe, surface water as heat source or sink is not considered 'geothermal' by definition, but 'hydrothermal' as to the EU Directive 2009/28/EU; in North America however, lake and river water is included in the term 'geoexchange'). The heat pump supplied up to 100 kW heat and achieved an annual COP of almost 2.2 (including river water pump) in 1938/39 [12]. More heat pumps were installed for other buildings in Zurich, due to the restriction on coal supply from abroad during the Second World War: for an indoor swimming pool in 1941, for supply to the district heating net in 1942, and for two buildings of the city administration in 1943/44. The heat pump in the town hall had a very long service life of 63 years, with the compressor replaced in 1964, before being retired in 2001. It was still operational for heritage purposes in 2008 [12].

In North America, the years between 1945 and the early 1950s were a heyday of heat pump development. The first true ground-source heat pump was installed in Indianapolis in 1945 [15], a direct-expansion system with horizontal pipes in the ground, in 3 circuits totalling 152 m, and a compressor with 2.2 kW. The system was monitored from October 1945 to May 1946, and used 6357 kWh of electricity during 1630 operating hours in this winter with lows of -24 °C. The heat pump saved 5.1 tons of coal or 2970 l of fuel oil which would be required according to calculations for conventional heating. An article from 1947 [16] listed the ground-coupling methods already available at that time (fig. 3); we find vertical U-pipes, coaxial pipes and screw-type (helicoidal) pipes as well as horizontal pipes and groundwater wells. The article mentions that the Union Electric Company in St. Louis had built a test plant with helicoidal pipes, installed in boreholes 5-7 m deep and drilled using a rig for setting power poles.

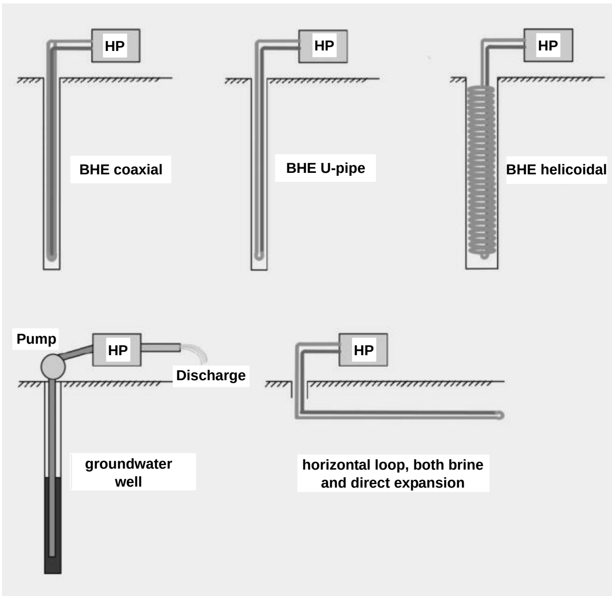

Fig. 3. Ground-coupling methods listed by [16] in 1947; re-drawn and harmonised by the author

Detailed research on ground coupling is documented from a project starting 1948 in Philadelphia, conducted by Philadelphia Electric Company in collaboration with Chrysler Air Temp Sales Corp. [17-19]. Pilot plants were installed in two similar homes of company employees in Whitemarsh and Lansdowne, suburbs of Philadelphia. As opposed to the Indianapolis direct expansion system, circulation of brine (water/monoethylene-glycol) in horizontal loops (iron water supply pipes) was used. The three publications [17-19] can be considered as the first scientific papers on ground source heat pump technology, as they discuss the experiments and results under different perspectives. Monitoring started in Oct. 1948, and until 1950 the temperature in the pipes in the ground did not fall below -1 °C. Minimum evaporation temperature was -3 °C in 1948/49 and -6 °C in 1949/50. There were several incidents with the heat pumps and fans, including a total of 12 refrigerant leaks. The ground coupling however proved reliable even in time of maximum heat or cold demand [19]. System SPF in the winter season was 2.5 and 2.7, respectively.

The largest ground-source heat pump of that time was constructed 1948 as a groundwater heat pump for the Equitable Building, in Portland OR [20]. The development mushroomed, and also theoretical work for ground loop design methods started. L.R. Ingersoll at the University of Wisconsin in Madison investigated the theory of heat conduction in the underground, and published several calculation methods for evaluating temperature development in the ground system, based on the line source theory. Papers like [21] introduced pipe sizing methods on a scientific basis.

