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C.4.

SHALLOW GEOTHERMAL SYSTEMS, GROUND SOURCE HEAT PUMPS

a) Technology

Dr. Burkhard Sanner
http://www.sanner-geo.de

ABSTRACT

Geothermal Heat Pumps, or Ground Source Heat Pumps (GSHP), are systems combining a heat pump with a ground heat exchanger (closed loop systems), or fed by ground water from a well (open loop systems). They use the earth as a heat source when operating in heating mode, with a fluid (usually water or a water-antifreeze-mixture) as the media transferring the heat from the earth to the evaporator of the heat pump, utilising that way geothermal energy. In cooling mode, they use the earth as a heat sink.

With BHE geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet any demands.

More than 25 years of R&D focusing on BHE in Europe resulted in a well-established concept of sustainability for this technology, as well as sound design and installation criteria. Recent developments are the Thermal Response Test, which allows in-situ-determination of ground thermal properties for design purposes, and thermally enhanced grouting materials to reduce borehole thermal resistance.

Despite the use of geothermal heat pumps for over 50 years now (first in USA), market penetration of this technology, is still at its infancy, with fossil fuels dominating the market of heating of buildings and air-toair heat pumps dominating the market of cooling of buildings. In some countries, namely Germany, Switzerland, Austria, Sweden, Denmark, Norway, France and USA, already larger numbers of geothermal heat pumps are operational. In these countries meanwhile installation guidelines, quality control and contractor certification becomes a major issue.

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1. INTRODUCTION

First, two abbreviations have to be mentioned, which are used frequently throughout this text:

- GSHP Ground Source Heat Pump
- BHE Borehole Heat Exchanger (in USA, the term Vertical Loop is common)

Most European countries do not boast abundant hydro-geothermal resources that could be tapped for direct use (some exceptions are e.g. Iceland, Hungary, France). The utilization of lowenthalpy aquifers that enable the supply of a larger number of customers by district heating is limited so far to regions with specific geological settings. However, the underground in the first approx. 100-200 m is well suited for supply and storage of thermal energy. The climatic temperature change over the seasons is reduced to a steady temperature at 10-20 m depth (fig. 1), and with further depth temperatures are increasing according to the geothermal gradient (average 3 °C for each 100 m of depth). In this situation the utilization of the ubiquitous shallow geothermal resources by GSHP systems is an obvious option. Correspondingly, a rapidly growing field of applications is emerging and developing in various European countries. A rapid market penetration of such systems is resulting; the number of commercial companies actively working in this field is ever increasing and their products have reached the "yellow pages" stage.

The climatic conditions in Central and Northern Europe, where most of the market development took place, are such that by far the most demand is for space heating; air conditioning is rarely required. Therefore, unlike the "geothermal heat pumps" in the USA, the heat pumps usually operate mainly in the heating mode. With the inclusion of larger commercial applications, requiring cooling, and the ongoing proliferation of the technology into Southern Europe, the double use for heating and cooling will become of more importance in the future.

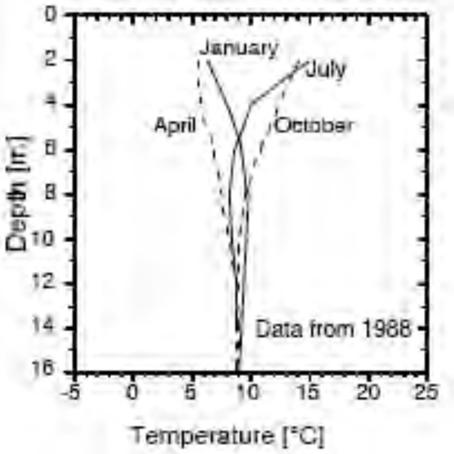


Fig 1: Underground temperatures from a borehole south of Wetzlar, Germany, not influenced by the heat pump operation

2. GSHP TECHNOLOGY STATUS

2.1 History and classification of ground coupling

Ground Source Heat Pumps (GSHP), or Geothermal Heat Pumps, are systems combining a heat pump with a system to exchange heat with the ground. The first GSHP has been operated in Indianapolis, USA, in 1945, with horizontal heat exchanger pipes. A brief history of GSHP is given in [1]. As early as in 1947, most of the different ground-coupling methods have been described, and most of them demonstrated (see fig. 2). The systems can be divided basically into those with a ground heat exchanger (closed loop systems), or those fed by ground water from a well (open loop systems). The means to tap the ground as a shallow heat source comprise:

- groundwater wells ("open" systems)
- borehole heat exchangers (BHE)
- horizontal heat exchanger pipes (incl. compact systems with trenches, spirals etc.)
- "geostructures" (foundation piles equipped with heat exchangers)

The ground system links the heat pump to the underground and allows for extraction of heat from the ground or injection of heat into the ground. To choose the right system for a specific installation, several factors have to be considered: Geology and hydrogeology of the underground (sufficient permeability is a must for open systems), area and utilisation on the surface (horizontal closed systems require a certain area), existence of potential heat sources like mines, and the heating and cooling characteristics of the building(s). In the design phase, more accurate data for the key parameters for the chosen technology are necessary, to size the ground system in such a way that optimum performance is achieved with minimum cost.

2.2 Groundwater wells

Main technical part of open systems are groundwater wells, to extract or inject water from/to water bearing layers in the underground („aquifers"). In most cases, two wells are required („doublette", fig. 3), one to extract the groundwater, and one to re-inject it into the same aquifer it was produced from. With open systems, a powerful heat source can be exploited at comparably low cost. On the other hand, groundwater wells require some maintenance, and open systems in general are confined to sites with suitable aquifers. The main requirements are:

- Sufficient permeability, to allow production of the desired amount of groundwater with little drawdown.
- Good groundwater chemistry, e.g. low iron content, to avoid problems with scaling, clogging and corrosion.

Open systems tend to be used for larger

installations.

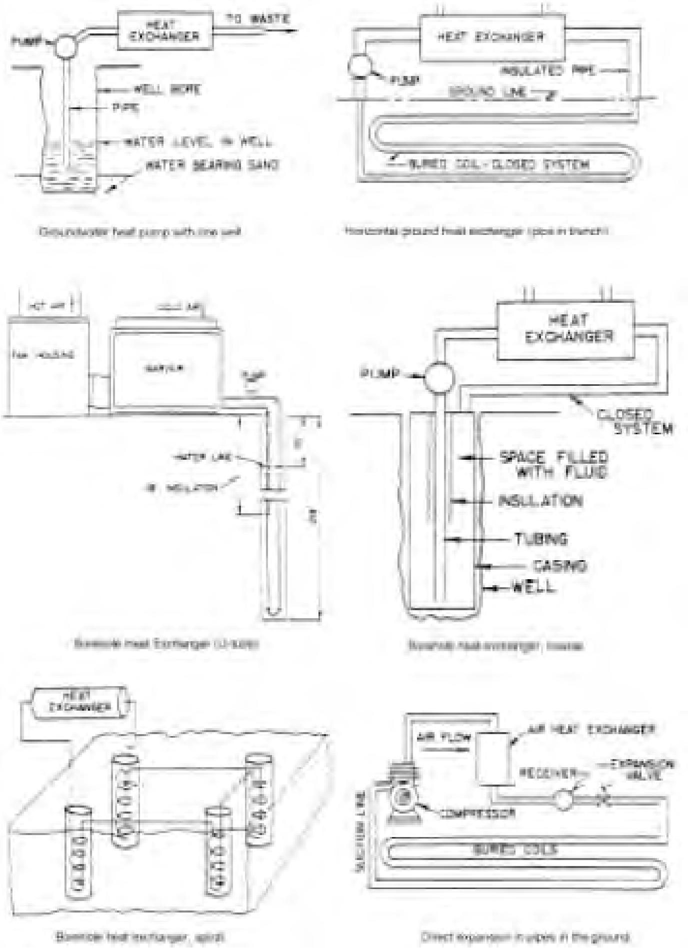
2.3 Horizontal loops

The closed system easiest to install is the horizontal ground heat exchanger (synonym: ground heat collector, horizontal loop). Due to restrictions in the area available, in Western and Central Europe the individual pipes are laid in a relatively dense pattern, connected either in series or in parallel (fig. 4).

To save surface area with ground heat collectors, some special ground heat exchangers have been developed (fig. 5): Spiral forms, mainly in the form of the so-called „slinky“ collectors, and trench collectors. Exploiting a smaller area at the same volume, these collectors are best suited for heat pump systems for heating and cooling, where natural temperature recharge of the ground is not vital. The main thermal recharge for all horizontal systems in heating-only mode is provided for mainly by the solar radiation to the earth´s surface. It is important not to cover the surface above the ground heat collector.

2.4 Vertical loops (BHE)

Because the temperature below the „neutral zone“ (ca. 10-20 m) remains constant over the year, and because of the need to install sufficient heat exchange capacity under a confined surface area, vertical ground heat exchangers (borehole heat exchangers, fig. 6) are widely favoured. In a standard borehole heat exchanger, plastic pipes (poly ethylene or polypropylene) are installed in boreholes, and the remaining room in the hole is filled (grouted) with a pumpable material.



Groundwater heat pump with one well

Horizontal ground heat exchanger (pipe in trench)

Borehole heat Exchanger (U-tube)

Borehole heat exchanger, coaxial

Borehole heat exchanger, spiral

Direct expansion in pipes in the ground

Fig. 2: Different types of ground heat exchangers as described in 1947, after [2]

Several types of borehole heat exchangers have been used or tested; the two possible basic concepts are (fig. 7):

- U-pipes, consisting of a pair of straight pipes, connected by a 180°- turn at the bottom. One, two or even three of such U-pipes are installed in one hole. The advantage of the U-pipe is low cost of the pipe material, resulting in double-U-pipes being the most frequently used borehole heat exchangers in Europe.
- Coaxial (concentric) pipes, either in a very simple way with two straight pipes of different diameter, or in complex configurations.

The borehole filling and the heat exchanger walls account for a drop in temperature, which can be summarised as borehole thermal resistance. Thermally enhanced grouting (filling) materials have been developed to reduce this losses (see chapter 3).

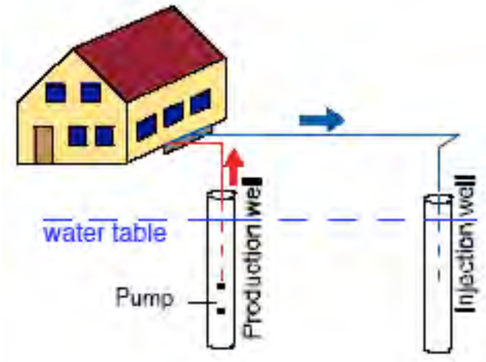


Fig. 3: Groundwater heat pump (doublette)

2.5 Energy piles

A special case of vertical closed systems are „energy piles“, i.e. foundation piles equipped with heat exchanger pipes (fig. 8 and 9). All kind of piles can be used (pre-fabricated or cast on site), and diameters may vary from 40 cm to well over 1 m.

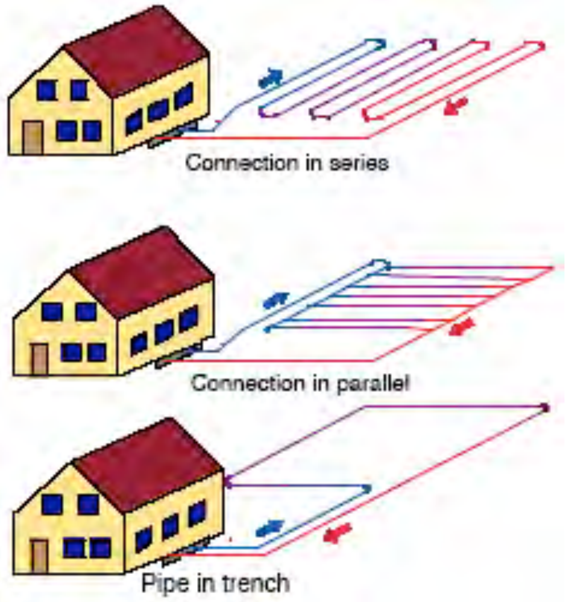


Fig. 4: Horizontal ground heat exchanger types

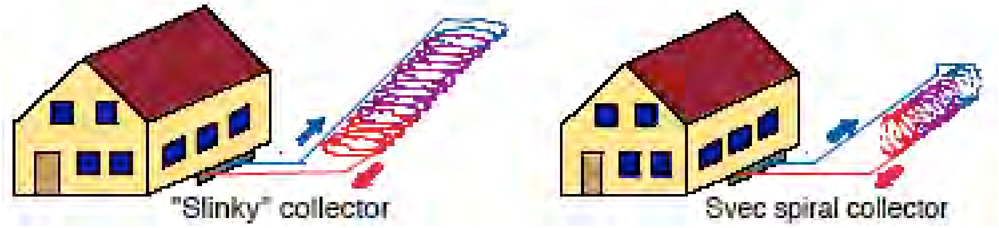


Fig. 5: Horizontal ground heat exchanger types for smaller areas

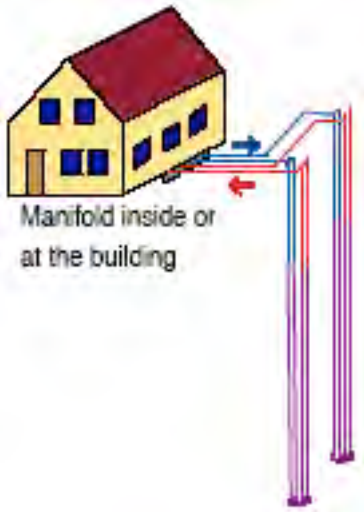


Fig. 6: Borehole heat exchangers (double-U-pipe)

2.6 Summary ground coupling

The technology most widely applied today is the borehole heat exchanger (BHE). From all

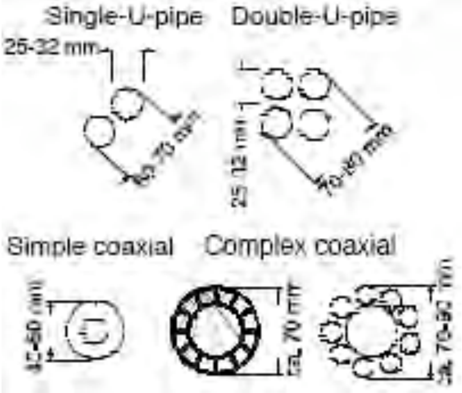


Fig. 7: Cross-sections of different types of borehole heat exchangers

of the different approaches shown in fig. 7, the U-tube design has the best cost-performance-ratio, and has out numbered all other designs by far. In Central Europe, the double-U-tube is popular, while in Northern Europe and North America the single-U-tube prevails. It can be said in general, that double-U-tubes allow for a thermal efficiency 15-25 % higher than single-U-tubes. Thus in regions with low drilling cost, but higher pipe cost, the single-U-tube is preferred, and in regions with high drilling cost and cheap pipes, the double-U-tube becomes more economic.

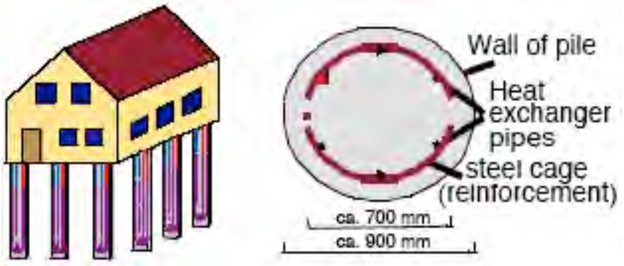


Fig. 8: Energy piles and cross-section of a pile with 3 loops

Experimental and theoretical investigations (field measurement campaigns and numerical model simulations) have been conducted over several years to elaborate a solid base for the design and for performance evaluation of BHE systems (see [3], [4], [5]). While in the 80´s theoretical thermal analysis of BHE-systems prevailed in Sweden [6], [7] monitoring and simulation was done in Switzerland [8], [9], and measurements of ground heat transport were made on a test site in Germany [10].

3. THE HEAT PUMP

Generally a heat pump can be considered as a device which uses heat on a low temperature level, and transfers the heat to a higher, useful temperature level using an external driving force (mechanical energy or high-temperature heat). This makes the heat pump suitable for using shallow geothermal energy for heating. Heat is extracted from the ground at temperatures between –5 °C and +10 °C and is supplied to a heating system with 35-55 °C. The smaller the temperature lift is in this case (e.g. 0 °C to 35 °C), the less driving energy is required and the better is the energy efficiency

An analogy to the heat pump can e found in virtually all modern households: the refrigerator. Also heat pumps can be designed in such a way that they can be used for both purposes, heating in wintertime and space cooling during summer. Such reversible heat pumps are built in large numbers in Japan and North America, while in Europe the heatingonly heat pump (house heating and domestic hot water) prevails.

3.1. Working principle of the heat pump

Heat pump working principles can be distinguished into compression and sorption cycles. Fig 9 shows the schematic of a compression heat pump. The working cycle is as follows: Heat on a low temperature level evaporates a medium with low boiling point (“refrigerant”, today usually a hydrofluorocarbon (HFC) or a mixture of different HFCs, or a natural refrigerant like propane or CO2), the steam then is compressed in a compressor (usually to some 20 bar) and thus is heated up. Under high pressure and high temperature the refrigerant transfers its heat to the heating water or to air, is cooled and condensed in this process. The refrigerant then moves back to the low pressure side through an expansion valve or a capillary tube, the temperature drops drastically, and the medium can be evaporated again on the low temperature side, re-starting the cycle.

The heat pump compressors usually are driven by electric motors.

Only for large heat pumps, units driven by gas- or diesel-engines are available. Heat pumps driven by internal combustion engines also allow use of the heat fom motor cooling and flue gas for heating. Systems using electric power from a heat-and-power co-generation unit to operate an electrically driven heat pump (examples can be found e.g. in Switzerland and Germany) could be seen as combustion-engine-driven heat pumps with electric power transmission.

Sorption heat pumps use reversible physico-chemical processes, where two materials are separated by heat, and release heat again during re-combination (absorption, adsorption, resorption). One medium has a low boiling point and thus again can use heat on a low temperature level. A typical example is water and ammonia, which is dissolved (absorbed) in the water. A sorption heat pump can also be realized using a solid material, like zeolite with the working medium water. The driving energy is not mechanical energy for a compressor, but heat for the separation process. This heat can be provided by natural gas, fuel oil, or waste heat. In their simplest form, an absorption heat pump consists of evaporator, absorber, solution pump, separator, condensor and expansion valve.

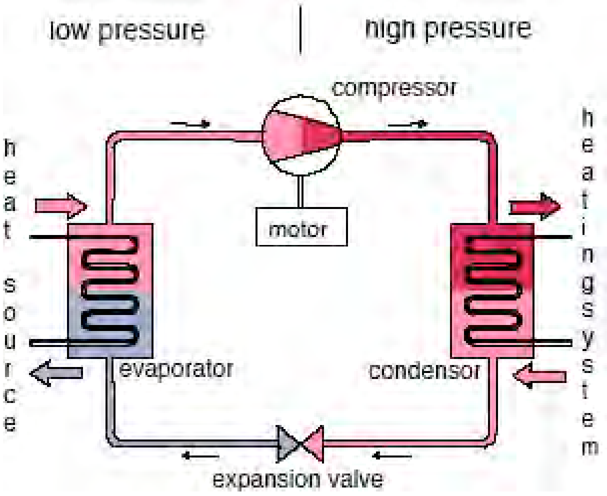


Fig. 9: Schematic of a compression heat pump

In the low capacity range, absorption heat pumps are available from ca. 25 kW heating capacity upward. With their water/ammonia or lithium bromide/water working media they are suitable for heat source temperatures well above 0 °C, which can be provided by ground- or surface water, and in some cases also by BHE.

3.2. Heat pump efficiency

In table 1, the most important efficiency parameters of a heat pump or a heat pump system, respectively, are listed. The ideal conditions of a heat pump, and thus also the benchmark for the highest possible coefficient of performance (COP), is described by the Carnot cycle (fig. 10). In the Carnot-cycle, the working medium undergoes the following cycle process:

leg 1-2 Isothermal evaporation heat consumption
leg 2-3 Isentropic compression driving energy input
leg 3-4 Isothermal condensation heat release
leg 4-1 Isentropic expansion

In the real heat pump process, the expansion is not isentropic, and the compression has to reach a temperature well above that of the isothermal condensation (fig. 10). The larger the isothermal part of leg 3- 4 is, the closer the heat pump reaches the Carnot process. The heat pump COP, compared to the ideal Carnot process, describes the Carnot efficiency hc, which can e.g. be written as:

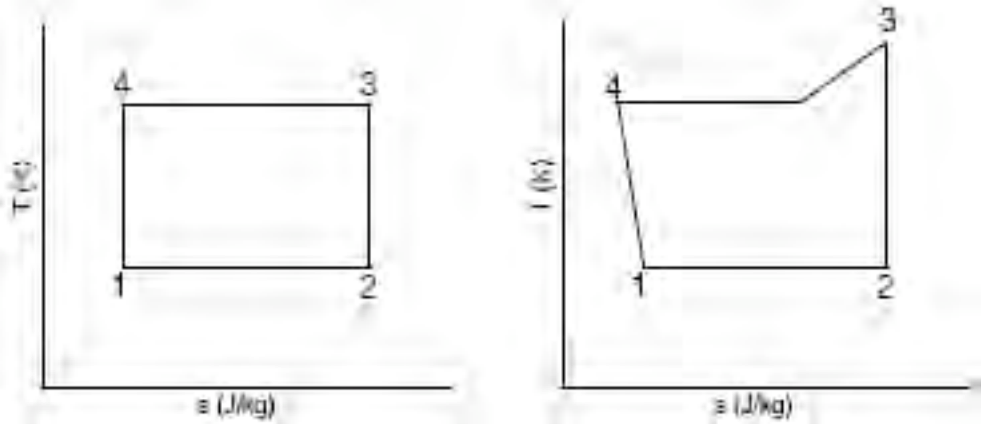


Abb. 10: Diagram showing temperature (T) versus entropy (s) of the Carnot cycle (left) and of a real heat pump cycle (schematic, right)

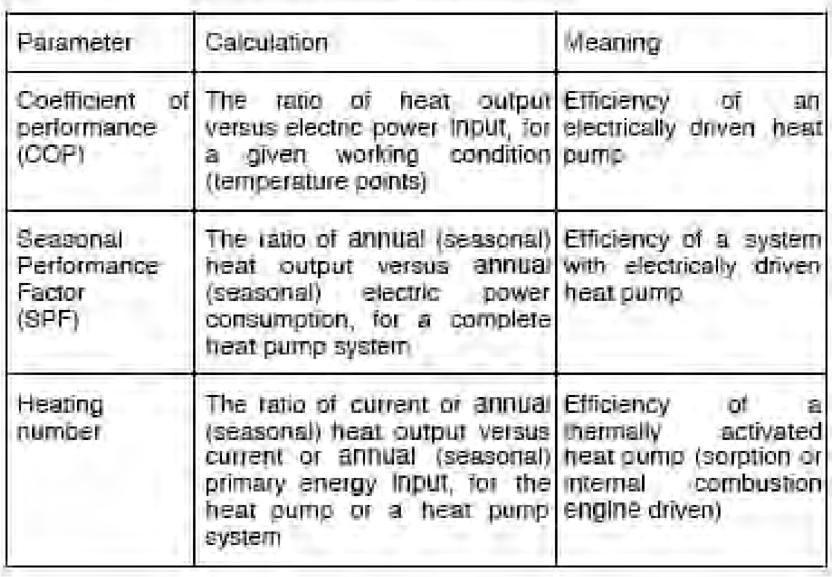
P
Pc
c = h

with: Pc activation energy of the Carnot heat pump P activation energy of the real heat pump

In a real heat pump, there are more differences to the ideal Carnot process.

Generally a certain superheating is required in the evaporator to secure complete evaporation in order to protect the compressor from liquid (which is not compressible). Further losses can be found in the compressor (e.g. dead room in a piston compressor) and in the expansion device.

Tab. 1: Heat pump performance parameters



Parameter	Calculation	Meaning
Coefficient of performance (COP)	The ratio of heat output versus electric power input, for a given working condition (temperature points)	Efficiency of an electrically driven heat pump
Seasonal Performance Factor (SPF)	The ratio of annual (seasonal) heat output versus annual (seasonal) electric power consumption, for a complete heat pump system	Efficiency of a system with electrically driven heat pump
Heating number	The ratio of current or annual (seasonal) heat output versus current or annual (seasonal) primary energy input, for the heat pump or a heat pump system	Efficiency of a thermally activated heat pump (sorption or internal combustion engine driven)

The COP of modern electric heat pumps could be increased steadily over the last years, using new refrigerants, better compressor types, etc. This becomes obvious in measurements from the Swiss test center for heat pumps in Töss, where heat pumps are tested independently under controlled conditions. Fig. 11 shows the increase in COP with time; because different conditions prevail for ground, water and air as heat source, three curves at different levels are shown.

The efficiency over a longer period is defined by the seasonal performance factor (SPF). Therefore the electric input and thermal output over e.g. a year is measured. In addition to the electric power consumption of the compressor, that of peripheral devices like pumps in the ground system are also considered. While the COP is measured under controlled circumstances and given temperature points, these values for SPF follow the actual system conditions of the installation over the test period. Thus the SPF is a more useful tool to describe the performance of a system for ground heat use, while the COP allows comparison between individual heat pump brands and types. With state-of-the-art groundwater heat pumps, typical SPF in Europe range today between 4.0 and 4.5, while heat pumps with BHE achieve ca. 3.8 to 4.3. A prerequisite for such high SPF are sufficiently sized ground source systems and heat distribution systems on a low temperature level (e.g. 35 °C with floor heating).

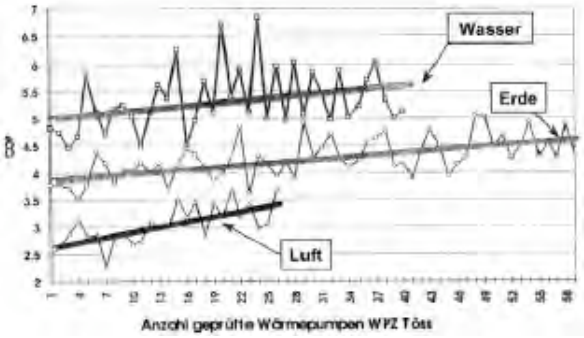


Fig. 11: Comparison of COP over time for heat pumps tested over the timeframe 1993-98 (source: FWS / Wärmepumpentest- und aus-bildungs-zentrum Töss)

4. PLANNING AND OPTIMIZATION OF BHE-SYSTEMS

When using (BHE), the required length for a given power output is highly dependent upon soil characteristics including temperature, moisture content, particle size and shape, and heat transfer coefficients.

Correct sizing of the BHE continues to be a cause for continued design concern, and special attention should be placed on minimizing interference between neighbouring BHE. Key points are building load, borehole spacing, borehole fill material and site characterisation.