In Europe this development on the other side of the Atlantic was mainly ignored in the difficult post-war time, when only few heat pumps where installed. A groundwater heat pump (thus truly 'geothermal' also by European definition) is said to be built around 1950 in Thun, Switzerland [12]. A heating capacity of 440 kW was achieved, and the low supply temperature to the heating system of 40 °C, unusual for that time, reportedly allowed for an excellent annual COP of 4.5.

The years of low fuel prices in the 1950s and 60s brought the development in America to a halt, prevented interest in heat pumps in Europe, and resulted in the retirement of many existing ground source heat pumps.

2.2. Development during the first and second oil price crisis, 1973-1985

In October 1973 the OPEC decided on a reduction of oil supply to the Western countries as retribution to the West supporting Israel in the Yom-Kippur-war. Oil prices soared, and alternatives were sought. It is much easier to replace oil in stationary applications like heating than in transport, and thus heat pumps became popular as heating option. It took some time after 1973 to develop the necessary equipment, and so the heat pumps were available quite in time for the second oil price crisis in 1980/81, caused by the revolution in Iran and the subsequent Iran-Iraq-war. Heat Pump sales and oil price development in Germany can be seen in fig. 4.

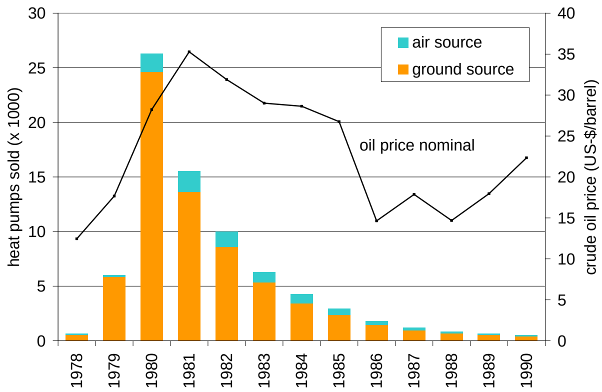

Fig. 4. Development of heat pump sales and crude oil price in Germany 1978-1990 (after data from BWP)

The development in Europe had started already before the oil price shock. A first ground-source heat pump in Germany, using horizontal loops, became operational already in 1969 [22]. Groundwater wells as heat source for heat pumps followed soon after [23]. The number of publications on the different types shows clearly that borehole heat exchangers (BHE) followed several years later (fig. 5, left). The shape of the graph clearly reflects the heat pump boom around 1980 as seen in fig. 4.

Thus for the second oil price crises, heat pumps were available from factories large and small, mainly in Austria, France, Germany, Sweden, Switzerland, but also elsewhere. In Germany, most were coupled to horizontal loops or groundwater wells, some used air as heat source. Many heat pumps were installed in bivalent systems as addition to existing boilers, causing a plethora of problems in control, hydraulics, and temperature levels. The lack of experience, quality, knowledge of the installers, etc. ruined the reputation of heat pumps in Germany around 1980, and the sales numbers dropped before the oil price did (cf. fig. 4). A similar development happened in France, the peak being slightly later, and in Austria, where the absolute numbers were lower and the decrease less drastic (fig. 5, right). Smaller companies simply disappeared, and the large boiler manufacturers, having started also on heat pumps, closed their respective departments. Only a few companies with good knowledge and experience, and sufficient persistence, continued and became the core of the positive evolution after 1990.

Borehole heat exchangers (BHE) had their start just during the boom. First experiments are reported from UK, Netherlands and Sweden. In Germany, first BHE were installed in the late 1970s, but not documented in publications. The first (West-)German document on regulation of GSHP [25], edited by the joint working group on water of the relevant state authorities, dealt mainly with groundwater heat pumps, but included also a few pages on the "new technology" of BHE, showing a coaxial BHE as example. A German company brochure [26] shows photos of drilling and installation for a coaxial BHE, made from corrugated stainless steel for the outer pipe, and a rubber hose for the inner pipe. The first Swiss experiments with BHE also started around the same time, with the first modern BHE made of PE-pipes installed in 1980 [27]; Austria followed soon after.