Due to the high capital costs involved, over-sizing carries a much higher penalty than in conventional applications.

Two important technical developments of recent years should be mentioned in this respect:

- Thermal Response Test to determine the thermal parameters of the underground in situ
- Grouting material with enhanced thermal conductivity

4.1 Thermal Response Test

For a thermal response test [11], basically a defined heat load is put into the BHE and the resulting temperature changes of the circulating fluid are measured (fig. 12). Since mid 1999, this technology now also is in use in Central Europe for the design of larger plants with BHE, allowing sizing of the boreholes based upon reliable underground data.

Thermal response test first was developed in Sweden and USA in 1995 [12], [13] and now is used in many countries world-wide, including Turkey. Together with reliable design software [14], [15], BHE can be made a sound and safe technology even for larger applications.

4.2. BHE design software

Practical use of heat transport calculation around pipes started in 1920 [17]. The earliest approach to calculating thermal transport around a heat exchanger pipe in the ground was the Kelvin line source theory in [18], [19]. PC-programs for quick and reasonably sound dimensioning of ground heat systems with borehole heat exchangers have been presented by [20], [21], [22] and [23]. The algorithms have been derived from modeling and parameter studies with a numerical simulation model SBM ([24], [25]), evolving to an analytical solution of the heat flow with several functions for the borehole pattern and geometry (*g*-functions, see [24]). Those *g*-functions depend on the spacing between the boreholes at the ground surface and the borehole depth. In the case of graded boreholes there is also a dependence on the tilt angle. The *g*-function values obtained from the numerical simulations have been stored in a data file, which is accessed for rapid retrieval of data by the PCprograms.

After first discussions in summer 1991, co-operative work on a new programme called “Earth Energy Designer” (EED) began in June 1992, and was presented in 1994 [26], and the b-version distributed in summer 1995 [27]. The program EED allows for calculation of heat exchanger fluid temperatures for monthly heat/cool loads.

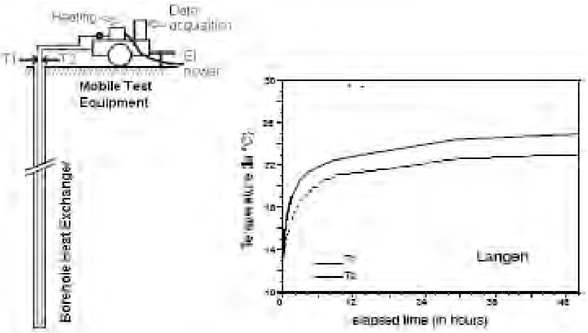


Fig. 12: left: Schematic of a Thermal Response Test right: Example of measured data from a Thermal Response Test, from [11]

Databases provide the key ground parameters (thermal conductivity, specific heat) as well as properties of pipe materials and heat carrier fluids. The calculation is done using 12 separate extraction steps. The steps are considered as 12 month, and the monthly average heat extraction/injection are the input data. In addition, an extra pulse for maximum heat extraction/injection over several hours can be considered at the end of each month.

The user can choose between different methods of establishing a monthly load profile. A printed output report and output files containing data for graphical processing were provided in version 1.0 under MS-DOS; version 2.0, running under MS-Windows 95 and higher, offers direct graphical output.

The borehole thermal resistance rb is

calculated in the program, using borehole geometry, grouting material and pipe material and geometry. It is also possible to give input data for rb, suing e.g. measured date from Thermal Response Test. The *g*-functions for borehole patterns can be browsed in a window, and the adequate function for the given layout is chosen directly. In the recent version, the borehole distance is typed in directly, and the program interpolates between suitable *g*-functions, keeping the borehole distance constant with changing borehole depth.

The current version of EED can be found under http://www.buildingphysics.com (go to „Software“), where also a demo version and the user manual can be downloaded. A total of 308 different borehole patterns is available, including boreholes in a straight line, in the form of L- or U-shaped lines, and as open or filled rectangles. Fig. 13 shows an example.

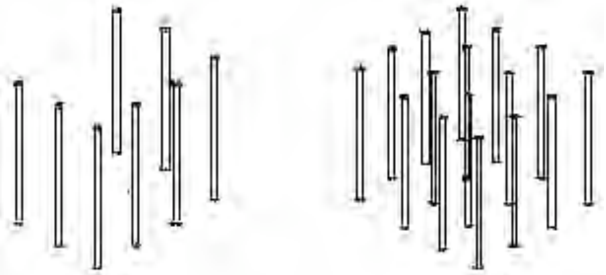


Fig. 13: Examples of g-functions left: U-configuration, 3 x 4 BHE, total 8 BHE, g-function no.112
right: Filled rectangular config., 4 x 4 BHE, total 16 BHE, no. 262

Calculations with EED were compared to numerical simulation, e.g. using the FD-code TRADIKON-3D [28], and a good agreement of predicted fluid temperatures was found [29]. [30] described the design of a field of BHE in a new development area. For 3 houses in a row with one BHE each and 10 m distance between BHE, the temperature development in the ground was simulated (fig. 14). A comparison was made to EED, where only an average value for fluid temperatures in all 3 BHE is given:

- In the two external BHE, simulated temperatures were up to 0.4 K higher than EED-values
- In the inner BHE, simulated temperature was up to 0.5 K lower than EED-values

Overall, EED showed a rather good agreement with the mean of the simulated temperatures.

An existing ground source heat pump (GSHP) plant with direct cooling was monitored from July 1995 on (UEG, Wetzlar, see paper on case studies in this volume). Fig. 15 shows the monitored mean brine temperature from July 1995 - July 1996 and the brine temperature calculated with EED. Monthly heat and cold demand was taken from measured data for EED calculation. Since the plant was operational over 3 years before monitoring started, temperature values for the fourth year were chosen for the graph in fig. 15. The exact load values for the three preceding years are not known, adding some possible error to the comparison. Also the exact distribution of simultaneous heat and cold generation in some months is unknown.

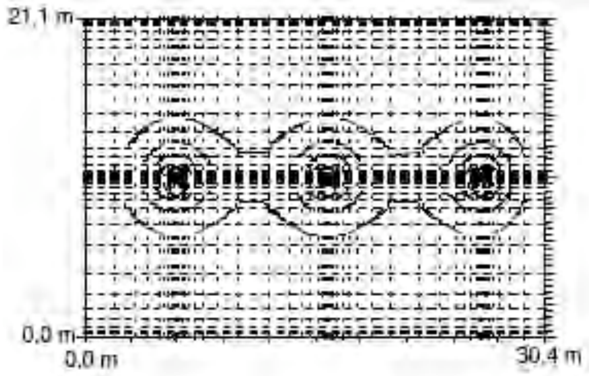


Fig. 14: Temperature distribution (isotherms) around 3 BHE, horizontal cross-section in 50 m depth, after 8 month heating, with FD-grid (after [30])

However, the curves in fig. 15 do not match exactly due to the uncertainties, but EED gives a rather good prediction of the temperatures found in reality.

4.3. BHE grouting optimization

Thermally enhanced grouting material is available in Europe in different mixtures and with several brand names. The advantage of its use is a significant reduction in the borehole thermal resistance (fig. 16), which governs the temperature losses between the undisturbed ground and the fluid inside the BHE pipes. The table in fig. 16 gives some values for typical BHE; the effect could meanwhile also be demonstrated in situ, using the Thermal Response Test on BHE with different grouting materials. The difficulty in developing a good grouting material is that different properties have to be combined in one material: good sealing of the borehole annulus, good thermal conductivity, and good pumpability (i.e. low wear on pumps). Material choices for this properties partly contradict each other, but suitable solutions meanwhile have been found in Germany.

7. CONCLUSIONS

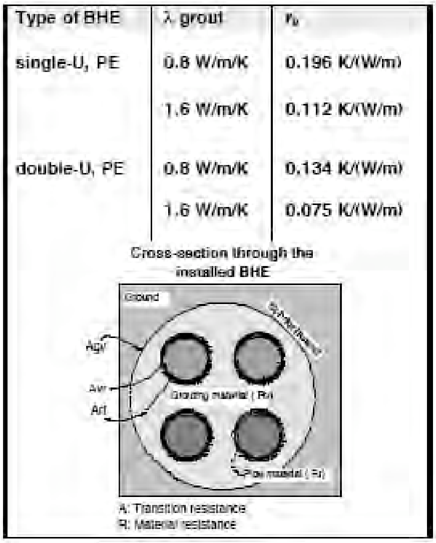
GSHP are no longer exotic. Their number has increased steadily over the years, and the technology is well understood. Optimization and further development will be required to keep GSHP efficiency in line with the advancements of competing heating and cooling systems. The main goals currently are

· cost reduction without decrease of efficiency and longevity quality certification not only for the heat pump, but for the ground coupling system also

· further increase in efficiency and design accuracy

· proliferation of GSHP into regions with no or low market penetration (e.g. Eastern Europe and the Mediterranean)

Looking back at a development over some 60 years since the first plants, some 25 years since the first BHE in Europe, and some 20 years of personal experience with GSHP by the author, the concept of shallow geothermal energy still has but started to explore its real potential.



Type of BHE	λ grout	r_b
single-U, PE	0.8 W/m/K	0.196 K/(W/m)
	1.6 W/m/K	0.112 K/(W/m)
double-U, PE	0.8 W/m/K	0.134 K/(W/m)
	1.6 W/m/K	0.075 K/(W/m)

Fig. 16: left: Table with data for rb for different grouting materials right: schematic of the concept of borehole thermal resistance rb

References

[1] SANNER, B. (2001): Some history of shallow geothermal energy use. - in: POPOVSKI, K. & SANNER, B. (eds.), International Geothermal Days Germany 2001 Bad Urach, Supplement pp. 3-12, GtV, Geeste

[2] KEMLER, E.N. (1947): Methods of Earth Heat Recovery for the Heat Pump. - Heating and Ventilating, Sept. 1947, S. 69-72, New York

[3] KNOBLICH, K., SANNER, B. & KLUGESCHEID, M. (1993): Energetische, hydrologische und geologische Untersuchungen zum Entzug von Wärme aus dem Erdreich. - Giessener Geologische Schriften 49, 192 p., Giessen

[4] RYBACH, L., HOPKIRK, R. (1995): Shallow and deep borehole heat exchangers – achievements and prospects. Proc. World Geothermal Congress 1995, 2133-2139

[5] RYBACH, L., EUGSTER, W.J. (1997): Borehole heat exchangers to tap shallow geothermal resources: The Swiss success story. In: S.F. Simmons, O.E. Morgan & M.G. Dunstall (eds.): Proc. 19th New Zealand Geothermal Workshop. Auckland, 63-69

[6] CLAESSON, J., ESKILSON, P. (1988): Conductive Heat Extraction to a deep Borehole, Thermal Analysis and Dimensioning Rules. Energy 13/6, 509-527

[7] ESKILSON, P., CLAESSON, J. (1988): Simulation Model for thermally interacting heat extraction boreholes. Numerical Heat Transfer 13, 149-165

[8] GILBY, D.J., HOPKIRK, R.J. (1985): The coaxial vertical heat probe with solar recharge, numerical simulation and performance evaluation. Proc. 2nd WS on SAHPGCS Vienna, 443-456

[9] HOPKIRK, R.J., EUGSTER, W.J., RYBACH, L. (1988): Vertical earth heat probes: mesurements and prospects in Switzerland. Proc. 4th int. Conf. Energy Storage JIGASTOCK 88, 367-371

[10] SANNER, B. (1986): Schwalbach Ground-Coupled Heat Pump (GCHP) Research Station. - Newsletter IEA Heat Pump Centre 4/4, pp. 8-10, Karlsruhe

[11] SANNER, B., REUSS, M., MANDS, E. & MÜLLER, J. (2000): Thermal Response Test - Experiences in Germany. - Proc. TERRA-STOCK 2000, pp. 177-182, Stuttgart

[12] EKLÖF, C. & GEHLIN, S. (1996): TED - a mobile equipment for thermal response test. -

62 p., Master´s thesis 1996:198E, Luleå University of Technology
[13] AUSTIN, W. (1998): Development of an in-situ system for measuring ground thermal properties. - 164 p., MSc-thesis, OSU, Stillwater OK
[14] HELLSTRÖM, G. & SANNER, B. (1994): Software for dimensioning of deep boreholes for heat extraction. - Proc. CALORSTOCK 94, pp.
195-202, Espoo/Helsinki
[15] HELLSTRÖM, G., SANNER, B., KLUGESCHEID, M., GONKA, T. & MÅRTENSSON, S. (1997): Experiences with the borehole heat exchanger software EED. - Proc. MEGASTOCK 97, pp. 247-252,Sapporo
[16] VDI (2001): Thermische Nutzung des Untergrundes / Thermal Use of the Underground. – Guideline, German Association of Engineers VDI, part 2, Beuth Verlag, Berlin
[17] ALLEN, J.R. (1920): Theory of Heat Loss from Pipe Buried in the Ground. - Journal ASHVE 26, 455-469 and 588-596
[18] INGERSOLL, L.R. & PLASS, H.J. (1948): Theory of the ground pipe source for the heat pump. - ASHVE Trans. 54, 339-348
[19] INGERSOLL, L. R., ADLER, F.T., PLASS, H.J. & INGERSOLL, A.C. (1950): Theory of earth heat exchangers for the heat pump. – ASHVE Trans. 56, 167-188
[20] CLAESSON, J. & ESKILSON, P. (1988): PC Design Model for Heat Extraction Boreholes. - Proc. 4th Int. Conf. Energy Storage JIGASTOCK 88, 135-137
[21] CLAESSON, J., ESKILSON, P. & HELLSTRÖM, G. (1990): PC Design Model for Heat Extraction Boreholes. - Proc. 3rd WS on SAHPGCS Göteborg, CITh 1990:3, 99-102
[22] CLAESSON, J. (1991): PC Design Model for Thermally Interacting Deep Ground Heat Exchangers. - IEA Heat Pump Centre report HPC-WR-8, 95-104
[23] HELLSTRÖM, G. (1991): PC-Modelle zur Erdsondenauslegung. – IZW Bericht 3/91, 229-238
[24] ESKILSON, P. (1987): Thermal Analysis of Heat Extraction Boreholes. - 264 p., PhD-thesis Lund-MPh-87/13, Lund University of Technology
[25] ESKILSON, P. & CLAESSON, J. (1988): Simulation Model for thermally interacting heat extraction boreholes. - Numerical Heat Transfer 13, 149-165
[26] HELLSTRÖM, G. & SANNER, B. (1994): Software for dimensioning of deep boreholes for heat extraction. - Proc. 6th Int. Conf. Energy Storage CALORSTOCK 94, 195-202
[27] SANNER, B., HELLSTRÖM, G. (1996): "Earth Energy Designer", eine Software zur Berechnung von Erdwärmesondenanlagen. - Proc. 4. Geothermische Fachtagung Konstanz, GtV, 326-333
[28] BREHM, D.R. (1989): Entwicklung, Validierung und Anwendung eines dreidimensionalen, strömungsgekoppelten finite Differenzen Wärmetransportmodells. - Giessener Geologische Schriften 43, 120 p.
[29] HELLSTRÖM, G., SANNER, B., KLUGESCHEID, M., GONKA, T. & MÅRTENSSON, S. (1997): Experiences with the borehole heat exchanger software EED. - Proc. 7th Int. Conf. Energy Storage MEGASTOCK 97, 247-252
[30] SZAUTER, S. (1998): Untersuchungen der gegenseitigen Beeinflussung von EW-Sonden durch Grundwasserfluß bei dichter Bebauung. - 92 p., Dipl. thesis, Giessen University

Proceedings of the International Conference on NATIONAL DEVELOPMENT OF GEOTHERMAL ENERGY USE andInternational Course/EGEC Busiess Seminar on ORGANIZATION OF SUCCESSFUL DEVELEOPMENT OF A GEOTHERMAL PROJECT, K. Popovski, A.Vranovska, S. Popovska Vasilevska, Editors

SHALLOW GEOTHERMAL SYSTEMS, GROUND SOURCE HEAT PUMPS

b. Examples from Germany

Dr. Burkhard Sanner
http://www.sanner-geo.de

ABSTRACT

Geothermal Heat Pumps, or Ground Source Heat Pumps (GSHP), are systems combining a heat pump with a ground heat exchanger (closed loop systems), or fed by ground water from a well (open loop systems). They use the earth as a heat source when operating in heating mode, with a fluid (usually water or a water-antifreeze-mixture) as the media transferring the heat from the earth to the evaporator of the heat pump, utilising that way geothermal energy. In cooling mode, they use the earth as a heat sink. With BHE geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet any demands. More than 25 years of R&D focusing on BHE in Europe resulted in a well-established concept of sustainability for this technology, as well as sound design and installation criteria.

In recent years, several larger plants for offices or commercial areas have been designed and built in the central region of Germany, and mainly in the Rhein-Main-area. Both systems with borehole heat exchangers (BHE) as well as with shallow geothermal doublets (ground water wells) are operational. New solutions had to be found to adapt the technology to certain site constraints, and innovative components like thermally enhanced grouting material have been used.

OUTLINE OF PRESENTATION

1. INTRODUCTION
2. EXAMPLES OF SMALL-SCALE APPLICATION OF GSHP IN GERMANY
2.1 Early GSHP-plant with BHE in Germany
2.2 Research plant Schöffengrund-Schwalbach
2.3 First direct cooling application
2.4 Residential houses
2.5 Energy piles
3. LARGER GEOTHERMAL HEAT PUMP PLANTS IN THE CENTRAL REGION OF GERMANY
3.1 Commercial plants for heating only
3.2 Chemical laboratory UEG in Wetzlar
3.3 Other commercial plants
4. UNDERGROUND THERMAL ENERGY STORAGE (UTES)
4.1 BHE storage system in combination with solar heat in Neckarsulm
4.2 Aquifer store for the Reichstag area in Berlin
5. MARKET AND ECONOMY
6. CONCLUSIONS

1. INTRODUCTION

First, some abbreviations have to be mentioned, which are used frequently throughout this text:

- GSHP Ground Source Heat Pump
- BHE Borehole Heat Exchanger (in USA, the term Vertical Loop is common)
- UTES Underground Thermal Energy Storage In Germany, there are three main areas of geothermal energy use:
- Shallow geothermal energy for heating and cooling purposes, including Underground Thermal Energy Storage (UTES)
- Deep geothermal plants for large heating demand (district heating)
- Electric power production by geothermal energy; this technology still is in the design and construction phase, with the first plant operational since Nov. 2003 in Neustadt-Glewe

The legal framework in Germany is given by the Federal Mining Act (BBergG), protecting the use of geothermal energy as to be licensed by the state authorities. Most smaller plants in shallow geothermal are exempt from this license and are subject to approval by the water authorities only.

The definition for geothermal energy in Germany is, according to the guideline VDI 4640 [1]: "Geothermal energy is energy stored in form of heat below the surface of the solid earth"

In the following, the target will be on shallow resources only (down to ca. 400 m). As many European countries do not boast abundant hydrogeothermal resources that could be tapped for direct use (some exceptions are e.g. Iceland, Hungary, France), the utilization of lowenthalpy aquifers that enable the supply of a larger number of customers by district heating is limited so far to regions with specific geological settings. On the other hand, geothermal heat pumps (GSHP) and UTES allow for geothermal energy use almost everywhere.

2. EXAMPLES OF SMALL-SCALE APPLICATION OF GSHP IN GERMANY

2.1 Early GSHP-plant with BHE in Germany

The area around Wetzlar is one of the birthplaces of BHE in Europe.

It can claim to have the first BHE application for a commercial building in Germany, built in 1980 for a new, small production site for optical glass fibers (fig. 1). The ground part consists of 8 BHE of a coaxial design (tube- in-tube), each 50 m deep in paleozoic rock, feeding the evaporator of a heat pump with 22 kW heating capacity. Even in this early plant had a cooling function, as it was possible to reject heat from the electric glassmelting furnaces into the BHE during summertime for thermal recovery of the underground.

Another of the early applications of BHE in Europe was in Switzerland, where a drilling company was asked to install plastic pipes in boreholes at a site in Rorschacherberg on the south shores of Lake Constance in 1980. In Switzerland, also the U-tube BHE which is the most common today was first introduced and later (in 1986) taken up by German drillers.

Fig. 1: "Verolum"-building in Schwalbach south of Wetzlar, first GSHP with BHE in a commercial application in Germany, built 1980,
photo from 1995; the BHE are located beneath the bushes to the left and front of the building

Sweden saw the first BHE about the same time. A difference which is still prevailing today is that BHE in Central Europe usually are backfilled or grouted, while BHE in Scandinavia mainly are inserted into open, water-filled holes. The reason is given by the hard, stable rocks in the Nordic crystalline platform. Another Swedish particularity is the use of single-U-tubes like in North America, compared to double-U-tubes in Austria, Germany and Switzerland.

2.2 Research plant Schöffengrund-Schwalbach

The owner of the Verolum plant, Helmut Hund, who was convinced of the potential of GSHP, started a R&D-activity to better understand the heat transport processes in the underground and to collect the necessary data and experience for correct design of BHE systems. With support from the Federal Ministry of Research and Technology (BMFT in this times), and in co-operation with Justus-Liebig-University in the neighbouring city of Giessen, a full-scale field experiment was installed adjacent to the Verolum building in 1985 (fig. 2) [2]. In this installation, experiments with two types of BHE were carried out (fig 3): The original coaxial one as developed by Helmut Hund, and in 1986 a double-U-tube design following an example from Switzerland, developed by Ernst Rohner sr. [3]. Towards the end of the project, also experiments with direct expansion in BHE were carried out (fig. 2, right). The results of the R&D-project are published in [4]. Again, a similar work to place in parallel in Switzerland at a site in Elgg (ZH), conducted by the Technical University of Zurich (ETH).

2.3 First direct cooling application

For commercial applications, space cooling during summertime is an issue even in a country with moderate climate, like Germany. On the other hand, space cooling by many is considered a luxury, and the installation and operational cost for electric air conditioners or chillers are not widely accepted. Thus, in 1987 an experiment was conducted to use the cold from 7 BHE each 50 m deep directly to cool a single room in an office building in Wetzlar (fig. 4). Fan coil units with two separate heat exchanger (one for the warm water of the hydronic heating circuit, the other for the water/antifreeze mixture from the BHE) were installed, and with only 120 W for a small circulation pump and the fans, a cooling power of roughly 2,5 kW could be achieved.

Fig. 2: left: Schwalbach GSHP research station, with light drilling rig, borehole field and buildings for HP and monitoring; photo from January 1988
right: Direct Expansion experiments in Schwalbach GSHP research station in 1989; note ice development on evaporator pipes leading to special BHE

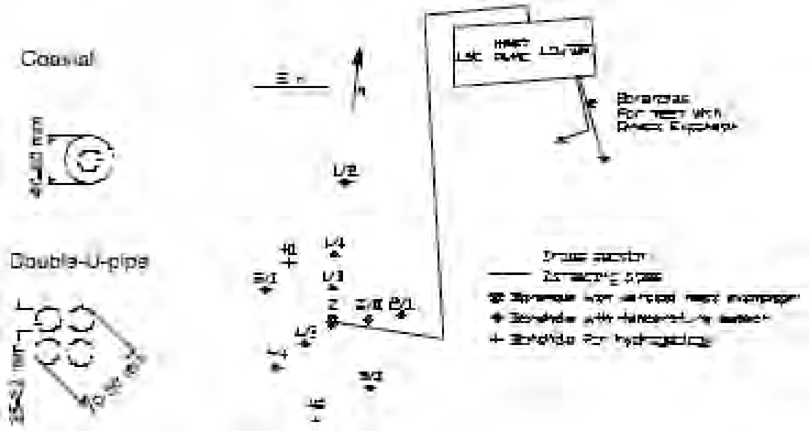


Fig. 3: left: Cross-section of typical BHE, as used in Schwalbach
right: Schematic plan of the test plant in Schwalbach

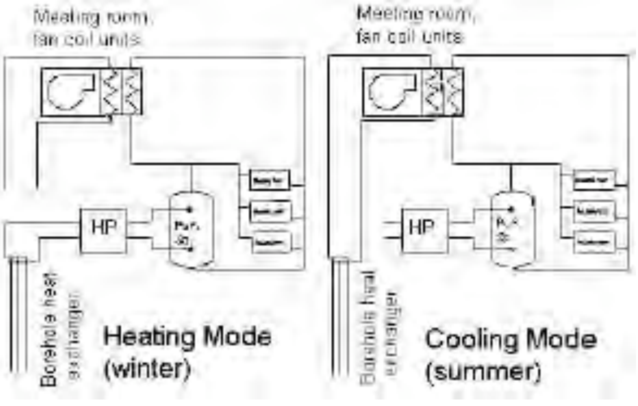


Fig. 4: Schematic of the first experiment with direct cooling from BHE, GSHP plant for heating and cooling in the office building of Helmut Hund GmbH (from [5])

2.4 Residential houses

From the beginning, GSHP were used in residential houses, which still account also for the largest number of applications. The basic principle did not change, but fine-tuning of the system design, manifolds, circulation pumps, etc., and also the use of new refrigerants like R 290 or R 407 c, allowed an increase in the seasonal performance factor from 2.5-3.0 in 1985 to around 4.0 in 2000. A state-of-the-art example for an individual residential house is selected from the city of Delbrück in the North-western part of Germany. The basic data are given in fig. 5.

Another, relatively new house was investigated by [6], it is located in Burg/Spreewald close to the Eastern border of Germany. The data are listed in fig. 6.

Over many years, most of the GSHP in residential houses were individual plants in the middle of houses heated by fuel oil or natural gas. Meanwhile, the first whole subdivisions are equipped with GSHP.

Examples are two new residential areas (fig. 7) in the Dortmund area with ca. 100-130 houses, where individual GSHP systems for each house are installed. A rather simple system schematic with only one BHE in the >100 m range is used in most houses, with a few exceptions. The heat pumps provide for heating and domestic hot water; there is no cooling, thus no artificial recharge of the ground. The heat extraction is larger than the possibility of natural recharge, and a low, but continuing decrease of temperature would occur. To counteract this and to secure long-term operation, the BHE length has to be increased (fig. 7).

3. LARGER GEOTHERMAL HEAT PUMP PLANTS IN THE CENTRAL REGION OF GERMANY

This chapter reviews shortly the early development of GSHP for commercial buildings, gives details on a selection of recent plants and explains specific problems during their realisation. The examples comprise, among others:

- UEG Wetzlar, a building with chemical laboratories and one of the first examples of direct cooling from BHE
- Naturwaren Maas, Gütersloh, a building with motor-driven GSHP
- DFS Langen (German Air Traffic Control Headquarters), with 154 BHE for heating and cooling, operating without antifreeze
- Baseler Platz Frankfurt, a building right in the center of Franfurt/Main, with very confined construction site and the need to avoid contamination by groundwater pollution found in the neighbourhood
- Arcade Hainburg, a small commercial district heated by a heat pump on a doublet more than 200 m deep

The lessons learned from these plants, and the economic circumstances will allow successsful realisation of further geothermal heat pump systems in the region.