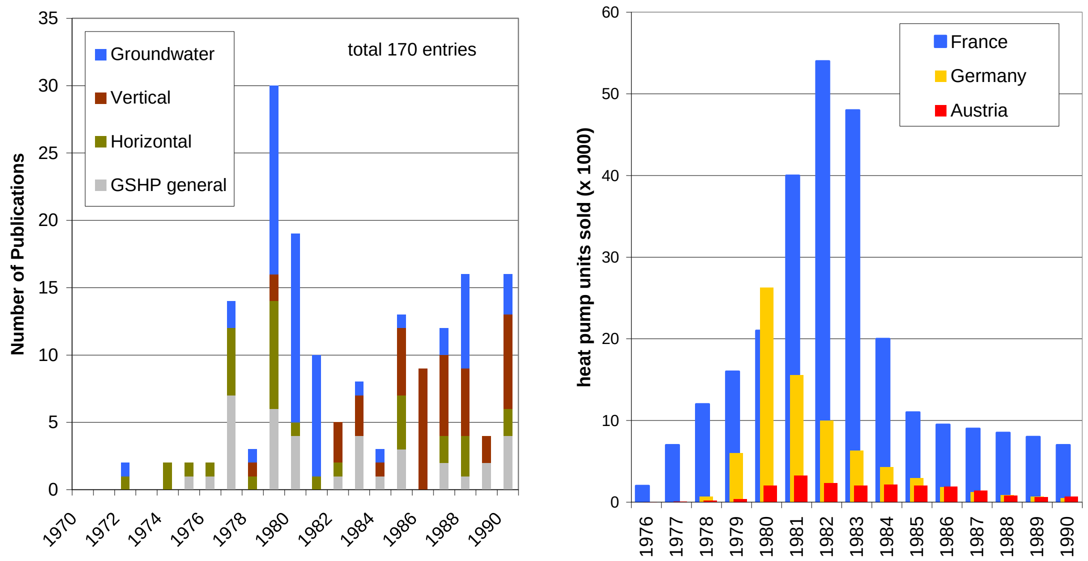

Fig. 5. Number of European publications on GSHP with different ground-coupling technology in the years 1970-1990 [24] (left) and development of heat pump sales in France, Germany and Austria 1976-1990; all heat pump types considered, heat pump water heaters excluded (after data from BWP and EHPA, right)

2.3. Development in Europe after the "boom and crash"

As a result of the market disaster, more cautious approaches were used in Germany. In Sweden, where no sales crash of the type in France and Germany happened, proper R&D had accompanied the development, and now also other countries followed that example. Numerous conferences and workshops allowed for exchange of experience and new discoveries; including some within the IEA heat pump programme [28-29]. For the German speaking countries in particular the Symposia in Rauischholzhausen, the meeting centre of Giessen University, had a pivotal role in bringing research and practice together [30].

On the R&D-side, more financial support was given for GSHP development in the countries where a heat pump market had started. In 1985 a private company, Helmut Hund GmbH, started on a project for a full-scale research station for BHE in cooperation with the University of Giessen and an installation company, Geotherm GmbH. The work was supported by the Federal ministry of research and technology (BMFT), and resulted in the Schwalbach GSHP research station shown in fig. 6 [31]. In 1986 this project became part of Annex 8 of the IEA Heat Pump Implementing Agreement. In Annex 8 'Advanced In-Ground Heat Exchange Technologies' institutions from Canada (NRC Ottawa), Germany (Giessen Univ. / Hund), Switzerland (ETH / Polydynamics) and USA (Oak Ridge NL) worked together. Each had either a test site for BHE, or used measurements from commercial plants with additional sensoring, like in Elgg ZH in Switzerland [32].