3.1 Commercial plants for heating only

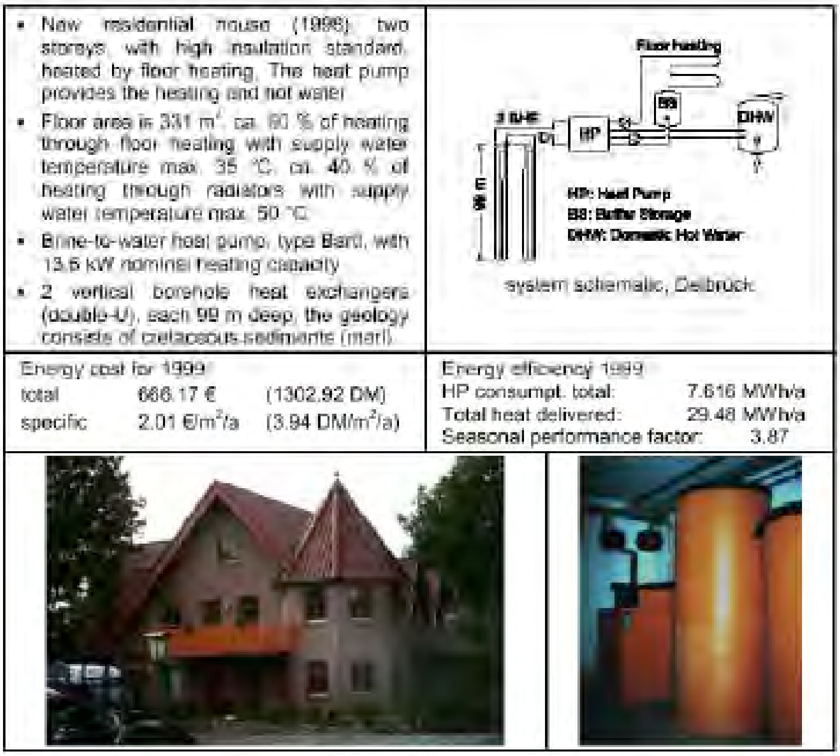
Since the first plants in Germany, comercial applications were part of the picture (e.g. the „Verolum" building [7]). In 1987, a small commercial building was monitored (Fig. 8); more information on that plant is given in [8]. With a floor heating system, a heat pump using R 22, and a seasonal performance factor of 2.9, it shows the state-of-the-art performance of the late 1980s.

A very interesting plant has been built recently in Gütersloh (fig. 9).

The heat pump compressor is not activated by an electric motor, but by a fuel-oil operated diesel engine. The heat from engine cooling is also used for house heating, and an additional peak boiler exists. This example may show that ground source heat pumps do not necessarily rely on electric power for operation.

3.2 Chemical laboratory UEG in Wetzlar

Because of the tremendous savings in direct cooling mode (no power for compressor required), today cooling is a standard feature of most commercial GSHPs in Germany. A well investigated example is the UEG building in Wetzlar (fig. 10), housing offices and laboratories. The GSHP with 47 kW heating capacity heats the building through lowtemperature radiators (a floor heating was not thought appropriate due to the special laboratory floors), and heats the ventilation air; in summertime, cold is provided directly from 8 BHE, each 80 m deep, for cooling the ventilation air and, in addition, some specific rooms with high internal heat load.



- New residential house (1998): two storeys, with high insulation standard, heated by floor heating. The heat pump provides the heating and hot water
- Floor area is 331 m², ca. 60 % of heating through floor heating with supply water temperature max. 35 °C, ca. 40 % of heating through radiators with supply water temperature max. 50 °C
- Brine-to-water heat pump, type Bartl, with 13.6 kW nominal heating capacity
- 2 vertical borehole heat exchangers (double-U), each 99 m deep, the geology consists of cretaceous sediments (marl)

system schematic, Delbrück

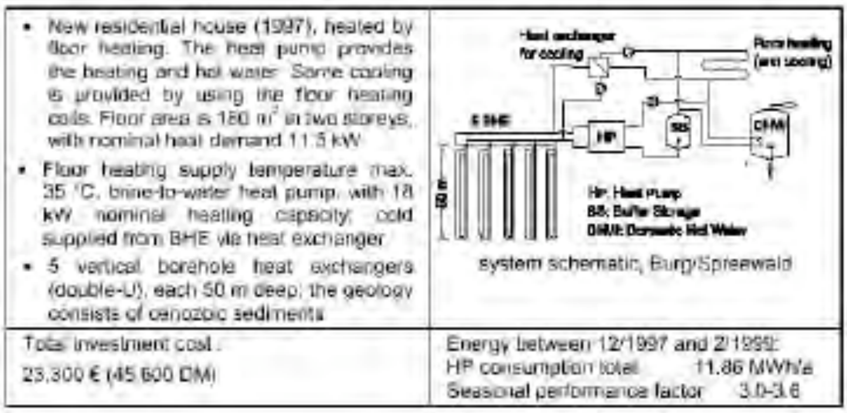
Energy cost for 1999

total	666.17 €	(1302.92 DM)
specific	2.01 €/m²/a	(3.94 DM/m²/a)

Energy efficiency 1999

HP consumpt. total:	7.616 MWh/a
Total heat delivered:	29.48 MWh/a
Seasonal performance factor:	3.87

Fig. 5: Residential house in Delbrück



- New residential house (1997), heated by floor heating. The heat pump provides the heating and hot water. Some cooling is provided by using the floor heating coils. Floor area is 180 m² in two storeys, with nominal heat demand 11.5 kW
- Floor heating supply temperature max. 35 °C, brine-to-water heat pump, with 18 kW nominal heating capacity; cold supplied from BHE via heat exchanger
- 5 vertical borehole heat exchangers (double-U), each 50 m deep, the geology consists of cenozoic sediments

system schematic, Burg/Spreewald

Total investment cost :
23,300 € (45,600 DM)

Energy between 12/1997 and 2/1999:

HP consumption total	11.86 MWh/a
Seasonal performance factor	3.0-3.6

Fig. 6: Data for residential house in Burg

In the chemical laboratories, a number of high-precision analytical equipment is operated, including Atomic Absorption Spectrometry (AAS), Gas-Chromatography (GC) and Mass Spectrometry (MS). Also a substantial number of PC's is in use. All those devices produce heat, and have strict requirements for ambient temperatures to work correctly. In consequence, cooling is crucial in the relevant rooms.

A specific problem in UEG-plant are the chemical exhausts. Air pressure in the rooms has to be kept higher than that in the exhausts at any time, to prevent inflow of possible toxic sub-stances. The result are high quantities of ventilation air even at very low or high outdoor air temperatures, whenever the chemical exhausts are operated. In the heating mode, a natural gas boiler assists the heat pump in this case. In cooling mode, the store covers all the load. The cooling circuit is divided into a loop for the central air handling unit, which is operated only when required, and a loop for the fan-coil units in the relevant rooms, in almost continuos operation.

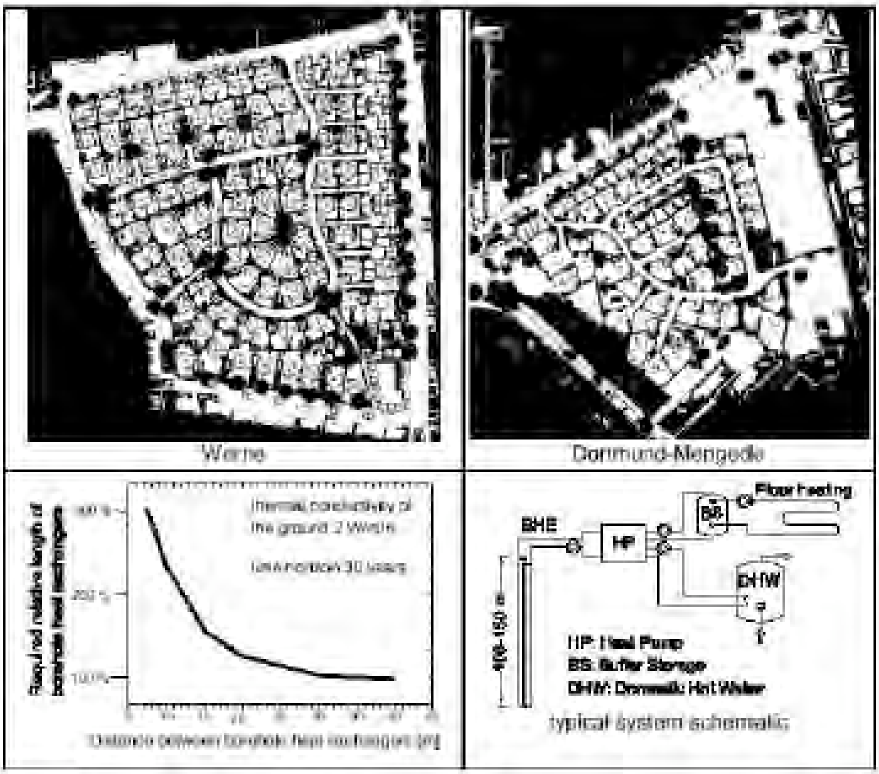
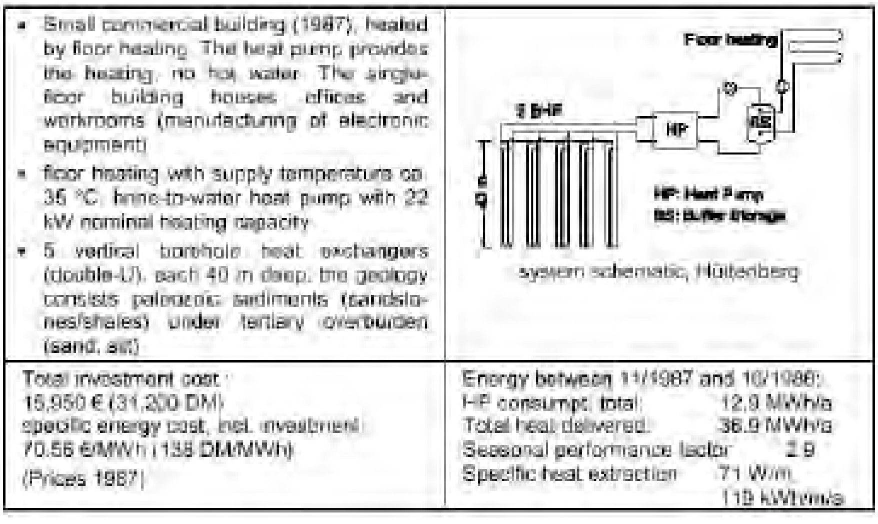


Fig. 7: Artist´s concept of geothermal subdivisions (above, graphics Behr + Partner, Schwerte); lower line left: Necessary increase in borehole length for 120 BHE with decreasing distance and lower line right typical system schematic for a house in Werne subdivision


- Small commercial building (1987), heated by floor heating. The heat pump provides the heating, no hot water. The single-floor building houses offices and workrooms (manufacturing of electronic equipment)
- floor heating with supply temperature ca. 35 °C, brine-to-water heat pump with 22 kW nominal heating capacity
- 5 vertical borehole heat exchangers (double-U), each 40 m deep; the geology consists paleozoic sediments (sandstones/shales) under tertiary overburden (sand, silt)

system schematic, Hüttenberg

Total investment cost:
15,950 € (31,200 DM)
specific energy cost, incl. investment
70.56 €/MWh (138 DM/MWh)
(Prices 1987)

Energy between 11/1987 and 10/1988:
HP consumpt. total: 12.9 MWh/a
Total heat delivered: 36.9 MWh/a
Seasonal performance factor 2.9
Specific heat extraction 71 W/m
119 kWh/m/a

Fig. 8: Small commercial building from 1987 in Hüttenberg/Hessen

UEG plant became operational in spring 1993 and thus started with a cooling season. During a full heating-cooling cycle in 1995/96, the performance of the plant could be monitored closely [9]. In fig. 24 the details of the energy flows are shown. The efficiency in heating mode could even be better with a different (floor) heating system, because the radiators require a higher supply temperature than a good floor heating; however, the constraints due to the building use do not allow for that.

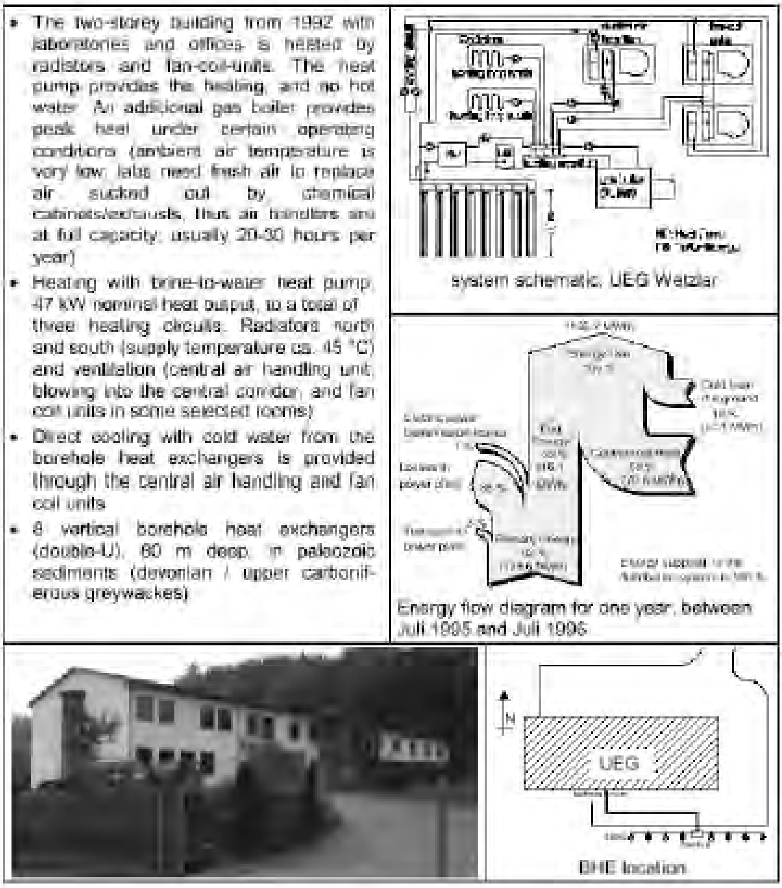
Fig. 11 shows the reduction in emissions of that plant, calculated for the monitored data from 1995/96 and compared to a conventional system with fuel oil for heating and an electric chiller for cooling. The reduction of CO2-emissions amounts to 48 %!