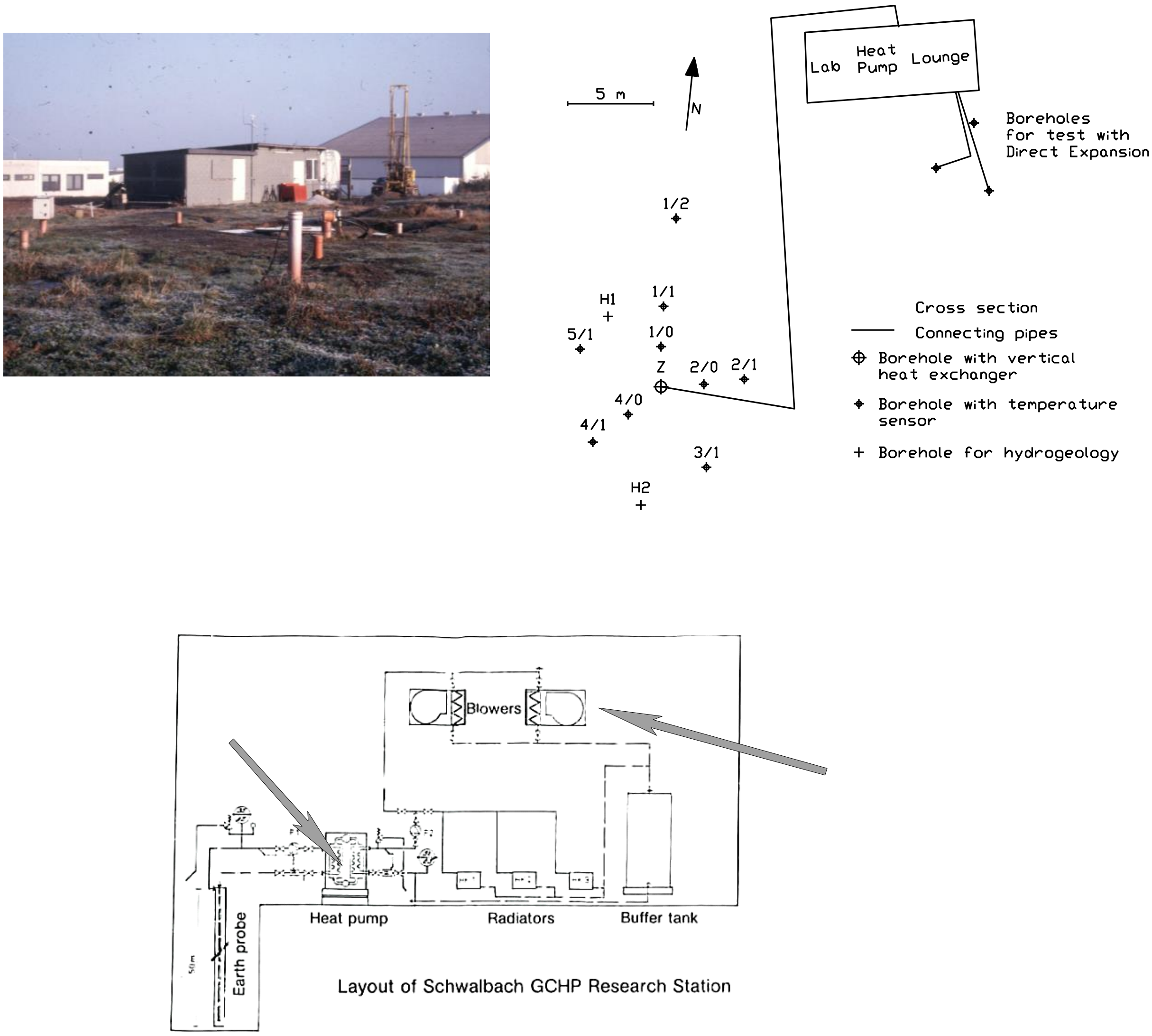

Fig. 6. Schwalbach GSHP-research station; seen from southwest on a very cold day in January 1988 (upper left), final plan of the installation as of 1988 (upper right), and schematic (from [33]) with photos of components (below)

Schwalbach GSHP research station was operated from 1985-89, the main results are summarised in [34]. The station consisted of a shack with heat pump and two fan-coil units towards the ambient air (fig. 6), coupled to a borehole heat exchanger (BHE) of 50 m depth (Z in figures 6 and 7). That BHE was surrounded by a number of boreholes with temperature sensor cables to the same depth, and two wells for hydrogeological investigation (fig. 6). The artificial heat load (the two fan-coil units) allowed for extracting heat from the ground, independent of any building heating requirement, creating a kind of ‘immobile TRT rig’. This feature was used e.g. to investigate the heat transport in the ground by running tests with relative stable temperature in the BHE over various time periods, up to one month (fig. 7, left). The pattern of the BHE and boreholes with sensors allowed for visualising the underground temperature distribution during heat extraction and recovery; an example is given in fig. 7 (right). A Finite-Difference-model TRADIKON-3D for numerical simulation of the heat transport was developed at Giessen University and validated using the data from Schwalbach [35]; in particular the sophisticated freezing algorithms included in TRADIKON-3D could be checked against real measurement data.

The IEA-cooperation strongly supported the work, with the possibility to compare the freezing effects with experiments at NRC Ottawa and the numerical simulation with the experiences from Oak Ridge NL in USA. Similar Research installations were built and operated in the following years in Europe, including:

- HTL Burgdorf, Switzerland (around 1995)
- EDF Lab les Renardières, France (around 2000)

- BRGM Orléans, France (around 2000, still operational)

and others.