- The building from 1999 with offices and a large storage hall is heated by radiators and fan-coil-units. The heat pump provides the heating, and no domestic water. An additional oil boiler provides peak heat
- The building consists of an office wing with three floors (800 m²) and a large hall for storage and dispatching of goods (1600 m²)
- Heating with two different temperature levels: brine-to-water heat pump with 30 kW nominal heating output, operated by fuel oil engine, thermal output ca. 30 kW, and fuel oil boiler (105 kW) for peak load (ca. 10 % of annual heat)
- 8 vertical borehole heat exchangers (double-U), each 100 m deep in cretaceous sediments

system schematic, Maas Gütersloh

Comparison of annual operation cost (from feasibility study); realized alternative right

Fig. 9: Commercial building “Maas Naturwaren” in Gütersloh



- The two-storey building from 1992 with laboratories and offices is heated by radiators and fan-coil-units. The heat pump provides the heating, and no hot water. An additional gas boiler provides peak heat under certain operating conditions (ambient air temperature is very low, labs need fresh air to replace air sucked out by chemical cabinets/exhausts, thus air handlers are at full capacity; usually 20-30 hours per year)
- Heating with brine-to-water heat pump, 47 kW nominal heat output, to a total of three heating circuits: Radiators north and south (supply temperature ca. 45 °C) and ventilation (central air handling unit, blowing into the central corridor, and fan coil units in some selected rooms)
- Direct cooling with cold water from the borehole heat exchangers is provided through the central air handling and fan coil units
- 8 vertical borehole heat exchangers (double-U), 60 m deep, in paleozoic sediments (devonian / upper carboniferous greywackes)

system schematic, UEG Wetzlar

Energy flow diagram for one year, between Juli 1995 and Juli 1996

BHE location

Fig. 10: Chemical laboratory “UEG” in Wetzlar, heated and cooled with BHE

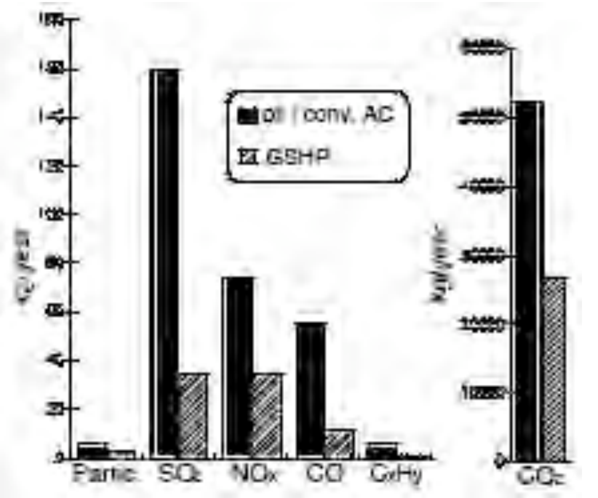


Fig. 11: Emission reduction for UEG building, compared to a conventional plant (design values)

3.3 Other commercial plants

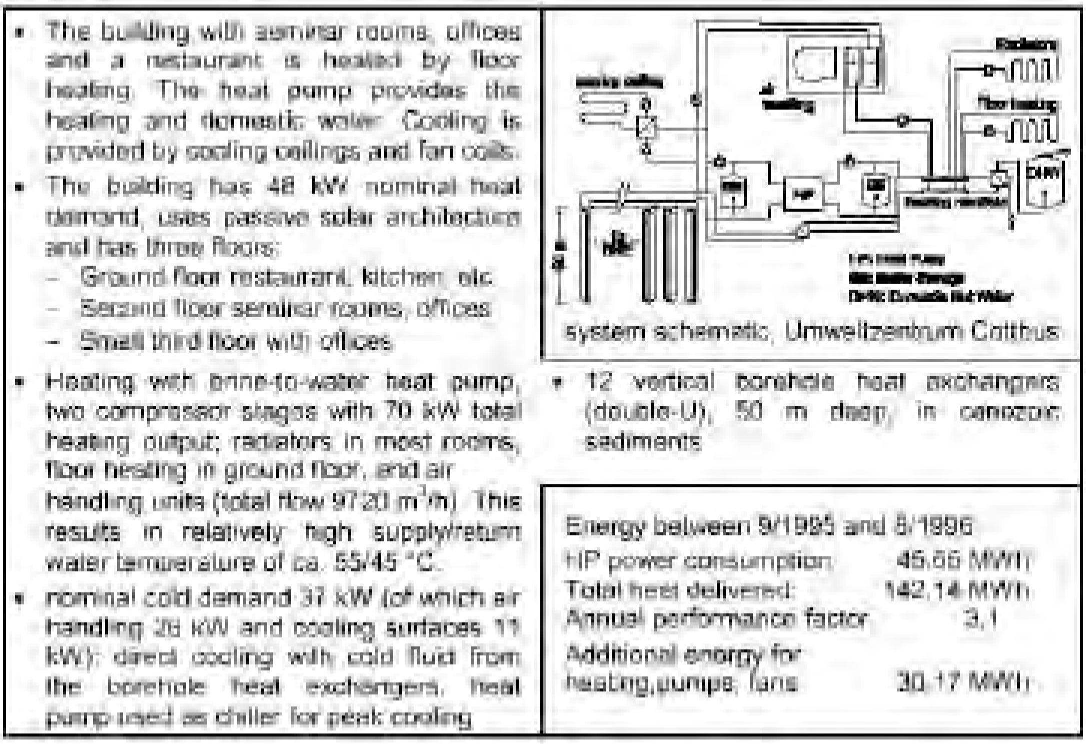
Another well-monitored example of a building with direct cooling is the “Umweltzentrum” Cottbus, housing teaching and meeting facilities for environmental issues. Fig. 12 shows the relevant data of this building from the eastern border of Germany. Table 1 lists some other larger plants in Germany.

The German Air Traffic Control has built new headquarters in Langen, just a few kilometers southeast of Frankfurt airport. The office building offers room for ca. 1200 employees, and is planned as a Low-Energy- Office (LEO). The basic data of the building are:

- total building volume 230’000 m3
- total floor area 57’800 m2
- heated/cooled area 44’500 m2

A borehole thermal energy storage with two borehole fields (fig. 13) comprising a total of 154 BHE each 70 deep is integrated into the heating and cooling system. The BHE system covers the base load of the building cooling and a part of the heating load. Both fields supply a total cooling capacity of 340 kW and 330 kW heating capacity, equaling 80 % of the annual cooling energy and allowing 70 % of the annual heating being covered by the heat pump (fig. 14). There are only a few plants in Europe with a capacity and number of BHE like in Langen.

For the first time in Germany, a thermal response test (carried out in summer 1999) was used as a basis for dimensioning a BHE field [12]. An almost 100 m deep test borehole was equipped with a BHE (later to become a part of the BHE field). The underground consists of quaternary and tertiary sand, gravel and clay.



- The building with seminar rooms, offices and a restaurant is heated by floor heating. The heat pump provides the heating and domestic water. Cooling is provided by cooling ceilings and fan coils.
- The building has 48 kW nominal heat demand, uses passive solar architecture and has three floors:
  - Ground floor restaurant, kitchen, etc.
  - Second floor seminar rooms, offices
  - Small third floor with offices
- Heating with brine-to-water heat pump, two compressor stages with 70 kW total heating output; radiators in most rooms, floor heating in ground floor, and air handling units (total flow 9720 m^3/h). This results in relatively high supply/return water temperature of ca. 55/45 °C.
- nominal cold demand 37 kW (of which air handling 26 kW and cooling surfaces 11 kW); direct cooling with cold fluid from the borehole heat exchangers, heat pump used as chiller for peak cooling

system schematic, Umweltzentrum Cottbus

- 12 vertical borehole heat exchangers (double-U), 50 m deep, in cenozoic sediments

Energy between 9/1995 and 8/1996

HP power consumption	45.66 MWh
Total heat delivered:	142.14 MWh
Annual performance factor	3.1
Additional energy for heating,pumps, fans	30.17 MWh

Fig. 12: Seminar building „Umweltzentrum“ in Cottbus, after [10] and [11]

Table 1: Data from some larger plants in Germany

Project name	heating/cooling capacity	No. BHE	Depth BHE
WAGO Minden	100 / 120 kW	44	100 m
Gladbeck-Wiesenbusch	280 / 180 kW	32[1]	60 m
DFS Langen	330 / 340 kW	154	70 m
MPI Golm	ca. 1000 / 1000 kW	160	100 m

Fig. 13: Layout of the two BHE fields for the office building in Langen, with the architest´s impression of the building to show its location in regard to the BHEs

The measured values are:

- Ground thermal conductivity b = 2,8 W/m/K
- Borehole thermal resistance rb = 0.11 K/(W/m)

There is a particularity of the BHE system for the German Air Traffic Control (DFS) headquarters. While most ground source heat pump systems make use of an antifreeze to cope with temperatures below 0 °C, in Langen only pure water is used. This is possible due to the priority of the cooling operation and the very exact design calculations.

Operation without antifreeze has an ecological advantage in the case of a leakage (the site is in the outer part of a groundwater protection zone), and also the cost for filling the large system with antifreeze can be avoided. Design with minimum heat supply temperatures of +4 °C also allows for a very good seasonal performance factor in heating mode.

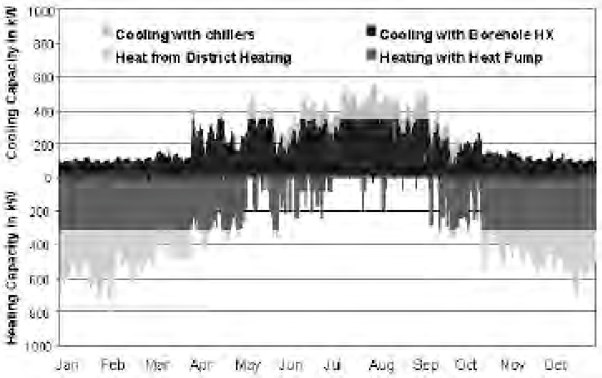


Fig. 14: Heating and cooling demand for the German Air Traffic Control (DFS) headquar-ters, data from simulation

To extract an energy amount as high as possible with source temperatures above +4 °C, the borehole thermal resistance has to be lowered. A material suitable to push the thermal conductivity of the borehole filling from a normal 0.6-0.8 W/m/K to ca. 1.6 W/m/K has been developed, and the heat transfer in the borehole could be enhanced substantially. A second thermal response test (fig. 15) was done at one of the final BHE (now with 70 m drilling depth). This allowed for measuring the influence of the thermally enhanced grout on the borehole thermal resistance:

- with conventional grouting rb = 0.11 K/(W/m)
- with thermally enhanced grout rb = 0.08 K(/W/m)

The lowering by more than 27 % is in good agreement with the theoretical calculation for an almost doubled thermal conductivity of the filling.

Another problem imposed by the groundwater protection zone is the requirement to keep temperature changes in the groundwater within certain limits. This requires balanced operation of the system at least in the average over several years, and a monitoring scheme comprising three observation wells and temperature readings at given intervals.

Fig. 15: left: Thermal Response Test equipment on site in Langen
right: Heat pump in DFS-headquarters, Langen; to the left
four motors driving the compressors. in the background and
above evaporator and condensor.

The layout calculations were done with the computer program „Earth Energy Designer“ (EED), allowing for calculation of the temperature of the heat carrier medium according to ground thermal parameters and heating/cooling loads. Several design alternatives were investigated, and the most promising optimized with further calculations. The design procedure resulted in a use of shallow geothermal energy adapted at optimum to the building needs. The innovative application of thermal site investigation, thermally enhanced grouting material, and the layout with pure water as heat carrier promises a high system efficiency.

A thorough economical analysis of the design was done and published in [13]. The BHE system allows, even with higher first cost, an annual cost saving compared to conventional heating and cooling plants. The cost comparison (fig. 16), regarding energy, maintenance and capital cost of the heat and cold generation, reveals that the Low Energy Office with BHE is the most economical solution for this building and this site, due to the low energy cost. The system was tested in winter 2001/02 and is fully operational since spring 2002.

The Rhein-Main-area is characterised by regions with good groundwater conditions. Hence the use of groundwater as heat source and sink for GSHP can be considered, in particular for larger installations. One groundwater well can deliver a much higher thermal output than one BHE, however, groundwater wells require certain hydrogeological and hydrochemical conditions and are also subject to maintenance.

One GSHP system with groundwater wells was constructed under particularly difficult conditions, right in the heart of the city of Frankfurt (fig. 17). It is intended for heating and cooling of a multi-storey building with offices and apartments.