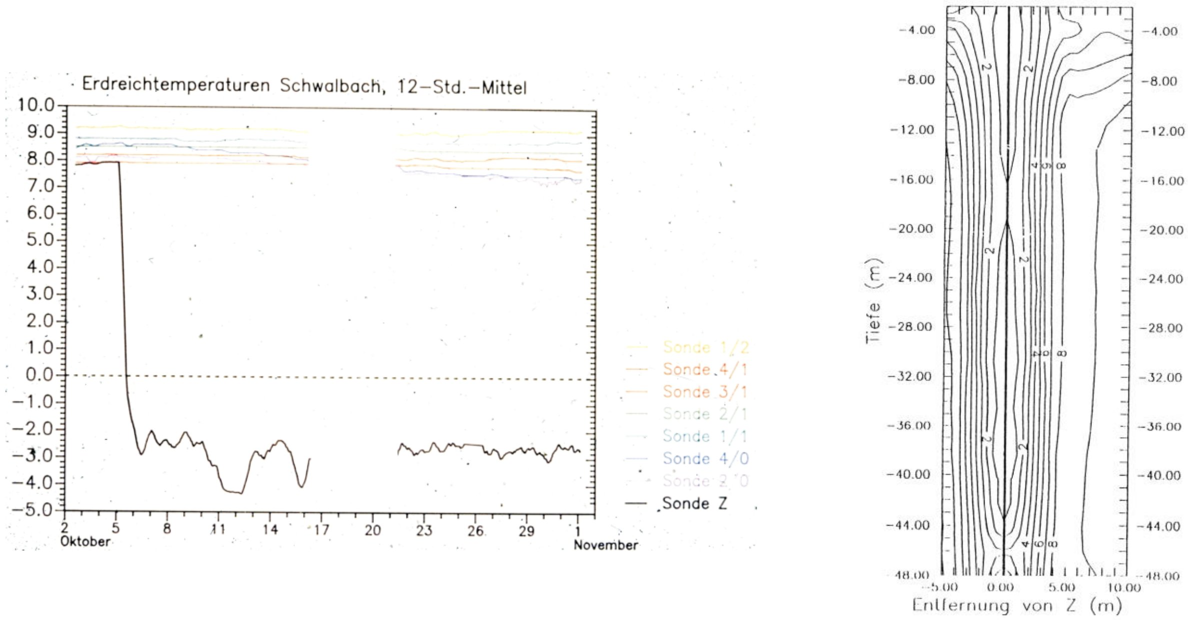

Fig. 7. Schwalbach GSHP-research station, original plotter graph from 1986 showing the temperature development in the BHE ("Sonde Z") and the surrounding observation boreholes (cf. fig. 6) during a long-term extraction test with target temperature -3 °C in October 1986 (left), and example of temperature distribution around BHE on 1.4.1987 (right)

2.4. Design methods for BHE installations- Software and TRT

In the beginning, the design of GSHP installations was done mainly by rules of thumb (usually 50 W/m in Germany and 55 W/m in Switzerland). Mathematical descriptions had already been developed during the first GSHP era in the USA around 1950, and furthermore in France, Germany and Sweden at the end of the 1970s; however, these methods could not be used by most practitioners. A group of Physicists and Mathematicians at Lund University started in the 1980s to create accurate descriptions of the heat transport [36], and later to simplify the calculations in the form of small computer programs. Together with the development of the PC, these methods could be easily applied and changed the design practice, at least for larger projects. For the single family house, the rules of thumb somehow survive until today, albeit guidelines in most countries meanwhile offer much better design options. In 1992 the mathematical excellence at Lund University and the practical experience at Giessen University were combined to create the first version of the program EED [37], which helped numerous BHE projects to a correct sizing. A similar development took place in the USA, resulting in programs like GLHEPRO and GSHPCALC.

The development of a method to determine the thermal conductivity of the underground, the TRT, also took place during the 1990s. The theoretical basis for the TRT was laid over several decades [38-39], and first practical applications were made in the 1980s, e.g. in a residential house [40]. These tests were made as a-posteriori verification of completed systems, and to understand the thermal interaction of heat exchangers and underground. In 1995 mobile test equipment was developed at Luleå Technical University to measure the ground thermal properties for BHE between some 10 m to over 100 m depth [41]. A similar development was going on independently since 1995 in the USA, in collaboration of an Oklahoma-based private company and Oklahoma State University [42-43]. Both test rigs imposed a step heat pulse on the ground, using an electric resistance heater. In Europe, further mobile TRT are reported since 1997 in the Netherlands [44], and since 1999 in Germany [45]. An excellent and very comprehensive account on the history of TRT, dealing in particular with the theoretical concepts and evaluation methods, is given in [46], a more practical summary with European focus in [47]. Today, TRT is a standard procedure in any larger BHE project (fig. 8), and first standards and guidelines exist (EN ISO 17628:2015 and the more comprehensive draft VDI 4640-5:2016).