There were several problems and constraints that had to be dealt with for the Baseler Platz project:

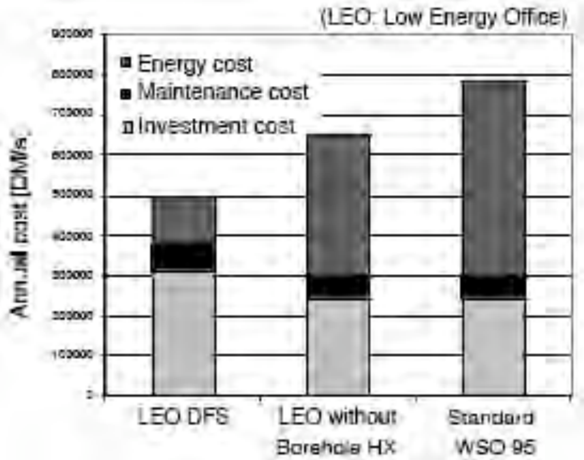


Fig. 16: Annual cost comparison for heating and cooling the German Air Traffic Control (DFS) headquarters (after [13])
Version LEO DFS: Borehole heat exchangers, heat pump, local heat net, chiller, first cost 4.5 million DM
Version LEO without BHE: Local heat net, chiller, first cost 3.5 million DM
Version Standard WSO 95: Local heat net, chiller, first cost 3.5 million DM

· Very limited area for drilling and installation

· Wellheads in the underground parking, below the static surface of the Tertiary water level; this did result in a temporary flooding of the lowest level of the parking during construction time, when the well pipes were cut by workers without permission from the planners

- Groundwater temperature of 21 °C in only 80 m depth (not suitable for direct cooling)
- Existence of contamination in the upper aquifer; because there are some possible connections between the aquifers in some distance from the site (fig. 18), an early warning system had to be developed to detect inflow of younger water into the Tertiary. This is done by testing, at regular intervals, the produced water for the Tritium content, which is higher in the younger water; an increase in Tritium will precede a possible contamination by some time.

Another groundwater heat pump currently is under construction to heat and cool a commercial area with several smaller shops in Hainburg (fig. 19). Two wells to a depth of ca. 200 m already have been drilled, and pumping test showed sufficient flow. The geology was somewhat different than expected, because the sedimentary layers in this area are influenced by the vicinity of the paleozoic rocks of the Spessart mountains to the East. Investigations with a mobile equipment for hydrochemical tests [14] revealed that no problems with scaling should be expected within the planned temperature range.

The two wells are locate beside the access road, with the connecting pipeline being buried beneath the road. From there, the individual lots receive the water and can use it as heat source or sink for individual heat pumps. The shop tenants (who might become owner of the lots or just lease the place) will be billed according to the amount of water they get from the central pipeline. This scheme allows for keeping the central pipeline on common grounds, with operation and maintenance of wells and pipeline by e.g. an Energy Service Company and the equipment in the shops in the hands of the tenants. Start of operation was for the heating season 2004/05.

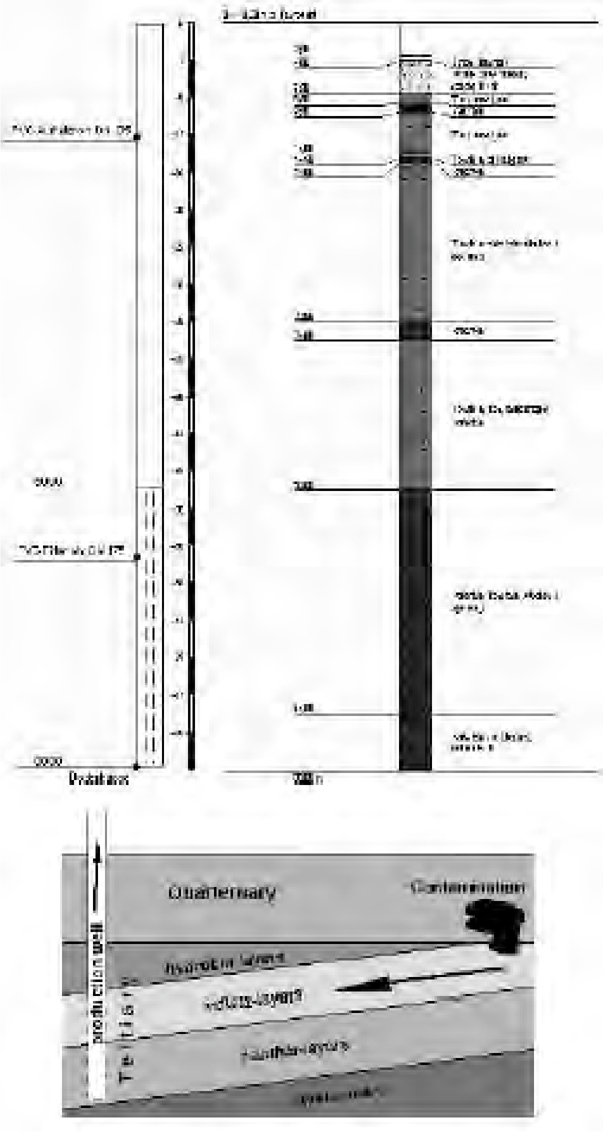


Fig. 18: above: Production well for FAAG building, Frankfurt below: Permeable layers could allow transport from a contaminated area in several hundred meter distance, monitoring is required

4. UNDERGROUND THERMAL ENERGY STORAGE (UTES)

While in GSHP-systems a heat pump is used to bring the temperature from the ground to a useful heating temperature, or to dump heat from space cooling into the ground, the ground itself is heated or cooled in a UTES system. Again, a distinction can be made between open and closed systems (fig. 20). The heat sources for heat storage can be various, however, waster heat or solar heat are typical.

For cold storage, the cold ambient air in wintertime or during night is the cold source.

The basic principle of an ATES can be seen in fig. 21 Two examples are shown here to illustrate the principle. The technology is well established for cooling purposes, in particular in the Netherlands, but still some R&D has to be done to achieve reliable and economic UTES for heat storage at elevated temperatures. One example, of a real heat store with temperature up to 80 °C, is a BHE store in Neckarsulm, using solar energy (fig. 23 and table 2).

Fig. 19: Plan of the commercial area in Hainburg to be heated and cooled by GSHP

4.1 BHE storage system in combination with solar heat in Neckarsulm

The store in Neckarsulm [15] is part of a solar assisted district heating system in a new building area with approximately 1300 flats and terraced houses in the final stage, to be realized within the next 5 years.

A solar contribution of about 50 % to the total heat demand (space heating and domestic hot water) is planned. The BHE store is connected directly to the district heating network without a heat exchanger to avoid temperature drops. There is no heat pump in the system; peak load is covered by a gas boiler. Two buffer stores (each 100 m3 water tank) help to cover short-time load peaks and solar collector production peaks.

One of the main advantages of the BHE-store is the possibility to extend the store by adding further boreholes in relation to the growth of the building area. A first experimental store with a volume of ca. 4300 m_was built in autumn 1997. The store consisted of 36 double-U-pipes with a depth of 30 m and a borehole distance of 2 m. The bore-hole diameter was 115 mm. Each 6 boreholes were connected in series. This store was mainly used for charging and discharging experiments.

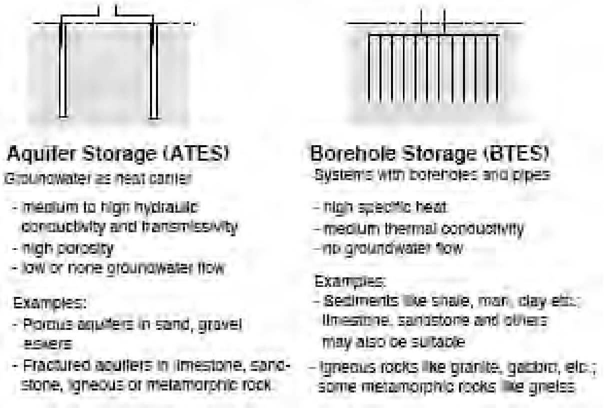


Fig. 20: Distinction of UTES-systems

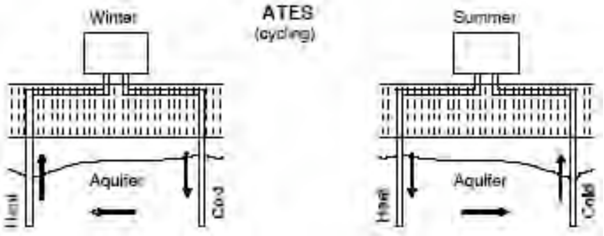
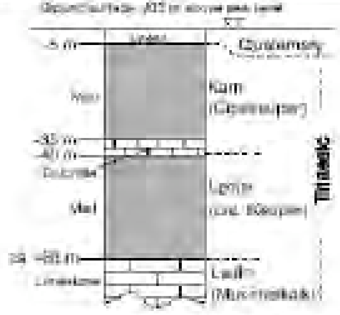


Fig. 22: Operating principle of an ATES-system, with cycling operation ("warm" and "cold" wells)

The heat transfer capacity of the BHE used first was found to be not as good as estimated. Reasons for that are a closer than planned distance between the U-pipes (65 mm shank spacing) and a lower thermal conductivity of the grout-ing material. This effect decreased the perfor-mance of the overall system. In addition, the discharging of the store was reduced due to the network return temperature. Simulations show-ed that the heat transfer capacity of the BHE could be improved significantly by enlarging both the borehole diameter from 115 to 150 mm and the pipe shank spacing from 65 to 100 mm. Therefore the extension of the store from 4.300 m_ to 20'000 m_ with additional 132 bore-holes was made with this new borehole geometry. System operation started in January 1999. Besides the monitoring of the overall system (especially the interaction between the collectors and the store during charging and the effect of the network return temperatures on discharging), special attention will be paid on the combined heat and mass transfer inside the store. .

Table 2: Geological situation at Neckarsulm BTES

Mean underground thermal conductivity until 35 m depth	$\lambda = 2$ W/mK
Mean volumetric heat capacity of the ground	$c_v = 3$ MJ/m³K
Groundwater level between 10 and 15 m below ground level	
Stratigraphy: ▪ Overburden of Loess (silt) down to a depth of ca. 5 m ▪ The subsequent layers consist of Upper Triassic sediments (Muschelkalk and Keuper, see right) ▪ The layers with marls have very low hydraulic conductivity ($k_f = 5 \cdot 10^{-9}$ m/s)	 Geological cross-section at the Neckarsulm BTES site

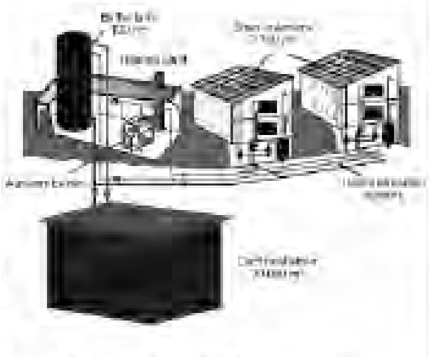
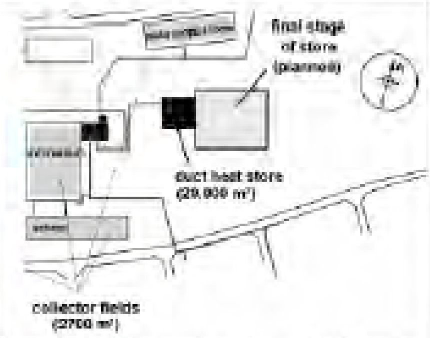
Subdivision Amorbach in Neckarsulm, Germany	start of operation 1/1999
Short description of plant: BTES >600 vertical BHE, depth 30 m Borehole spacing 2 m with a sqare drilling pattern (fig. 6) Polybuthene-double-U-pipes as BHE After the installation of the heat exchanger pipes the borehole is refilled with a suspension of bentonite, sand, cement and water Total storage volume about 20'000 m³ The store is insulated on top with 20 cm of extruded polystyrole, extending 4 m horizontally further out from the peripheral boreholes. The refilled ground above the store has a thickness of 2-3 m. 2'700 m² solar collector area	 Schematic of the Neckarsulm-Amorbach BTES
Geology s. table 2	Storage supply temperature up to 80 °C
BTES system in Neckarsulm Amorbach, with chimneys of the peak boiler, two buffer storage tanks, and senior citizens home with solar collector roof in the background 	 Overview of the project site in Neckarsulm-Amorbach

Fig. 22: Basic data for the BTES (BHE-store) in Neckarsulm

If the ongoing project leads to sucessful results it is planned to extend the duct store stepwise according to the growth of the build-ing area and simultanuosly increasing collector area. The extension will take place in eastern direction. At the final stage the total heat demand of the building area will amount to approximately 10'500 MWh/a and the available collector area to 15'000 m_. According to present simulations a storage volume of about

150'000 m_ will be necessary to achieve a solar fraction of 50%. The heat recovery factor of the store will reach 75 to 80 % depending on the depth of the store, i.e. on the surface/volume-ratio.