Fig. 8. Typical TRT-setup at BHE on a site under development, in summer 2016 (left)
and very mobile TRT on the same site in Northern Germany (right), photos Kahl/UBeG

2.5. Market and guidelines for GSHP

The 1990s were also the time when work on guidelines for shallow geothermal energy started in Europe, first with AWP T1 in Switzerland and then with VDI 4640 in Germany, the first draft of which was published in 1998. In the USA, IGSHPA has provided guidelines for the ground part of GSHP since about 1990, and there are also some ASHRAE standards for more general issues. An account of the European standardisation efforts was given in [48]. Table 1 lists the currently available standards and guidelines on GSHP in the European countries. A new technical committee was established with the European Standards Committee CEN in 2016 and will have a first meeting in January 2017, CEN/TC 451 “Geothermal and water boreholes”. The very broad scope on water and geothermal was questioned by some countries, and it remains to be seen if this new initiative can result in a useful set of harmonized standards for GSHP in Europe one day.

In the absence of signals from the oil price front, market development was mainly due to financial support programs. In Germany, incentives were provided e.g. by electric utilities like RWE, or (since 1995) from the Federal Ministry of Economy; their impact can be seen in fig. 10. Similar incentive programmes existed in North America, mainly initiated by electric utilities like Niagara Mohawk, with the goal to reduce peak power demand by increasing the use of GSHP, showing a more stable demand profile. The experiences from R&D, design knowledge and eventually guidelines helped to secure the new growth in Europe and to re-build costumer confidence lost in 1980. The downward trend e.g. in Germany could be stopped and reversed, starting a steady increase of GSHP well into the first years of the 21st century (fig. 10). Information campaigns helped also, and in Switzerland a working GSHP was even installed as an exhibit in a popular museum of natural history in St. Gallen (fig. 9).

Table 1. Standards and guidelines relevant to ground source heat pumps in Europe

Country	Number	Title in English	Year
Europe	EN 15450	Heating systems in buildings – Design of heat pump heating systems	2007
AT	ÖWAV-Regelbl. 207	Thermal use of groundwater and underground - Heating and cooling	2009
DE	DIN 8901	Refrigerating systems and heat pumps - Protection of soil, ground and surface water	2002
DE	VDI 4640-1 to -5	Thermal use of the underground - Fundamentals, approvals, environmental aspects (-1), Ground source heat pump systems (-2), Underground thermal energy storage (-3), Direct uses (-4), Thermal Response Test (draft, -5)	2001 to 2015
CH	SN 546 384/6	Borehole heat exchangers	2010
CH	SN 546 384/7	Use of the heat of the groundwater	2015
FR	NF X10-960-1 to -4	Boreholes for water and geothermal - vertical borehole heat exchangers - General issues (-1), pipe loops of polyethylene 100 (PE 100) (-2), of cross-linked polyethylene (PE-X) (-3) and of polyethylene with higher temperature resistance (PE-RT) (-4)	2013
FR	NF X10-970	Boreholes for water and geothermal - vertical borehole heat exchangers - Installation, commissioning, maintenance, abandonment	2011

IT	UNI 11466	Geothermal systems with heat pump – requirements for the dimensioning and design	2012
IT	UNI 11467	Geothermal systems with heat pump – requirements for installation	2012
IT	UNI 11468	Geothermal systems with heat pump – environmental requirements	2012
IT	UNI/TS 11487	Geothermal systems with heat pump – requirements for the installation of direct expansion systems	2013
IT	UNI 11517	Geothermal systems with heat pump – requirements for the qualification of companies installing geothermal heat exchangers	2013
SP	UNE 100715-1	Design, installation and maintenance of shallow geothermal installations - closed vertical systems	2014
SE	SGU Normbrunn-07	Drilling of wells for energy and water	2008 (2016 new)
UK	DECC MIS 3005	Requirements for contractors undertaking the supply, design, installation, set to work commissioning and handover of microgeneration heat pump systems (with sizing tables MCS 022)	2011
UK	GSHPA	Closed-loop Vertical Borehole - Design, Installation & Materials Standards	2011
UK	GSHPA	Thermal Pile - Design, Installation & Materials Standards	2012

3. The market today

This chapter looks at the market situation in Europe, which is very fragmented and in some areas fragile. Reports from North America since decades show much higher numbers and more stable conditions, mainly due to the universal request for heating and cooling, as opposed to the heating-dominated market in a large part of Europe. The German GSHP market since the 1970s (fig. 10) elucidates nicely some factors influencing the sales numbers, like events on the world markets, dedicated R&D, standards and incentives. The market in Germany developed quickly in the first years of the new Millennium and had another peak around 2006-2008. One reason was the insecurity in supply of natural gas from Russia, which had replaced fuel oil in the majority of houses in Germany. Alas, since that time the GSHP sales numbers are decreasing, while the share of air-source heat pumps is growing (fig. 11). In 2015, for the first time less than 30 % of new heat pumps in Germany used a geothermal source! A similar, but slower trend can be seen for Switzerland, still showing approximately 36 % of ground source in the heat pump market (fig. 11). Even more negative developments are reported from France. The situation throughout Europe is quite diverse, with some countries showing huge numbers of installations, and others with about the same population, but almost no GSHP [50].

Fig. 9. GSHP in the museum of natural history in St. Gallen, Switzerland (photo from 1993), from [49]

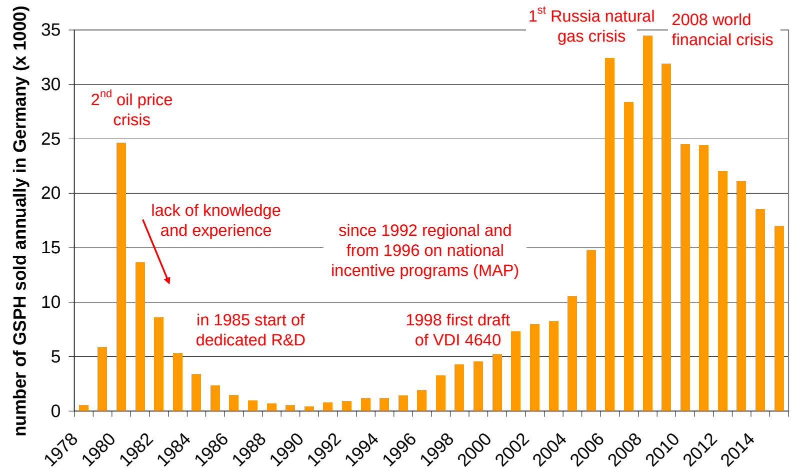

Fig. 10. GSHP sales in Germany 1978-2015 and influencing events (sales numbers after data from BWP)

In countries with substantial market development since many years (e.g. Sweden) already a replacement market has developed, as heat pumps achieve the end of their service life while the ground-coupling installations are far from worn out. If this 're-powering' is done using new, more efficient heat pumps, it also requires thorough checks to make sure the old ground installation is capable to deliver the required heat (or inject the heat from cooling); this is often the case in combination with building refurbishment (e.g. better insulation), leading to reduced heat demand.

A specific challenge for the GSHP market of today is the low percentage of new construction. This requires addressing the existing building stock, a sector where geothermal installations are not easy to deploy. In Switzerland, a country with notoriously low new construction ("Switzerland is built up already"), an impressive share of >30 % of all drilling is done for existing buildings [24], while the overall amount of BHE installation is rather stable since 2011 at approximately 2500 km of new BHE each year.

In the 21st century the development of GSHP continued steadily, and is well documented in material available online. Environmental aspects, work quality and permitting processes became more important, and in Switzerland, the country with the highest density of BHE world-wide, discussion even started about possible thermal over-use of the underground.

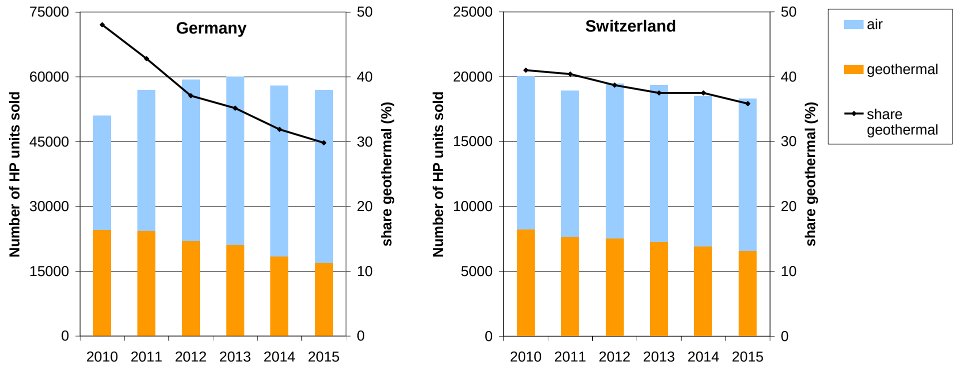

Fig. 11. Heat pump sales 2010-2015 in Germany and Switzerland, and share of geothermal in total, after data from BWP and FWS

4. What might be achieved in the future?

A basic fact not to be forgotten is that we are under the control of geology and climate – we cannot change the rock or soil outside the borehole, nor the overall temperature field. For BHE this means that optimisation by engineering is confined to the size of the borehole, and what we put inside. This is valid analogously for horizontal loops, energy piles etc. For BHE the parameter of 'Borehole Thermal Resistance' was introduced, combining all the effects from the rock outside the borehole into the fluid in the pipes [51]. No borehole thermal resistance, i.e. r_b = 0 K/(W·m), would mean instantaneous transfer of heat from the rock into the fluid and vice versa. Hence r_b can be used as a parameter to describe the quality of a BHE design, as influenced by geometry, pipe material, grouting, flow volumes, surfaces etc.