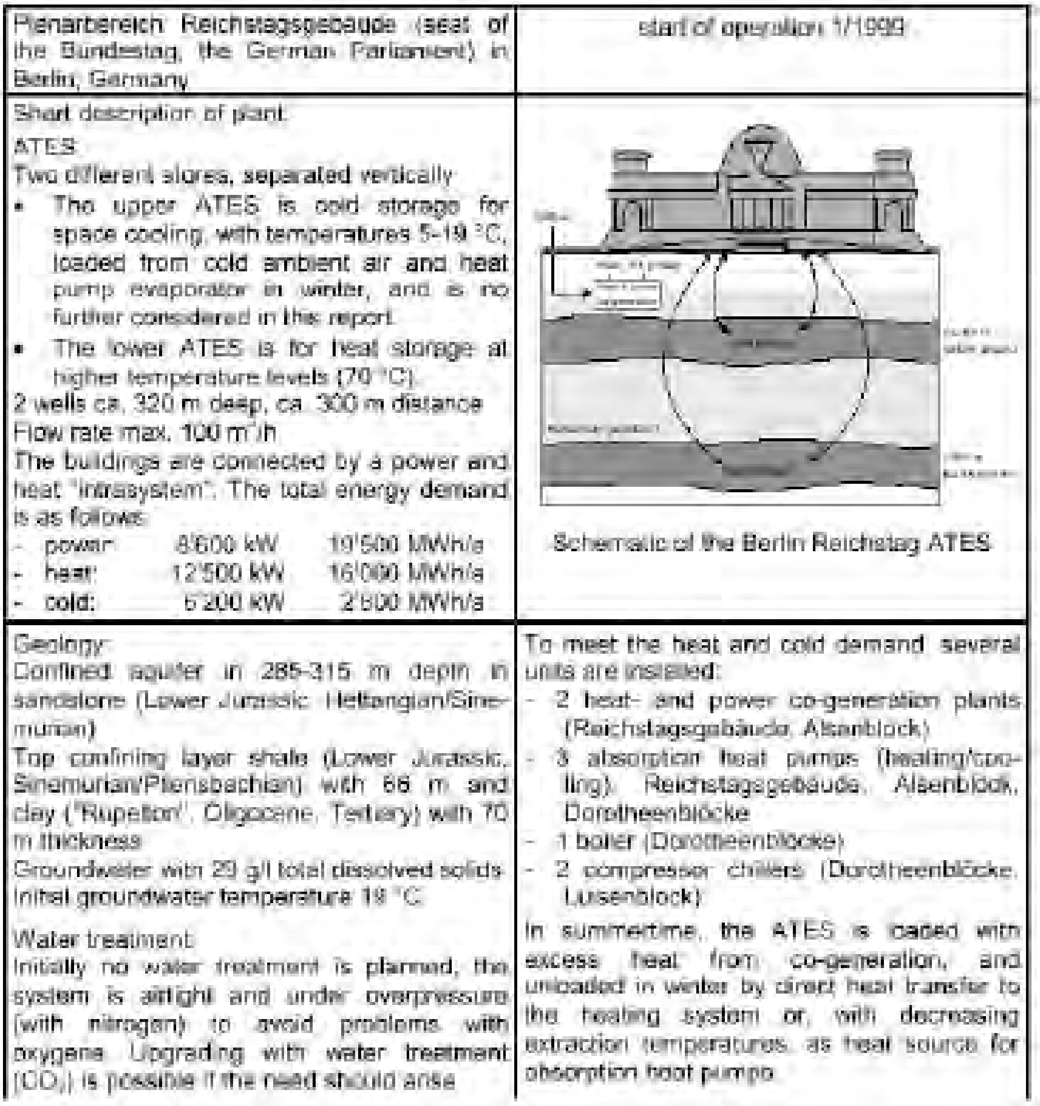
A quasi-steady- state operation will be reached after approximately 5 years.

4.2 Aquifer store for the Reichstag area in Berlin

The most prominent example for aquifer storage (ATES) in Germany has been built for heating and cooling of the Reichstag building in Berlin, now seat of the German Parliament (Bundestag). Fig. 23 gives some details.

5. MARKET AND ECONOMY

It is rather difficult to find reliable numbers of installed heat pumps in Europe, and in particular for the individual heat sources. Fig. 25 gives some recent data for the number of installed units in the main European heat pump countries. The extremely high number for Sweden in 2001 is the result of a large number of exhaust-air and other air-to-air heat pumps; however, Sweden also has the highest number of GSHP in Europe (see 1998 values in fig. 24). In general it can be concluded, that market penetration of GSHP still is modest throughout Europe, with the exception of Sweden and Switzerland (table 3). There is still ample opportu-nity for further market growth, and the technological prospects endorse this expectation. In Germany, the trend is positive (fig. 25), with a share of GSHP (ground and water) of about 82 % in 2002.



Plenarbereich Reichstagsgebäude (seat of the Bundestag, the German Parliament) in Berlin, Germany	start of operation 1/1999
Short description of plant ATES: Two different stores, separated vertically ▪ The upper ATES is cold storage for space cooling, with temperatures 5-19 °C, loaded from cold ambient air and heat pump evaporator in winter, and is no further considered in this report. ▪ The lower ATES is for heat storage at higher temperature levels (70 °C). 2 wells ca. 320 m deep, ca. 300 m distance Flow rate max. 100 m^3/h The buildings are connected by a power and heat "intrasystem". The total energy demand is as follows: - power: 8'600 kW 19'500 MWh/a - heat: 12'500 kW 16'000 MWh/a - cold: 5'200 kW 2'800 MWh/a	Schematic of the Berlin Reichstag ATES
Geology: Confined aquifer in 285-315 m depth in sandstone (Lower Jurassic: Hettangian/Sinemurian) Top confining layer shale (Lower Jurassic, Sinemurian/Pliensbachian) with 66 m and clay ("Rupelton", Oligocene, Tertiary) with 70 m thickness Groundwater with 29 g/l total dissolved solids Initial groundwater temperature 19 °C Water treatment: Initially no water treatment is planned, the system is airtight and under overpressure (with nitrogen) to avoid problems with oxygene. Upgrading with water treatment (CO_2) is possible if the need should arise	To meet the heat and cold demand several units are installed: - 2 heat- and power co-generation plants (Reichstagsgebäude, Alsenblock) - 3 absorption heat pumps (heating/cooling): Reichstagsgebäude, Alsenblock, Dorotheenblöcke - 1 boiler (Dorotheenblöcke) - 2 compressor chillers (Dorotheenblöcke, Luisenblock) In summertime, the ATES is loaded with excess heat from co-generation, and unloaded in winter by direct heat transfer to the heating system or, with decreasing extraction temperatures, as heat source for absorption heat pumps.

Fig. 23: Aquifer storage for the German Parliament in Berlin

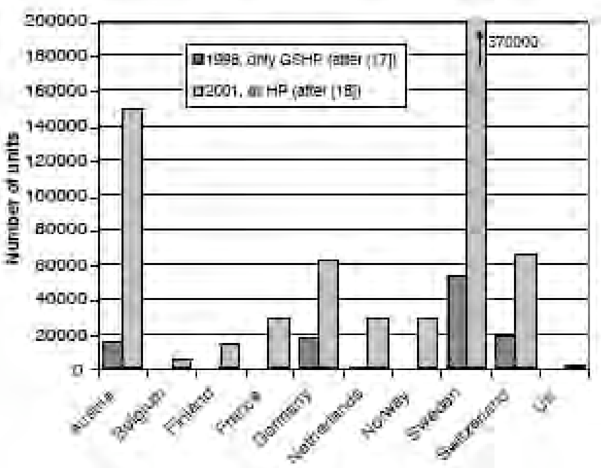


Fig. 24: Number of installed heat pump units in some European countries (after data from [16] and [17])

Tab. 3: Share of ground coupled heat pumps in total residential heating market (after data from [18])

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

6. CONCLUSIONS

GSHP are no longer exotic. Their number has increased steadily over the years, and the technology is well understood. For residential houses, they begin to become a routine option when planning the heating system.

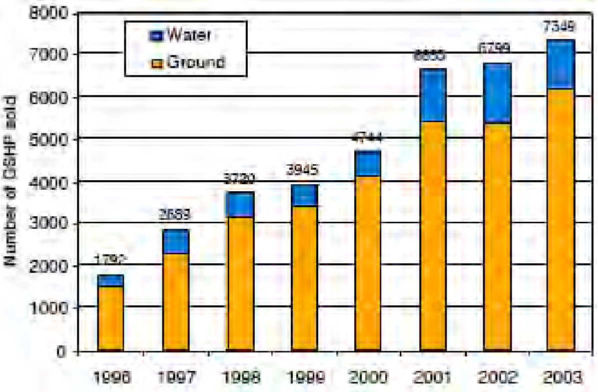


Fig. 25: Number of annual ground source heat pump sales in Germany, according to heat sources (after data from IZW e.V., Hannover and BWP e.V., Munich; heat pumps used for hot tap water production only are not included)

The use of GSHP for commercial applications can yield economic and environmental advantages. In particular in cases were heating and cooling is required, the ground as heat source and sink can act as a kind of seasonal buffer storage. In this paper only an overview of the development and the current use with some examples could be given.

There are other plants and also other technologies, e.g. the use of larger diameter horizontal pipes buried in the ground for pre-heating and pre-cooling ventilation air directly. This technology is know in Germany as air-earth heat exchangers (L-EWT), and is used e.g. in a new office building in Frankfurt-Niederrad. Also the use of foundation piles as heat exchangers is becoming popular for those building that require a pile foundation [19]. These piles, equipped with plastic pipes, are known as "energy piles", and some of the recent high buildings in Frankfurt use them. The main purpose here is to assist space cooling.

References

[1] VDI (2000): Thermische Nutzung des Untergrundes / Thermal Use of the Underground. – Guideline, German Association of Engineers VDI, part 1, Beuth Verlag, Berlin

[2] SANNER, B. (1986): Schwalbach Ground-Coupled Heat Pump (GCHP) Research Station. - Newsletter IEA Heat Pump Centre 4/4, pp. 8-10, Karlsruhe

[3] ROHNER, E. (1991): Entwicklung und Stand der Erdsonden-Anlagen in der Schweiz.- Symp. Erdgekoppelte Wärmepumpen Rauischholzhausen, IZW-Berichte 3/91, pp. 33-40, Karlsruhe

[4] KNOBLICH, K., SANNER, B. & KLUGE-SCHEID, M. (1993): Energetische, hydrologische und geologische Untersuchungen zum Entzug von Wärme aus dem Erdreich. – Giessener Geologische Schriften 49, 192 p., Giessen

[5] SANNER, B. (1990): Ground Coupled Heat Pump Systems, R&D and practical experiences in FRG. - Proc. 3rd IEA Heat Pump Conf. Tokyo 1990, pp. 401-409, Pergamon Press, Oxford

[6] HÄNEL, K. & HEINRICH, S. (1999): Wirtschaftlichkeit von Wärmepumpen – Realisierung ... am Beispiel einer Wohnanlage in Burg Spreewald. - Proc. OPET-Seminar Erdgekoppelte Wärmepumpen zum Heizen und

Klimatisieren von Gebäuden. pp. 65-76, GtV, Geeste

[7] SANNER, B. (1996): Die "Erdgekoppelte" wird 50 - 50 Jahre Erdgekoppelte in den USA, 15 Jahre Erdwärmesonden in Mitteleuropa. - Geothermische Energie 13/96, p. 1-5, Neubrandenburg

[8] SANNER, B., BREHM, D. & KNOBLICH, K. (1990): Design and Monitoring of four ground-coupled heat pump plants with vertical earth probes. - Proc. 3rd Workshop on Solar Assisted Heat Pumps with Ground Coupled Storage, pp. 63-79, CIT 1990:3, Göteborg

[9] SANNER, B. & GONKA, T. (1996): Oberflächennahe Erdwärmenutzung im Laborgebäude UEG, Wetzlar. - Oberhess. Naturw. Zeitschr., vol. 58, pp. 115-126, Giessen

[10] HÄNEL, K. (1996): Bericht über Ergebnisse aus dem Verhalten und dem Energiebedarf des Umweltzentrums Cottbus. - Report, 10 p., Brandenburg Technical University, Cottbus

[11] HÄNEL, K. (1999): Erdwärmeanlage am Umweltzentrum Cottbus. - Proc. OPET-Seminar Erdgekoppelte Wärmepumpen zum Heizen und Klimatisieren von Gebäuden. pp. 77-83, GtV, Geeste

[12] SANNER, B., REUSS, M., MANDS, E. & MÜLLER, J. (2000): Thermal Response Test - Experiences in Germany. - Proc. TERRA-STOCK 2000, pp. 177-182, Stuttgart

[13] SEIDINGER, W., MORNHINWEG, H., MANDS, E. & SANNER, B. (2000): Deutsche Flugsicherung (DFS) baut Low Energy Office mit größter Erdwärmesondenanlage Deutschlands. - Geothermische Energie 28-29/00, pp. 23-27, Geeste

[14] KNOCHE, G., KOCH, M. & METZGER, J.W. (2001): Mobile Test Equipment for Investigations on Groundwater for Use in High Temperature Aquifer Thermal Energy Storage Plants (HT-ATES) – First Results. – Proc. IGD 2001 Bad Urach, Supplement, ISS/GtV, Skopje/Geeste

[15] SEIWALD, H., HAHNE, E. & REUSS, M. (1999): Underground seasonal heat storage for a solar heating system in Neckarsulm/Germany. - Bull. Hydrogeol. 17 (Proc. EGC Basel 99), p. 349-357, Peter Lang SA, Neuchatel/Bern

[16} SANNER, B. (1999): Prospects for ground-source heat pumps in Europe. - Newsletter IEA Heat Pump Center 17/1, pp. 19-20, Sittard

[17] DONNERBAUER, R. (2003): Neuer Trend: Vom Boden an die Wand. – VDI-Nachrichten 16/2003, p. 11, Düsseldorf

[18} VAN DE VEN, H. (1999): Status and trends of the European heat pump market. - Newsletter IEA Heat Pump Center 17/1, 10-12, Sittard

[19] KNOBLICH, K. & SANNER, B. (1999): Geotechnik im Einsatz für Heizen und Kühlen - Energiepfähle. - Geotechnik 22/1, pp. 48-55, Essen