Because the ‘specific heat extraction rate’ of a BHE has no meaning without clearly defined boundary conditions, the ‘Hellström-Efficiency’ was introduced to allow comparison of BHE installations. It is defined as the ratio of heat extraction (under sustainable conditions) possible in a given, real installation to a heat extraction calculated under the assumption of r_b = 0 K/(W·m) [52]. While specific heat extraction rate and r_b may vary according to the rock type, BHE design, size of the project (number of BHE), load profiles, etc., the Hellström-Efficiency η_H always shows how close a given installation is to the theoretical optimum. Any claims for heat extraction rates that would result in η_H of 100 % or more can be dismissed as physically impossible. New designs and materials might help to move closer to the optimum in routine installations, but not beyond.

The key document identifying future R&D-goals for renewable heating and cooling, the ‘Common Roadmap’ of the RHC-Platform [53], lists the Key Performance Indicators towards 2020 as given in table 2. The main areas are addressed: the efficiency of the heat pump and system, the efficiency of the ground-coupling components, and the cost for installation and operation. In the light of the constraints concerning higher efficiency, the issue of cost reduction seems to be the most important target.

Table 2. Key Performance Indicators (KPI) for 2020 as in the Common Roadmap of the RHC-Platform* from June 2014 [53]
(* the full name is: European Technology and Innovation Platform for Renewable Heating and Cooling)

KPI	Target
SG1	A Seasonal Performance Factor in the order of 5 for 2020
SG2	A Hellström-efficiency (a measure of the impact of borehole thermal resistance) of about 80% in 2020
SG3	A further decrease in energy input and reduced costs for operating the geothermal heat pump system

The topics for R&D advancing towards these targets in Europe are also listed in the Common Roadmap [53]. The most important as to the author´s view are:

- Improved vertical borehole drilling technologies to enhance safety and reduce cost of BHE installations, improved installation technologies and geometries for ground heat exchange technology.
- Improved pipe materials for BHE and horizontal ground loops. New pipes for higher temperatures. Better thermal transfer fluid.
- Integration of design of the shallow geothermal system and building energy system with regard to optimum thermal use and operational strategy.

And in a more general and non-technological sense:

- Creation of a new European wide database to map conductivities and potential (to 100 m depth or more) and feasibility of vertical BHE systems. (author´s remark: and with link to the new European Geological Data Infrastructure EGDI).
- Measures to increase awareness, harmonisation of shallow geothermal standards, EU-wide training certificate for shallow geothermal installers.

In November 2016, the Steering Committee of the Geothermal Panel of the RHC-Platform agreed on the following updates to the topics, among others:

- Optimisation of the borehole-grout-pipe system, solving current grouting problems (fractures, freezing, and other), and development of measuring and control tools.
- Improvement in shallow geothermal drilling technology for cost reduction and reduced impact (automation, minimum invasiveness, drilling for refurbishment, also with a view to historical buildings).
- Demonstrate applicability of shallow geothermal for industry and municipalities (district heating), including use of high-temperature heat pumps or UTES at elevated temperature, defrosting of infrastructure, etc.

Indeed, a lot more can be done to make ground source heat pumps better, i.e. more effective, more economic, easier to install, avoiding any risk for ground and groundwater, broadening the area of application within the existing building stock, industry, infrastructure etc. We can capitalise on the intrinsic advantages in efficiency ground coupling offers for heating and cooling, and on the reliability achieved, and go beyond.

Looking back at about 40 years of well-documented development in Europe, 70 years of experience in North America, and more than a century of ideas and proposals, the status achieved today is characterised by sound knowledge and good design (albeit some shortcomings in practical execution cannot be overlooked). Often a certain feeling of déjà-vu goes with seeing new developments praised; an example are helicoidal ground heat exchangers, already a part of Zoelly´s patent application in 1913, seen again in the USA in the 1940s, claimed a novelty in several patent applications in France and Germany and subject to R&D in Canada in the 1980s, and now part of new R&D in Italy and in EU-projects. The author is confident that, despite some current economic retardation e.g. in the residential heating sector, the success story of GSHP is far from ending.

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